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A Network Performance Evaluation Model for Assessing the Impacts of High-Occupancy Vehicle Facilities

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Energy Division

A NETWORK PERFORMANCE EVALUATION MODEL FOR ASSESSING THE IMPACTS OF HIGH-OCCUPANCY VEHICLE FACILITIES

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A Network Performance Evaluation Model for Assessing the Impacts of High-Occupancy Vehicle Facilities

Abstract

A model to assess the impacts of major high-occupancy vehicle (HOV) facilities on regional levels of energy consumption and vehicle air pollution emissions in urban areas is developed and applied. This model can be used to forecast and compare the impacts of alternative HOV facility design and operation plans on traffic patterns, travel costs, mode choice, travel demand, energy consumption and vehicle emissions. The model is designed to show differences in the overall impacts of alternative HOV facility types, locations and operation plans rather than to serve as a tool for detailed engineering design and traffic planning studies. The Network Performance Evaluation Model (NETPEM) combines several urban transportation planning models within a multi-modal network equilibrium framework including modules with which to define the type, location and use policy of the HOV facility to be tested, and to assess the impacts of this facility.

Main features of NETPEM that distinquish it from other urban transportation planning models are its ease of use and flexibility in modelling many alternative HOV lane/ramp facilities. Spreadsheet templates are used both to prepare all input data except for the link and person trip table files. They are also used to examine all of the network performance statistics in combined tables and graphs at the end. The template used to specify the HOV facility allows for direct adjustments to the facility between modelling runs. Lastly, the three basic travel models within NETPEM -- equilibrium assignment, modal split and elastic demand -- can all be solved together until the entire system converges and have all been developed to include recent advances in transportation modelling.

Actually, the NETPEM program itself contains only the urban traffic modelling routines. The calculations of modal fuel consumption and vehicle emissions based upon link volumes and travel times from NETPEM are accomplished by running the results of NETPEM through the Performance Evaluation Module called PERMOD. This two-stage process allows the user of NETPEM and PERMOD to vary the impact parameters required for PERMOD such as fuel consumption and pollution emission

rates to see how such changes affect the magnitude of impacts without having to rerun the travel models themselves. It also streamlines the execution of NETPEM by not having these data and calculations required within it.

In addition to the standard network link, person trip and transit travel time files required for typical applications of most urban transportation planning models, spreadsheet templates are used to specify data parameters and impact coefficients to NETPEM and PERMOD. Since NETPEM and PERMOD are both programmed in the standard Pascal programming language, the codes can be executed on mainframe or microcomputers with some coversions required. The software and User's Manual provided with this report is for NETPEM-PC (which includes all of the spreadsheet templates plus PERMOD). Screen and cursor control made possible through the use of microcomputer software make this version of NETPEM easiest to use.

NETPEM-PC can be run on IBM PC, XT or AT computers. Networks having a maximum of 30 zones, 400 nodes and 1000 links can be run on these computers with 640K of RAM, while larger networks can be run on computers with more addressable memory. Spreadsheet templates are used to specify parameters, and to examine tables and graphs of the model's impact estimates, regardless of the computer used to execute the NETPEM network models. As an example application of NETPEM-PC, the potential impacts of five different HOV lane/ramp facilities, when added to a major expressway in the Pittsburgh metropolitan area, are forecasted. The results of these example runs, and potential improvements to NETPEM, are discussed. Strategies for applying NETPEM to larger and more varied networks are also discussed. A companion document, ORNL/Sub/85-27439/1, provides the "NETPEM-PC User's Manual" for those wishing to use the program.

1 Introduction

Energy planning has received considerable attention since the oil embargo of 1973-74 and the rapid inflation in motor vehicle fuel prices in the years 1978-80. The U.S. Federal Government has encouraged programs intended to reduce energy consumption and pollution emissions. A transportation strategy that has shown to be effective in this sense for some urban networks is the use of high-occupancy vehicle (HOV) lanes [5, 12, 26]. In the past decade, many HOV lane/ramp facilities have been built or implemented, and their impacts have been simulated with the help of different models.

One evaluation of the limitations and merits of existing models for predicting travel volumes concludes that most of the currently available travel demand models have inherent errors caused by the assumptions considered during their development [8]. This observation is similar to that of Kocur and Hendrickson [18] who showed that a detailed estimation of the impacts of carpooling and vanpooling can lead to results that differ substantially from those obtained by very simple models.

The purpose of the research described in this report is to develop a model to simulate and forecast the effects of HOV facilities on regional energy consumption and vehicle pollution emissions. This research was motivated by the current need for an appropriate assessment tool with which to evaluate the effects of alternative HOV facility design and operation plans on these and other impact measures. As such, this model should be considered as only one evaluation tool in a broader engineering economic analysis of HOV facilities, since more than just these particular impact measures must be considered in a complete evaluation scheme.

Throughout the development of this model, substantial efforts were made to incorporate the findings of previous modelling research and survey literature on existing HOV facilities into a flexible and applicable modelling framework [7, 8, 9, 15, 16, 32]. Flexibility is achieved by integrating computer software routines into a modular structure that allows a user to access, modify and execute individual parts of the entire model without changing its global design. The goal is to provide an assessment tool that is more accurate than quick-response or sketch planning techniques, and more sensitive to facility design and operation changes, without having its use become too burdensome in hardware, software, data preparation and report generation requirements. Excessive implementation requirements often prevent well constructed forecasting tools from being implemented, validated and employed for their intended purposes.

The Network Performance Evaluation Model (NETPEM) requires the user to fulfill the procedural requirements of four basic model preparation and result evaluation stages through which computer software routines called *modules* are executed and reports or datasets are generated according to user directives. Detailed descriptions of the modules and the models that they contain are given in later sections of this report. The four stages of model implementation can be summarized as follows:

1. *Multimodal Network Model Development.* A standard ASCII dataset describing the network structure of nodes, zones and highway links must be coded. NETPEM is designed to be used with fairly aggregate networks. Zone-to-zone travel times and costs per person trip by bus transit based upon information derived from transit schedules and route configurations are input to NETPEM as additional data. A zone-to-zone person trip table of all highway and transit trips for the appropriate time-of-day period is required. Percentages of person trips that travel by each mode from each origin zone in the base case are required if modal split is to be performed.

2. *Model Calibration and Parameter Specification.* NETPEM can be run as a straight equilibrium assignment model, assignment with modal split, or assignment with modal split and elastic demand. The user specifies the type of model to be run interactively during each run session. Each of these modelling options requires a set of modelling parameters to be calibrated in NETPEM or otherwise specified to the model via the spreadsheet templates. NETPEM also requires that several program control parameters be specified by the user to define the accuracy of certain iterative routines or to limit their execution.

3. *HOV Facility Design and Use Policy.* By means of the HOV facility specification template, the user defines the location, restrictions, use policy and other design characteristics of the HOV facility for which impacts are to evaluated. Assumptions as to how the HOV lane/ramp facility will affect the travel times and capacities of adjacent non-HOV lanes must also be specified by the user from a set of alternative traffic interaction assumptions provided.

4. *HOV Performance Evaluation.* After completing the above stages and executing the model, NETPEM outputs datasets containing link volumes and travel times for non-HOV's and HOV's, zone-to-zone bus travel times, and several other travel statistics needed to assess the performance of the network and to compute energy and environmental impacts. Without any changes by the user, these modelling results are read directly into the Performance Evaluation Module (PERMOD), which writes a summary table of network performance statistics by mode to a file that is viewed and graphed by the user via another spreadsheet template. Graphs of the primary impact measures by mode are programmed into the evaluation spreadsheet for direct use by the analyst. Graphs of the other impact measures can be prepared by the user, and additional impact measures can be computed through the manipulation of the output data files.

As a preview to the composition of this report, Section 2 provides an overview of NETPEM. Sections 3-8 present the model formulations and solution procedures used in NETPEM. Section 9 describes the fuel consumption and pollution emissions calculations performed in PERMOD, while Section 10 reviews the step-by-step sequence of these calculations and the templates used to specify rates of energy use and pollution emissions for each mode. Section 11 presents example applications of NETPEM by forecasting the impacts of adding alternative HOV facilities with different use policies to a major freeway in the Pittsburgh eastern commuting corridor. Section 12 describes some strategies for using NETPEM to simulate other types of HOV lane/ramp facilities.

2 Overview of the Network Performance Evaluation Model

2.1 Structure of the Network Performance Evaluation Model

The various modules of NETPEM that are used to model HOV lane/ramp facilities in a highway network, forecast travel demand, mode split and route choice, and to assess the energy and emission impacts of these facilities, are shown in Figure 1. The modules are numbered in the order in which they will be described. The five basic modules of the system are:

1. *Initial Development of the Network Model.* This step includes the typical assembly of information and data required for using most urban transportation planning models.

Link data including end nodes, free-flow travel times, capacities and lengths are input as one file. Other data files include a person trip table that will be split among modes by the modal split model on the basis of travel times and costs and other modal split parameters, a description of the HOV facility if one is to be added, and zone-to-zone scheduled bus trips and average bus route distances. These files are read into NETPEM at the start of execution.

2. *Traffic Assignment Module.* Estimates user equilibrium highway link volumes given the non-HOV auto person trip table.

Auto trips are assigned first, from which equilibrium travel times are obtained for the highway links. The HOV facility can itself impact the travel times of non-HOV trips if the HOV facility imposes restrictions or otherwise affects congestion in the non-HOV lanes, ramps and routes. HOV's are assumed to use one of the equilibrium

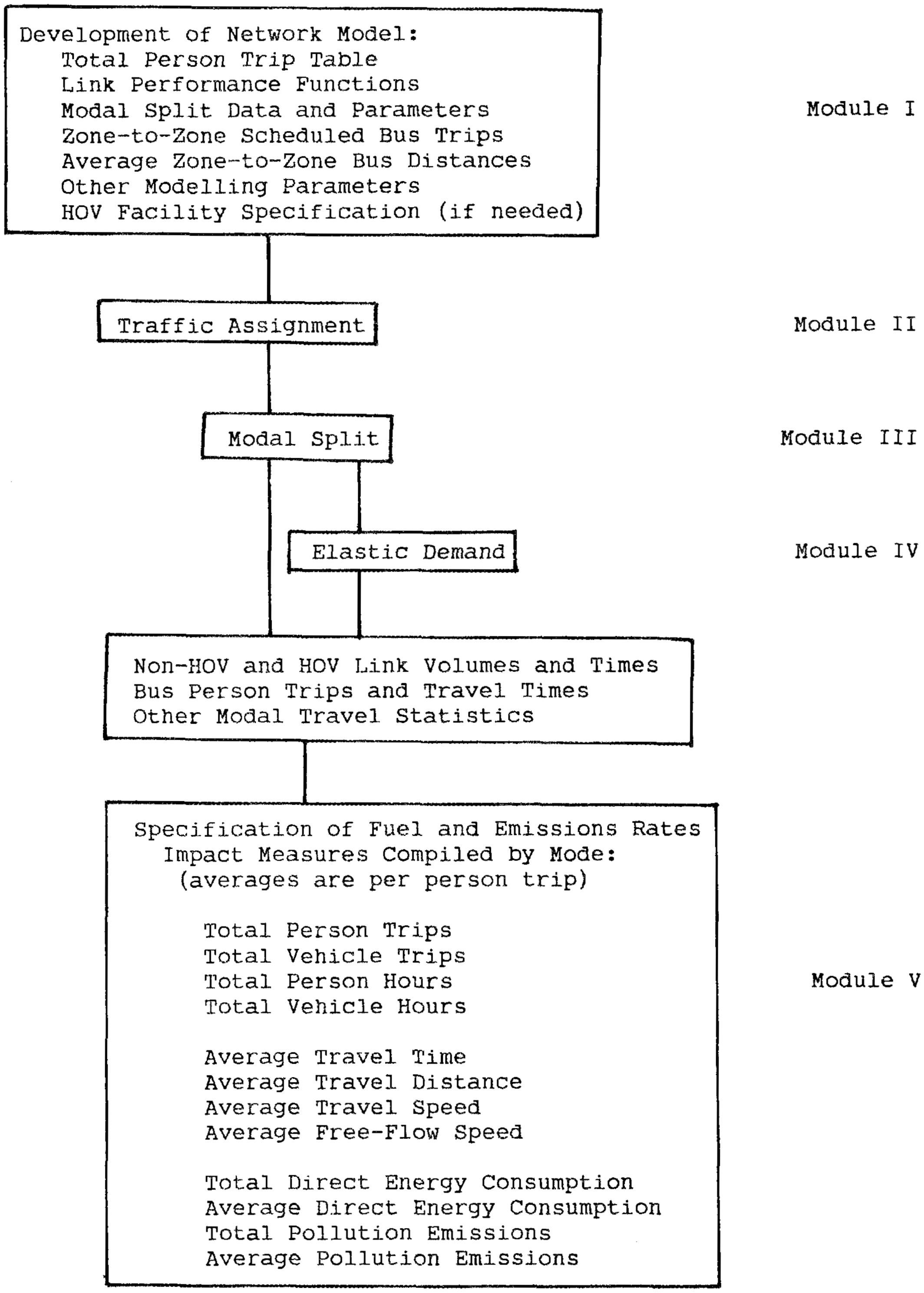

Figure 1: Basic Structure of the Network Performance Evaluation Model

non-HOV routes for all trips or parts of trips that cannot make effective use of the HOV facility. Bus travel times are determined on the basis of HOV and non-HOV travel times depending upon whether a particular zone-to-zone bus route uses the non-HOV highway network or can make effective use of the HOV facility. The assumption used in the examples presented later is that bus travel times are 35% greater than their applicable HOV or non-HOV travel time.

3. *Modal Split Module.* Splits total person trips between each pair of zones into person trips by alternative transportation modes.

In the current version of NETPEM, person trips are divided among four alternative modes of travel, which are defined to be:

- auto: includes all person trips via a privately operated vehicle providing one or two person trips.
- pool3: includes all person trips via a privately operated vehicle providing three person trips.
- pool4+: includes all person trips via a privately operated vehicle providing four or more person trips.
- bus: includes all person trips via regularly operated public transit routes with vehicles that can carry 20 or more passengers.

The above definitions are meant to be as concise as possible. For example, a taxi carrying two passengers falls into the "auto" category, whereas a privately operated vehicle in which the driver and two passengers are all making purposeful trips belongs to the "pool3" category. The pool3 and pool4+ categories were chosen so that the impacts of 3+ versus 4+ lane use policies could be compared. Although all vanpools are averaged into the 4+ category, a discussion is provided in Section 11 as to how to vary the percentage of vanpools in the HOV fleet.

Additional modes can be added to NETPEM with some modifications to the program. However, each additional mode can substantially increase memory requirements and CPU time. The modes defined above are considered to be reasonable choices for a first version of NETPEM. To economize on memory even further, the two pool categories are first assigned to the network separately, and then travel statistics for all HOV's are reported together. This particular aspect of the program can be altered as NETPEM is upgraded to larger and faster microcomputers.

4. *Elastic Demand Module.* Determines total person trips between each origin-destination pair of zones on the basis of modal travel costs between these zones.

As congestion increases, travelers may not only change their mode choices, but they may also choose to forego some trips, shift trips to other times of day, or to combine trips by trip chaining. To allow for elasticity in the total number of person trips between each pair of zones, this fourth module is required. The sum of per trip modal travel costs between each pair of zones is used in a relatively simple multinomial logit function to determine changes in travel demand relative to modal travel costs in the base network.

5. *Performance Evaluation Module.* - Generates tables and graphs depicting modal person and vehicle trips, travel times, volumes, energy consumption and vehicle emission impacts.

Once modal link volumes, travel times and other outcomes of a model's run have been computed by NETPEM, energy and environmental impacts as well as other network performance impact measures can be generated for terminal display or hardcopy output by using PERMOD. The procedures that PERMOD incorporates for calculating and tabulating energy use and vehicle emissions impacts are described by Southworth and Janson [25]. These calculations are made on the basis of modal energy use and emission rates specified by the user via a series of spreadsheet templates. After the user has specified a desired set of impact coefficients to each template, a macro function within each template is used to write a data file to disk that is used by PERMOD, along with HOV and non-HOV link volumes and travel times, and bus person trips and times, to calculate the modal impacts and to summarize them into one final table.

3 Specification of Model Parameters and Coefficients

Modal split parameters, direct energy consumption and pollution emission rates, HOV facilities and use restrictions, and other model coefficients are specified by the user prior to executing NETPEM or PERMOD through the use of spreadsheet templates. These templates allow the user to enter values (or use the default values provided) for each group of parameters and other coefficients required. Another template allows the user to add alternative HOV facilities to the network, or to change the HOV facility use policies.

The specification of fuel consumption and emissions rates -- referred to here as the impact coefficients -- is explained in Section 9, where the Performance Evaluation Module (PERMOD) is explained, and in Section 10, where the data used in our example applications are described. However, the manner in which an HOV facility is added to an existing network model is described next.

3.1 Specification of the HOV Facility

Adding an HOV facility to the network is accomplished by means of a spreadsheet template named HOVFAC by which the user specifies the nodes through which the facility passes, nodes at which the facility may be entered and exited, and the facility's estimated impact on the link performance functions of non-HOV links. Several HOV facilities may be introduced to the network in succession or simultaneously.

Link Data Required to Add an HOV Facility to the Network

1. From-node of HOV link.
2. Whether HOV facility may be entered at this node (1=yes, 2=no; always yes for a diamond lane).
3. To-node of HOV link.
4. Whether HOV facility may be exited at this node (1=yes, 2=no; always yes for a diamond lane).
5. Average (free-flow) travel time on the HOV link (hours).
6. Effect of the HOV link on the road capacity of adjacent highway links (capacity factor).
7. Effect of the HOV link on the free-flow travel time of adjacent highway links (time factor).
8. Length of the HOV link (miles).

The above data must be specified for every HOV link that is to be added to the network model. The location of an HOV facility is defined by the nodes at which it starts, stops and passes through. By specifying whether vehicles may enter or exist the HOV facility at these nodes, the user effectively defines the HOV facility type as a series of links that can be entered and exited at many or just a few locations. The user may also specify two additional factors that will be applied to the capacities and free-flow travel times of adjacent non-HOV links so as to model the effect of the HOV facility on the performance of these links as well. The two HOV facility types that would typically be modelled in NETPEM by specifying the above data elements are:

1. *Diamond Lanes.*
   This HOV facility type has an independent lane that is not physically separated from the non-HOV lanes. Other vehicles can violate the HOV restriction and enter into this lane. Therefore, the free flow travel time in the diamond lane may be higher than that specified for a physically separated lane. The sequence of from-nodes and to-nodes used to specify a diamond lane must agree exactly with the nodal sequence of the adjacent non-HOV links. Entrance to or exit from the HOV lane is permitted at any node held in common by this lane and the regular highway network.

2. *Physically Separated Lanes.*
   This type of HOV facility does have a physically separated lane. The direction of the flow is either the same as or counter to the flow of adjacent non-HOV lanes (if such lanes exist) as indicated by the direction in which the link is coded. (All links are coded as directed arcs). Entrance to or exit from this type of HOV facility is permitted at any node held in common by this lane and the regular highway network. The original capacity of an adjacent highway link is reduced for non-HOV users if the HOV lane is formed from an existing lane.

The case of a physically separated facility that does not impact adjacent highway links is the only case in which the pairs of from-nodes and to-nodes that identify links of the HOV facility are not required to have identically matching pairs in the existing highway network. The reason for this is that NETPEM must be able to uniquely identify adjacent highway links in the regular highway network in order to account for the effects of the HOV facility on the travel times and capacities of these links. In addition, since travelers can merge into and out of a diamond lane at almost any point along its length, their route choice decisions cannot be constrained to any degree greater than the aggregated representation of the network for all highway users.

The value of the factor that changes the capacity of adjacent non-HOV links can range from 0.5 (one of two auto lanes is converted into an HOV lane) to 1.0 (the capacities of the adjacent links are unaffected). A value of 0.33 for this factor would be used for the case in which one of three freeway lanes was converted to a diamond lane. Effects of weaving can be taken into account by adjusting this factor upwards or downwards. For a physically separated lane, the intimidation of large barriers may be a reason to use a factor such as 0.4 when removing one of three lanes for HOV use only.

The value of the factor used to adjust the free-flow travel times of adjacent non-HOV links must be greater than or equal to 1.0. A value of 1.0 means that the presence of an adjacent HOV facility is not expected to increase the free-flow travel time of existing highway links at all. The use of the HOV facility specification template to specify each of these parameters will be further explained and illustrated at the start of the example application section.

4 Design of the Traffic Assignment Module

This section describes equilibrium assignment of highway vehicle trips to an urban transportation network assuming fixed travel demands. Later sections explain the modal split and elastic demand models used in NETPEM and how these models are solved for with equilibrium assignment. Conditions for user equilibrium in transportation networks were identified by Wardrop [31], and the user equilibrium traffic assignment problem was first formalized as a mathematical program by Beckmann *et al*. [2]. Several authors [10, 11, 22] have since described the Frank-Wolfe method of traffic assignment by which a solution to this problem can be found or approximated, although a modified version of the Frank-Wolfe method called the PARTAN technique has been shown to converge more rapidly towards the equilibrium solution [14, 19]. The PARTAN technique is always used in NETPEM when solving the equilibrium assignment problem.

The network assignment problem assumes that a directed network is given, where N is the set of nodes, A is the set of directed arcs and Z is the set of nodes (called zones) at which flows (e.g. vehicle trips) originate or terminate. Each pair of indices (i,j) denotes an arc from node i to node j. Let x_{ij}^{rs} equal the portion of flow on arc (i,j) that originates from zone r and terminates at zone s. This notation allows flows between specific origin-destination pairs to be distinquished from the total flow x_{ij} on arc (i,j), which equals the sum of these O-D specific flows. Lastly, let q_{rs} be defined as the total flow from node r to node s. The equilibrium traffic assignment problem can thus be formulated as follows:

$$\text{Minimize} \quad \sum_{(i,j)\in A} \int_0^{x_{ij}} f_{ij}(y)\, dy \tag{1}$$

$$\text{subject to:} \quad \sum_{s\in Z} \left[\sum_{(i,k)\in A} x_{ik}^{rs} - \sum_{(k,j)\in A} x_{kj}^{rs} \right] = q_{rk} \quad \text{for all } k\in N,\ r\in Z \tag{2}$$

$$\sum_{\substack{r\in Z \\ s\in Z}} x_{ij}^{rs} = x_{ij} \quad \text{for all } (i,j)\in A \tag{3}$$

$$x_{ij}^{rs} \geq 0 \quad \text{for all } r\in Z,\ s\in Z,\ (i,j)\in A \tag{4}$$

In this notation, y is simply an integration variable for each impedance function. Equation (2) requires conservation of flow at each node, equation (3) insures the proper inflow and outflow at each origin-destination zone, and equation (4) requires that each arc flow be non-negative. Note that the summation of flows in equation (2) could have been performed over all origins $r \epsilon Z$ instead of over all destinations $s \epsilon Z$, the only difference being that the right-hand-side of equation (2) must then be expressed as $-q_{ks}$ instead of as q_{rk}.

Figure 2 shows the structure of the traffic assignment module. This module reads data from three input files and writes the equilibrium link flows and impedances to an output file. The three input data files contain the following information:

1. *Program Control File.* Contains global network data and program control parameters including the number of nodes, number of zones, number of arcs, maximum number of equilibrium assignment iterations, a trip table adjustment factor, and various printing switches.

2. *Zone-to-Zone Trip Matrix File.* Contains the zone-to-zone person trip table for all modes of travel, which will be split between modes in the modal split module.

3. *Network Link File with Performance Function Parameters.* Contains the from-node, to-node, free-flow travel time (hours), the practical capacity (vehicles/hour) and the length (miles) of each link.

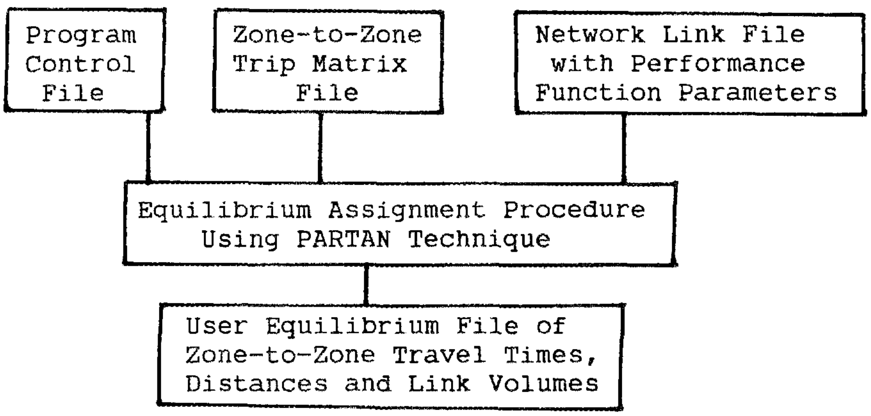

Figure 2: Basic Structure of the Traffic Assignment Module

Each of the input files can be created by using any brand of software that allows the option of writing standard ASCII files to a disk. Many types of text editing, spreadsheet and database software programs have this capability. The core of the assignment procedure is the PARTAN technique [14, 19]. The results of the assignment are written to intermediate output files for post-processing by the Performance Evaluation Module (PERMOD).

5 Design of the Modal Split Module

In this section, we extend the problem of traffic assignment to include alternative transportation modes. For ease of description, only three modes are considered: drive-alone auto, car or van pools, and buses. However, there are actually two pool modes to which trips are split in NETPEM -- pool3 and pool4+. Hence, the reader can generalize the various equations shown below that pertain to pools as applying to each of these two categories. It is assumed throughout this section that the total number of trips between each pair of zones is known and remains constant. Elastic demand will be treated in the next section. The multinomial logit model is the particular type of modal split model used in NETPEM.

In a transportation network where different travel modes are available, person trips between each pair of zones choose between these modes. Disaggregate models based on individual choices have been widely used and shown to resemble discrete travel choices more adequately than aggregate models [21]. However, modelling the choice probabilities of individuals requires that large datasets on individual preferences be gathered and used, which makes the application of such models rather burdensome. Ahsan [1] shows that an aggregate treatment of travel times and costs may be incorporated into the multinomial logit model to estimate the aggregate probabilities of mode choices by travelers between common origin-destination pairs.

NETPEM uses an aggregate approach for calculating zone-to-zone modal choice probabilities. The probability that a person trip from origin zone r to destination zone s will travel by mode m, denoted as P^m_{rs}, is actually a function of many variables. Relative mode performances in terms of travel time and cost as well as individual preferences are factors that determine the split of the total person trips q_{rs} among the alternative modes. Studies on modal choice modelling, such as [4, 20, 23, 24, 27, 28], have shown that, in addition to the average in-vehicle travel time $IVTT^m_{rs}$ for trips from zone r to zone s by mode m, other factors such as the average out-of-pocket cost $OPTC^m_{rs}$ for such trips relative to the average annual income Inc_r of persons residing in origin zone r are significant determinants of modal split.

Assuming that these probabilities have been estimated or observed, the number of person trips from zone r to zone s that travel by mode m is given by the formula:

$$q^m_{rs} = q_{rs} * P^m_{rs} \tag{5}$$

where, q^m_{rs} = number of person trips from zone r to zone s using mode m,

q_{rs} = total number of person trips from zone r to zone s,

P^m_{rs} = probability that a person trip from zone r to zone s chooses mode m.

Different models exist with which to estimate P^m_{rs} for each pair of zones (r,s) and each mode m, of which the multinomial logit model used in NETPEM is one. In order to calibrate the logit model, we must first calculate the *utility* of each mode m to travelers between each pair of zones based upon the observed modal preferences of person trips from each origin zone and the average travel times and costs of trips by each mode between each pair of zones. Data used to calibrate the modal split model is only required by origin zone, which is compatible with the aggregation levels of census data and other household surveys. This calibrated function is then used to calculate values of zone-to-zone modal utilities based upon the average zone-to-zone travel times and costs of trips by each mode.

The relative utility V^m_{rs} of mode m to trips from zone r to zone s is given by:

$$V^m_{rs} = \alpha^m_{rs} + \beta\ OPTC^m_{rs} / Inc_r + \gamma\ IVTT^m_{rs} \tag{6}$$

where, α^m_{rs} = constant factor of utility for trips by mode m from zone r to zone s,

$OPTC^m_{rs}$ = average out-of-pocket cost for trips by mode m from zone r to zone s,

$IVTT^m_{rs}$ = average in-vehicle travel time for trips by mode m from zone r to zone s,

Inc_r = average annual income of travelers from zone r,

β, γ = constant calibration parameters for the model.

The next equation is the multinomial logit function used to calculate zone-to-zone modal choice probabilities by comparing (in exponential form) the utility of a person trip by mode m to the sum of person trip utilities for each of the available modes. These modal choice probabilities are calculated separately for each zone pair.

$$P^m_{rs} = exp[V^m_{rs}] \ / \ \Sigma_n \ exp[V^n_{rs}] \tag{7}$$

where, P^m_{rs} = probability that a person trip from zone r to zone s chooses mode m,

V^m_{rs} = relative utility of mode m to a trip from zone r to zone s,

exp = exponential expression.

The superscript n is used instead of m to designate travel modes in the denominator of equation (7) so as not to be confused with the specific mode m to which the equation applies. In this form of the model, the calibration parameters β and γ are assumed to be the same for all trips throughout the region, but the modal utility values are unique to travelers between each pair of zones. An initial set of zone-to-zone travel times and costs must be obtained for each mode in order to calculate the a^m_{rs} parameters in the modal utility formula by calibrating the multinomial logit model to the base case. In NETPEM, the initial auto trip table is assigned to the network via the equilibrium assignment module. After adjusting the HOV and bus travel times and costs on the basis of the equilibrium assignment results, a set of a^m_{rs} parameters are computed that exactly reproduce the base case person trip tables when used with the base case travel times and costs.

The initial person trip tables containing the q^m_{rs} values for the base case are computed in NETPEM by factoring an "observed" total person trip table for all modes by "survey" percentages of trips by each mode from each origin. The user enters the number of person trips by each mode for each origin zone via a spreadsheet template named MSPLIT. The format of this template and examples of all data entered to it can be found in the Appendix. A list of these data elements required for the modal split calibration and execution are:

Modal Split Constants for All Origin Zones

1. The OPTC modal utility coefficient beta β.

2. The IVTT modal utility coefficient gamma γ.

3. A road distance to airline (straight line) distance ratio used to estimate the distances traveled by HOV's to pick-up and deliver passengers.

4. A pick-up dwell time of HOV's at each pick-up site (minutes).

5. The average occupancy of autos carrying 1 or 2 person trips.

6. The average out-of-pocket cost per vehicle trip mile by auto and pools (cents per vehicle trip mile).

7. The average bus fare per person trip for trips between all zones (cents).

Modal Split Data Required for Each Origin Zone

1. Average annual income per traveler from each origin zone (dollars).
2. Land area of each zone (square miles; used to estimate pool rider pick-up distances and times).
3. Number of auto, pool and bus person trip origins from each zone during a typical time span of the analysis period.
4. Average number of person trips per car or van pool.
5. Percentage of poolers traveling in 3 person pools.

NETPEM disaggregates the initial total person trip table into to separate modes according to the numbers of person trips traveling from each origin zone by each mode m as initially given. The problem is then to calculate the zone-to-zone modal utilities and modal split probabilities of person trips after the HOV facility has been introduced to the network, and to reach an acceptable convergence of the modal split and assignment models together. The procedure used in NETPEM to achieve this is explained in the next section.

6 Solving for Modal Split and Assignment

One approach to solving for modal split and assignment consists of performing modal splits and traffic assignments in an iterative manner until the system has sufficiently converged. The flowchart of this scheme is shown in Figure 3. After each assignment, modal person trip tables are recalculated. Each new auto trip table is input to the next execution of equilibrium assignment. This process is repeated until the modal trip tables do not change significantly from one iteration to the next. The rate at which this process converges depends upon the starting solution, and on the shape of the modal split and link performance functions.

In the above procedure, the initial auto trip table is assigned to the network via the equilibrium assignment module. After adjusting the HOV and bus travel times on the basis of the equilibrium assignment results, the modal split alpha parameters (α_{rs}^{m}) are calibrated. If no HOV facility has been added to the network, then the base case modal trip tables will be exactly reproduced by the modal split calculations. The user can thus check to see whether any errors are produced by this procedure for the base case. The user can also skip modal split at this time if straight equilibrium assignment with no modal split is desired. If an HOV facility is added to the network after the initial assignment and modal split calibration, then the new modal trip tables will probably be different from the base case.

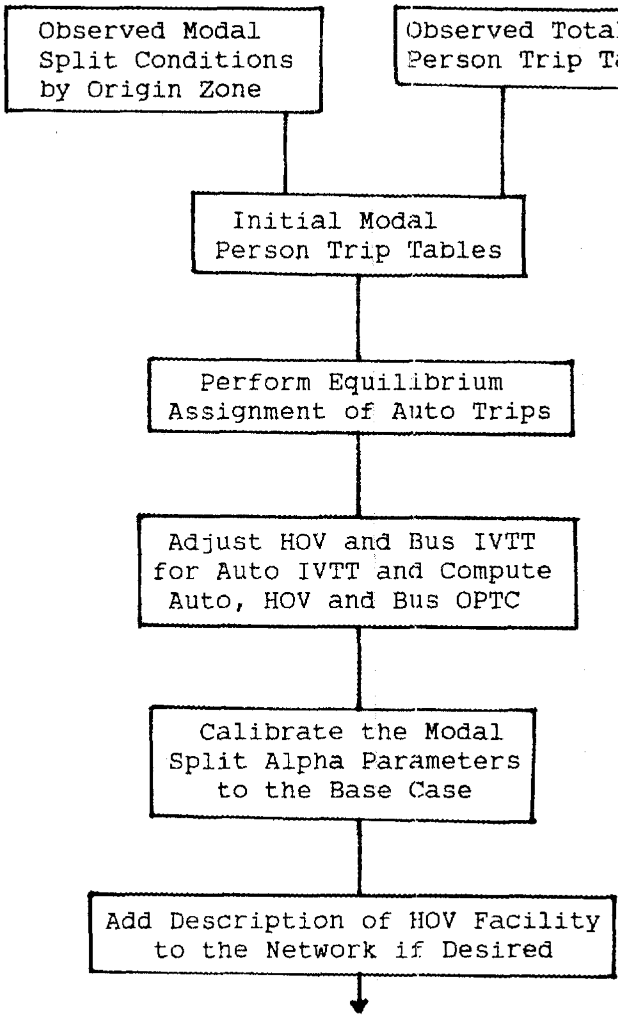

Figure Continued on Next Page

Figure 3: Iterative Solution Procedure to Modal Split and Assignment

In the next execution of equilibrium assignment, an HOV facility added to the network will only affect the assignment of auto trips to the extent that this facility impacts the performance of the non-HOV links. The number of HOV vehicles on a road is a very small percentage of total vehicles; therefore, an HOV facility significantly affects congestion for non-HOV travelers only when there is a reduction in the number of lanes available for autos or if ramp metering affects non-HOV traffic flow in some way. This assumption allows us to obtain auto travel times by performing the assignment of auto trips separately from HOV trips.

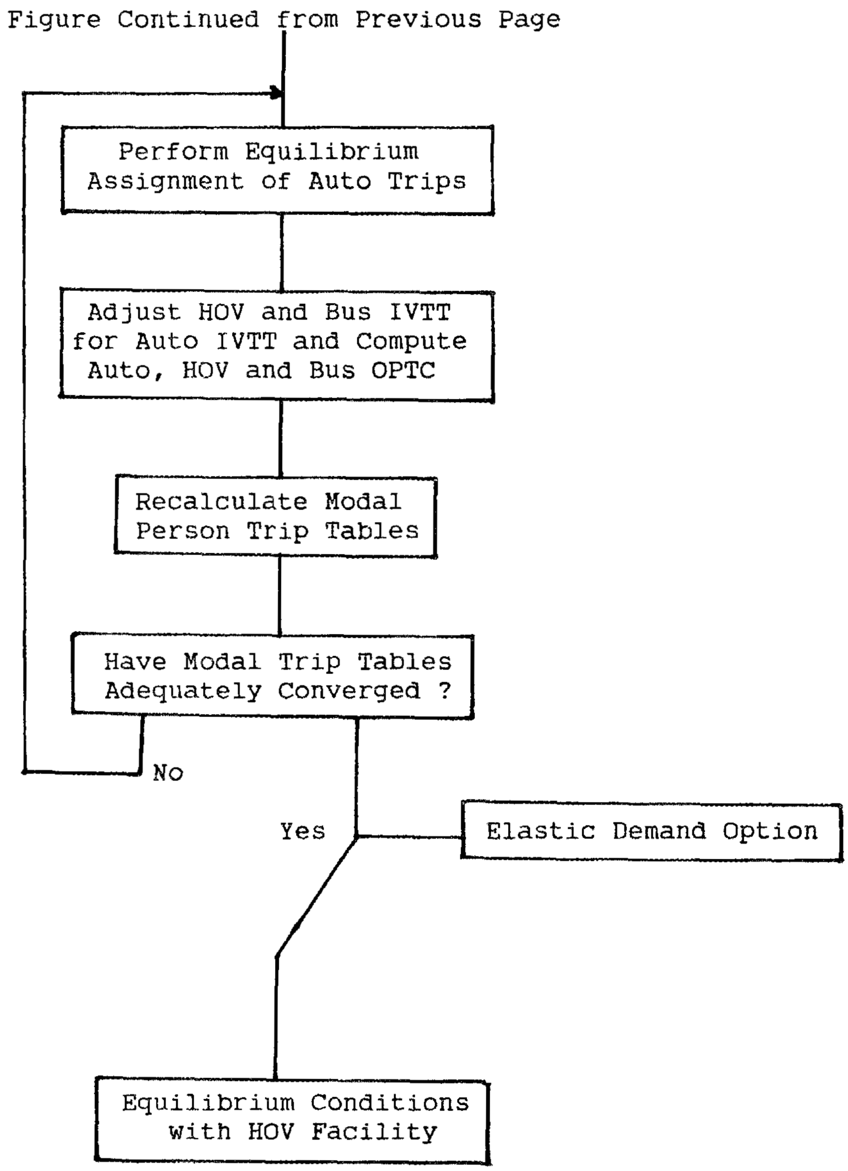

Figure 3 continued: Iterative Solution Procedure to Modal Split and Assignment

The following steps outline in greater detail how modal split and assignment are solved for in NETPEM in order to clarify the flowchart given in Figure 3.

Step 1: Calculation of zone-to-zone modal IVTT and OPTC matrices with which to calibrate the multinomial logit model.

An observed (or estimated) zone-to-zone auto vehicle trip table is assigned to the base highway network using the equilibrium assignment module. This auto vehicle trip table represents a subset of total zone-to-zone trips derived directly from the total person trip table using the "observed" modal split probabilities. This assignment results in zone-to-zone auto trip travel times $IVTT^{a}_{rs}$ that are used to approximate zone-to-zone travel times via pools according to the following equation developed by Kocur and Hendrickson [18].

$$IVTT^{p}_{rs} = IVTT^{a}_{rs} + n_r*dwell + rdsld*\mathit{sqrt}[n_r*Area_r/N^{p}_{r}]*[\mathit{sqrt}(n_r-0.5)-0.71]/avgsp \quad (8)$$

where, $IVTT^{a}_{rs}$ = in-vehicle travel time by auto from zone r to zone s as obtained from the equilibrium assignment solution,

$IVTT^{p}_{rs}$ = in-vehicle travel time by pool from zone r to zone s,

n_r = average number of person trips per pool trip from zone r,

N^{p}_{r} = total number of person trips in pools from zone r,

avgsp = average speed of pool vehicle between passenger pick-ups,

rdsld = road distance to straight line distance ratio,

dwell = average dwell time to pick up a passenger,

$Area_r$ = land area of zone r,

sqrt = square root expression.

As stated earlier in this report, initial bus travel times are determined from a current transit schedule and route distances, and then adjusted on the basis of the auto and HOV travel times depending upon whether the bus uses non-HOV links only or can make effective use of the HOV facility.

Values of OPTC per auto person trip between each pair of zones are calculated on the basis of fixed and variable costs per auto vehicle trip as given by the following equation:

$$OPTC^{a}_{rs} = c^{a}_{0} + c^{a}_{1}*d^{a}_{rs} + c^{a}_{2}*IVTT^{a}_{rs} \quad (9)$$

where, c^{a}_{0} = fixed cost per trip such as tolls and parking,

c^{a}_{1} = variable cost of vehicle operation strictly related to travel distance,

d^{a}_{rs} = average travel distance by auto from zone r to zone s as approximated from the equilibrium assignment,

c_2^a = variable cost of vehicle operation strictly related to travel time.

$IVTT_{rs}^a$ = in-vehicle travel time by auto from zone r to zone s.

Values of OPTC per auto person trip are obtained from the above formula by dividing by the average occupancy of auto vehicle trips. This factor might be in the range of 1.1 to 1.3 depending upon the mix of auto vehicle trips providing one or two person trips. Values of zone-to-zone auto travel time $IVTT_{rs}^a$ are obtained directly from the equilibrium solution. An average zone-to-zone auto travel distance d_{rs}^a is approximated by taking a weighted average of path distances to which trips from zone r to zone s were assigned in the assignment process as explained in references [13] and [25].

Values of OPTC per pool person trip are also calculated on the basis of fixed and variable costs per vehicle trip, including the travel time and distance required for passenger pick-ups, as shown by equation (10):

$$OPTC_{rs}^p = [c_0^p + c_1^p * d_{rs}^p + c_2^p * IVTT_{rs}^p] / n_r \qquad (10)$$

where, c_0^p = fixed cost per trip such as tolls and parking, plus vehicle leasing and insurance costs (per person trip) for contractual car and van pooling arrangements.

c_1^p = variable cost of vehicle operation strictly related to travel distance,

d_{rs}^p = average travel distance by auto from zone r to zone s as approximated from the equilibrium assignment,

c_2^p = variable cost of vehicle operation strictly related to travel time.

$IVTT_{rs}^p$ = in-vehicle travel time by auto from zone r to zone s as obtained from the equilibrium assignment solution.

Note that OPTC per pool vehicle trip is divided by the average number of persons in a pool so as to represent OPTC per pool person trip. The approximation that $IVTT_{rs}^p$ equals $IVTT_{rs}^a$ plus additional time to pick up passengers was explained above. The estimation of d_{rs}^p from d_{rs}^a is identical for this base case of the network model when no HOV facility exists, except that dwell time is excluded and the distance traveled to pick-up passengers is not converted to time, as shown by equation (11) below.

$$d^p_{rs} = d^a_{rs} + rdsld*sqrt[n_r*Area_r/N^p_r]*[sqrt(n_r-0.5)-0.71] \qquad (11)$$

Finally, OPTC per bus person trip is calculated directly from the transit system's zone-to-zone fare structure and held fixed throughout the model.

Step 2: Calibration of the multinomial logit modal split model.

Step 1 calculations, plus data on total person trips by each mode from each zone and their average incomes, provide all the information required to calibrate the multinomial logit coefficients α^m_{rs} for each mode and O-D pair, as well as the two other parameters β and γ.

The multinomial logit calibration process is explained in references [17] and [22]. The result of the calibration procedure is a set of parameters that, when used in equation (6) with estimates of zone-to-zone modal IVTT and OPTC per person trip, yield a set of zone-to-zone modal utilities per person trip. These utilities, when placed into equation (7), yield a set of zone-to-zone mode choice probabilities that agree with the modal split percentages by origin zone calculated on the basis of observed data.

Step 3: The combined modal split and assignment procedure.

Once the modal split parameters have been calibrated in Step 2, the following steps are performed to equilibrate modal split and assignment.

1. Calculate zone-to-zone auto person trips q^a_{rs} by using the zone-to-zone auto choice probabilities P^a_{rs} found in Step 2 based upon initial conditions of the network and the matrix of zone-to-zone total person trips q_{rs}. Use equation (5) for these calculations.

2. Introduce the HOV facility at this time by changing the link performance functions of non-HOV links affected by new HOV lanes if a facility is to be evaluated that will have such impacts on non-HOV links.

3. Solve for equilibrium traffic assignment by loading zone-to-zone auto vehicle trips (derived from auto person trips) onto the highway network.

4. Compute the matrices $IVTT^m_{rs}$ and $OPTC^m_{rs}$ for each mode m, and recalculate all three modal person trip tables using equations (5-7).

5. Determine the largest percentage change of any one O-D cell between a new modal trip table and that of the previous iteration. If the largest percentage change is less than a prespecified convergence value $\epsilon>0$, then STOP. Otherwise, return to Step 3.3 above.

Because of many simplifying assumptions used in the design of NETPEM, there are very few differences in how the model is solved when the HOV facility is or is not present. Calculations of $IVTT^{p}_{rs}$ and $OPTC^{p}_{rs}$ for car and van pools using equations (8), (10) and (11) were explained earlier for the case in which no HOV facility is present. If the HOV facility is added, then pool trips between O-D pairs of zones that can make use of this facility will do so, since the travel times and costs of the HOV route will be less than the equilibrium travel times and costs of other routes.

To determine for which O-D pairs the HOV facility provides a better route and will thus be used by pool trips, we execute the shortest path algorithm following Step 3.3 above with the equilibrium travel times held constant for non-HOV links and HOV links open to use by the pools. Pools that can or cannot benefit from the HOV facility will be revealed by the shortest paths found. The best travel times and distances for the pool trips are assumed to be approximated by this set of paths. Equations (8), (10) and (11) are then used to add the required times and distances for passenger pick-ups, and the IVTT and OPTC matrices are computed and used in Step 3.4 above. The other change that adding the HOV facility introduces to the network model is that it may change the free-flow speed or capacity of some non-HOV links. These changes are made in Step 3.2 above.

Comments Regarding Alternative Combined Model Formulations

The solution of modal split and assignment as explained above reveals that NETPEM does not solve this problem as a "combined model". The formulation of modal split and assignment as a combined model requires that the integral of the inverse of the modal split function be added to the equilibrium assignment objective function [22]. A similar requirement is necessary for a super-networks formulation. This combination of objective function terms can only be achieved if the travel cost variable in the link performance functions is identical to the travel cost variable in the modal choice function.

Transportation researchers have often debated the proper form of a *composite cost* or a *generalized travel cost* that could be correctly used in the link performance functions, modal split models and elastic demand equations of combined models. However, a primary concern in attempting to use either combined or super-network formulations of these problems is that the inclusion or exclusion of specific cost factors becomes critical. Equations such as those used to calculate modal utilities in NETPEM can no longer be calibrated to observed modal trip tables in such a way that the α^{m}_{rs} coefficients exactly compensate for the errors in trips estimated by the IVTT and OPTC factors.

Inability to calibrate a modal split function in a combined model such that the base case modal trip tables are exactly reproduced is the main reason why combined model formulations and solution techniques were not used in NETPEM. In addition, implementation of a combined model also requires that much more travel cost information be available, and that the user has gone to great lengths to correctly include these costs and their weighting parameters within the structure of the model. In comparison, by calibrating the modal split function to the observed trip tables as is done in NETPEM, many missing or relatively fixed cost factors affecting mode choice other than IVTT and OPTC are adjusted for in an approximate manner by the a^{m}_{rs} parameters.

The assumptions made to formulate and solve the combined model imply that mode choice decisions are made differently than the way they are solved for in NETPEM. Which assumptions, and thus which model form, is a more valid representation of aggregate choice behavior is a matter of extensive debate among transportation researchers. NETPEM assumes that the primary factors affecting mode choice are IVTT and OPTC. These two factors are converted into modal utilities, which are then used in the multinomial logit model to split person trips between modes.

While NETPEM uses an iterative solution approach, it also incorporates a restart procedure by which previous solutions of the assignment problem are used as good starting solutions to new assignment problems created by modal split and/or elastic demand changes to the auto person trip table [33]. By adopting this restart strategy, and the PARTAN assignment technique, NETPEM reduces the computational effort of each new assignment in comparison to more traditional solution techniques.

7 Design of the Elastic Demand Module

This section extends to the modal split and assignment model in NETPEM to include elastic demand. Changes in travel costs brought about by changes in the types and levels of transportation supply in a network can affect the total number of person trips electing to travel between each pair of zones. If travel costs increase for a particular mode, travelers might not only change their mode or destination choices, but may also forego some trips. To accommodate demand elasticity, which may be a very important consideration in certain situations, the elastic demand module is required.

In a model of modal split and assignment with elastic demand, the option of traveling or not traveling can be included as an alternative destination or as an alternative mode. The appropriate representation of elastic demand within the model depends on how the decision to travel or not travel is considered to be made. The no-travel option includes trips foregone, trips shifted to times of day outside of the analysis period, and trips combined with other trips by way of trip chaining strategies. In order to model the no-travel option as an alternative mode, the utility of not traveling from zone r to zone s, denoted as V_{rs}^{nt}, can be estimated as the average weighted utility of the actual modes from zone r to zone s as given by the following equation.

$$V_{rs}^{nt} = \Sigma_m \, q_{rs}^m \, V_{rs}^m \,/\, \Sigma_m \, q_{rs}^m \tag{12}$$

Other composite functions of modal utilities have also been derived for the no-travel option. However the utility of not traveling is computed or calibrated, one can back calculate the amount by which the total number of trips from zone r to zone s, q_{rs}, must be increased in order that the individual q_{rs}^m values remain unchanged in the base case, and the remainder represents potential travelers electing not to travel. In NETPEM, the utility of not traveling is accounted for implicitly in an elastic demand function that compares, for each O-D pair of zones, the sum of current modal utilities to the sum of base case modal utilities in a simple logit equation. The form of the elastic demand model used in NETPEM is shown by equation (13).

$$q'_{rs} = q_{rs}^o \; [\; \Sigma_m \, exp \; V_{rs}^{m'} \,/\, \Sigma_m \, exp \; V_{rs}^{mo} \,]^{DF} \tag{13}$$

where, q_{rs}^o = total number of person trips from zone r to zone s in the original observed trip table (= base case),

q'_{rs} = new total number of person trips from zone r to zone s after the elastic demand calculation,

V_{rs}^{mo} = utility of mode m to a person trip from zone r to zone s calculated for the base case,

$V_{rs}^{m'}$ = utility of mode m to a person trip from zone r to zone s calculated for the current mode split,

DF = a parameter that allows the user to adjust the elasticity of demand, although it is not equal to the elasticity of demand (default = 1.0),

exp = exponential expression.

The form of the elastic demand function used in NETPEM as shown above is only one of many possible alternatives. One consequence of using this particular function is that elastic demand cannot be calculated independently of modal split, since the function is based upon the modal split utilities. It seems reasonable to assume, however, that if the form of the model chosen by the user allows travelers to forego trips, shift their time-of-day of travel, or strategically chain trips, then the option of changing modes should also be included.

Alternatively, the no-travel alternative could be treated as a higher level travel decision very much like destination choice. The value of not traveling from zone r to zone s can be associated with the average weighted $IVTT^{m}_{rs}$ and $OPTC^{m}_{rs}$ values for trips made from zone r to zone s. In this case, a demand function much like a trip distribution function can be used to allocate trips between the travel and no-travel options. Here again, we can back calculate the amount by which the number of trips between each pair of zones would need to be increased such that each q^{m}_{rs} number of trips remained unchanged in the base case. This alternative model, which does allow demand to be elastic independently of modal split, is only given here as an example and not suggested to be preferred. Equation (13) is the only form of the elastic demand model used in NETPEM.

8 Solving for Modal Split and Assignment with Elastic Demand

The iterative approach used in NETPEM to solve for modal split and assignment with elastic demand is shown in Figure 4. This procedure consists of doing successive iterations of assignment and modal split, and using equation (13) with each new set of modal utilities to compute a new total person trip table for all modes. These iterations are continued by the user of NETPEM until the change in overall travel demand (i.e., total number of person trips between all zones pairs) from one iteration to the next is sufficiently small. The decision as to when to terminate this iterative procedure is made interactively by the user of NETPEM during execution.

Elastic Demand Versus Trip Distribution

Allowing demand to be elastic takes into account that the overall level of travel demand may change in response to supply changes in the transportation system. Only in cases where the total number of person trips made during an analysis period are expected to increase or decrease significantly with travel costs does the allowance for elastic demand become an important flexibility of the model.

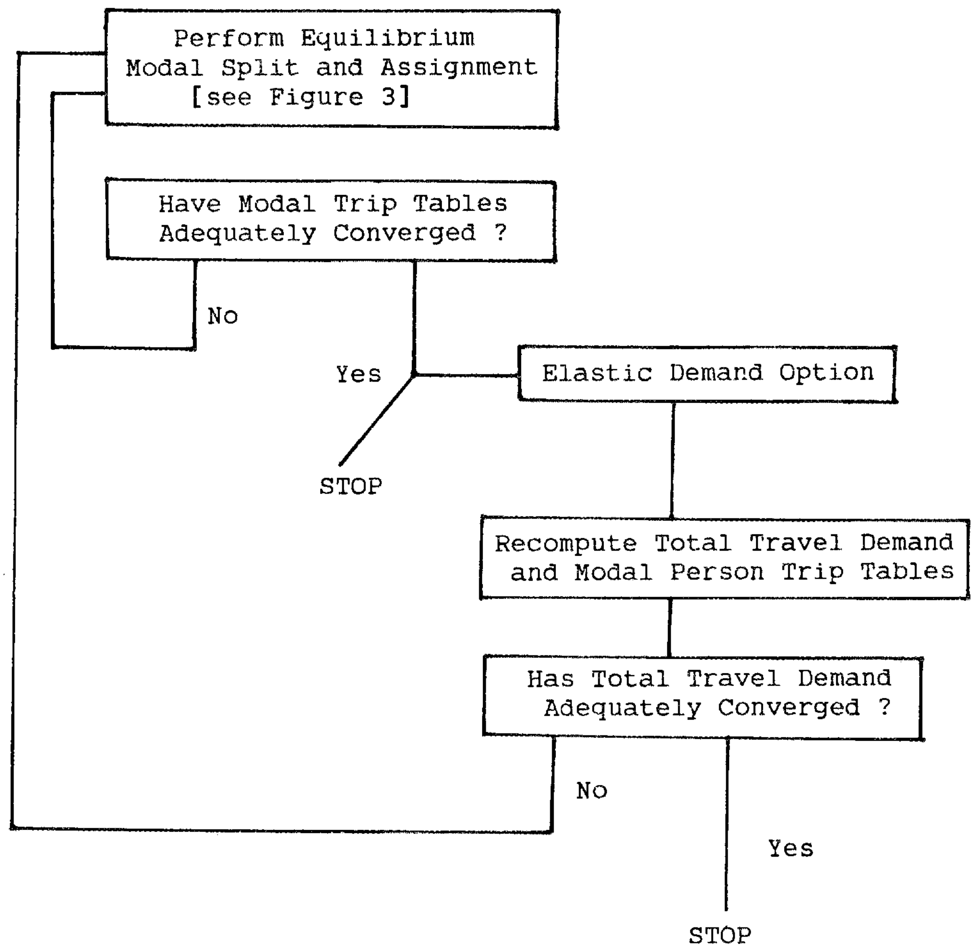

Figure 4: Iterative Solution Procedure to Modal Split and Assignment with Elastic Demand

In some transportation problems, the number of person trips that travel between each pair of zones is a function of modal travel costs and other factors that affect destination choice, such as the trip generation and attraction attributes of the zones. Several different models exist with which to estimate the zone-to-zone cell entries of the trip distribution matrix, each of which could be solved in conjunction with the assignment and modal split models in much the same manner as explained for elastic demand.

In the version of NETPEM described in this report, trip distribution is not offered as a modelling option because the impacts of a new HOV facility on trip distribution are considered secondary to the impacts on route and mode choice, and travel demand. There may be certain HOV studies for which trip distribution might be an important modelling option, such as the evaluation of multi-corridor HOV facilties of the sort being constructed in Seattle, Los Angeles, Houston and Washington, D.C. [26]. However, the inclusion of trip distribution within NETPEM was not considered to be a priority modelling objective of this project.

9 Direct Energy Consumption and Pollution Emissions

This section describes the Performance Evaluation Module (PERMOD) that is used to summarize the impacts of transportation system changes such as the addition of an HOV facility to the network. PERMOD, which is Module V of NETPEM, aggregates the impacts of each NETPEM modelling run into summary tables by mode. These modal impact calculations, such as fuel consumption and pollution emissions, are performed on the basis of equilibrium link volumes and travel times, and travel distances, that are reported by NETPEM at the end of a modelling run. By comparing the impacts before and after different HOV facilities have been introduced to the network, measures of effectiveness for alternative transportation management strategies are derived.

9.1 Direct Energy Consumption

As noted by Southworth and Janson [25], there are no well developed procedures to perform detailed analyses of direct energy consumption in transportation networks. However, they adopt a procedure whereby fuel consumption per mode is calculated on a link-by-link basis using travel times and distances. Their model involves the use of fuel consumption equations for different vehicle types that are functions of link speeds and distances. These equations can be specified as rates of fuel consumption per unit distance for discrete travel speeds. PERMOD linearly interpolates rates of fuel consumption for the in-between speeds as explained below.

9.2 Auto and Pool Fuel Consumption

The method used in the Performance Evaluation Module of NETPEM to estimate auto and pool fuel consumption is based on research performed at General Motors Research Laboratories (GMRL) [6]. Fuel consumption per vehicle per unit distance is estimated as a linear relationship of the inverse of speed. When multiplied by the distance of a link, this equation can be used to estimate the fuel consumed by per vehicle on a given link for a given travel time as follows:

$$F^m_k = k^m_{0,k}\ d_k + k^m_{1,k}\ t^m_k \tag{14}$$

where, F^m_k = fuel consumed per mode m vehicle trip on link k (gal/veh),

$k^m_{0,k}$ = distance coefficient for mode m vehicle trips on link k (gal/veh-mile),

d_k = distance of link k (miles),

$k^m_{1,k}$ = travel time coefficient for mode m vehicle trips on link k (gal/veh-min),

t^m_k = travel time per mode m vehicle trip on link k (minutes).

The use of equation (14) is restricted to the range of speeds over which the relationship between fuel consumption per unit distance and speed was found to be reasonably linear for a given vehicle type. To accomodate non-linearities in the relationship between fuel consumption and vehicle speed, equation (14) can be replaced by a series of piecewise linear segments for successive speed ranges. Provided that data is available, a piecewise linear fuel consumption equation can be specified for each vehicle type in the form of fuel consumption rates per unit distance for successively greater speeds. The GMRL equations described in [6] are easily converted into this form by selecting points off of these equations for every 5 MPH increment of speed. For use in PERMOD, these fuel consumption rates are specified by using a spreadsheet template named FUECON, which includes a default set of fuel consumption rates that can be changed by the user if a different set of rates are preferred.

The complete set of fuel consumption rates for subcompact, compact and standard size vehicles, as included in the FUECON template, are listed below in Table 1. These rates were adopted by Boyce *et al.* [3], Janson *et al.* [13], and Southworth and Janson [25] in their studies.

These rates have probably changed significantly since their time of estimation because of technological changes in automobiles. For this reason, the analyst may want to specify different rates based upon more recent data by using the FUECON spreadsheet template to create a new file. A set of recently published ORNL fuel economy ratings covering the range 15 to 65 mph (in 10 mph increments) has been included in the Appendix to this report as Table A-11. These estimates are for

Table 1: Example Auto and HOV Fuel Consumption Rates (gal/veh-mi)

Speed (mph)	Vehicle Type Subcompact	Compact	Standard
1.0	0.4564	0.7552	0.9522
5.0	0.1220	0.1800	0.2226
10.0	0.0802	0.1081	0.1314
15.0	0.0663	0.0841	0.1010
20.0	0.0593	0.0722	0.0858
25.0	0.0551	0.0650	0.0767
30.0	0.0523	0.0602	0.0706
35.0	0.0503	0.0567	0.0663
40.0	0.0371	0.0498	0.0616
45.0	0.0379	0.0504	0.0623
50.0	0.0395	0.0531	0.0656
55.0	0.0420	0.0563	0.0696
60.0	0.0453	0.0608	0.0752
65.0	0.0497	0.0667	0.0825

selected vehicles traveling at constant speeds. PERMOD allows the user to define whatever number and size of speed increments are desired, and to experiment with vehcile type mixes.

9.3 Excess Fuel Consumption Due to Cold Starts

In addition to the "warm-engine" fuel consumption explained above, tests have also shown that autos consume a extra amount of fuel over the initial portion of any trip for which the engine must warm up to a more efficient level of operation [6]. This additional fuel consumption due to cold starts for each type of vehicle is calculated in PERMOD using data specified by the user via a spreadsheet template named COLDEX.

The cumulative amounts of excess fuel consumed over successively greater lengths of initial trip distance are listed below in Table 2 for the same vehicle types described earlier. The user must also specify the percentage of vehicles of all types that are assumed to begin from a cold start.

These rates have probably changed significantly since their time of estimation because of technological changes in automobiles. For this reason, the analyst may want to specify different rates based upon more recent data by using the COLDEX spreadsheet template to create a new file. PERMOD allows the user to define whatever number and size of distance increments are desired.

Table 2: Example Cumulative Excess Fuel Consumption Amounts (gals)

Total Distance (miles)	Vehicle Type Subcompact	Compact	Standard
0.6	0.0506	0.0586	0.0799
1.2	0.0559	0.0706	0.0932
1.9	0.0613	0.0826	0.1039
2.5	0.0666	0.0892	0.1119
3.1	0.0719	0.0946	0.1172
3.7	0.0746	0.0999	0.1225
4.4	0.0773	0.1039	0.1279
5.0	0.0799	0.1079	0.1332
5.6	0.0812	0.1105	0.1359
6.2	0.0826	0.1119	0.1385
6.8	0.0826	0.1119	0.1412
7.5	0.0826	0.1119	0.1438
8.1	0.0826	0.1119	0.1452
8.7	0.0826	0.1119	0.1465
9.3	0.0826	0.1119	0.1478
9.9	0.0826	0.1119	0.1484

9.4 Vehicle Mix Assumptions

One assumption made in the calculation of fuel consumption impacts is that the vehicle mix compositions of the non-HOV and HOV vehicle fleets are homogeneous and uniform for all zones in the network. By using a spreadsheet template named COMPOS, the user specifies two sets of vehicle fleet mix percentages -- one set for the non-HOV fleet and a second set for the HOV fleet. These percentages indicate the mix of subcompact, compact and standard size vehicles in each of these fleets.

Vans are assumed to have the same fuel consumption characteristics as standard (or full) size vehicles. The user specifies a single average fuel consumption per mile for buses. The vehicle mix percentages specified for the non-HOV and HOV fleets are used by PERMOD to combine these vehicle fuel consumption rates into a set of rates for an average vehicle in each of these two modes. Examples of these percentages as they would be specified in the COMPOS template are shown below.

Fuel consumption rates for high-occupancy vehicles are identical to those for non-HOV's for each specific vehicle type. However, the average non-HOV results from a different mixture of vehicle types than the average HOV. Therefore, the average HOV fuel consumption rates will be different.

Table 3: Example Auto and HOV Fleet Composition Percentages

Type	Average Auto (%)	Average HOV (%)
Subcompact	0.12	0.05
Compact	0.30	0.20
Standard	0.58	0.75

Once the amount of fuel consumed per vehicle trip of each mode on each link has been calculated, the total fuel consumption by each mode is calculated as the product of fuel consumed per vehicle trip and the number of modal vehicle trips on each link as given by equation (15).

$$F^m = \Sigma_k \; F^m_k \; V^m_k + CS^m \quad \text{for each mode } m \tag{15}$$

where, V^m_k = volume of mode m vehicles assigned to link k,

CS^m = total cold start excess fuel consumed by all mode m vehicle trips,

F^m = total fuel consumed by all mode m vehicle trips.

The above summation of fuel consumption by mode over the entire network could alternatively be made over a subset of network links in order to examine the impacts of policies on fuel consumption over a particular subcomponent of the network.

9.5 Bus Fuel Consumption

Bus fuel consumption is more difficult to predict, since the rate of consumption tends to vary as operating and load conditions change. Southworth and Janson [25] present a table with energy coefficients for different transit modes per unit of distance traveled. Changes in bus fuel consumption derived from the operation of a new HOV facility represent a small percentage of the total energy consumption, because bus energy consumption is greatly affected by the location of bus routes and the number of scheduled bus trips.

Bus fuel consumption is calculated in PERMOD by multiplying a matrix of zone-to-zone bus distances by a matrix of zone-to-zone bus trips and a bus fuel consumption rate. Bus fuel consumption is assumed constant as long as the bus schedule and the bus routes do not change. The analyst may modify the files that contain bus distances and schedules if such changes are known when introducing HOV facilities to the network.

9.6 Pollution Emissions

Estimates of three types of vehicle pollution emissions are computed by PERMOD -- hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxide (NO). Emission rates per unit distance at successive speeds for each pollutant type are specified for light and heavy duty vehicle types via spreadsheet templates named HCEMIS, COEMIS and NOEMIS. Such rates can be obtained from the Mobile Source Emissions Model, which is supported by the U.S. Environmental Protection Agency [30]. A standard set of rates from the EPA is included within each of the templates, or the templates can be used to modify these values.

As a linear equation, vehicle emissions per modal trip on a specific link for a given travel time can be represented by the following equation.

$$E_k^{mp} = e_{0,k}^{mp} \, d_k + e_{1,k}^{mp} \, t_k^{mp} \tag{16}$$

where, E_k^{mp} = emissions of pollutant p per mode m vehicle trip on link k (grams/veh),

$e_{0,k}^{mp}$ = pollutant p distance coefficient for mode m vehicle trips on link k (grams/veh-mile),

d_k = distance of link k (miles),

$e_{1,k}^{mp}$ = pollutant p travel time coefficient for mode m vehicle trips on link k (grams/veh-min),

t_k^m = travel time per mode m vehicle trip on link k (minutes).

As with the fuel consumption rates, non-linearities in the relationship between vehicle emissions and vehicle speed are accounted for in PERMOD by using a series of piecewise linear segments over successive speed ranges. Computations of emissions are made within NETPEM by interpolating between the individual emission rates per mile specified at each 5 MPH speed increment, although PERMOD allows the user to define whatever number and sizes of speed increments are desired.

Emission rates are expressed in grams of pollution per vehicle-mile, and are a function of travel speed for each vehicle type. The calculations of emissions performed in PERMOD assume that all automobiles and vans are light duty vehicles, while only buses are heavy duty vehicles. Thus, the vehicle mix assumptions that do affect the average fuel consumption rates for the non-HOV and HOV vehicle fleets do not affect the average emission rates for these fleets. The average emission rates for high-occupancy vehicles are identical to those for non-HOV's.

The hydrocarbon (HC) emission rates for light and heavy duty vehicles, as included in the HCEMIS template, are listed below in Table 4. These rates were adopted by Southworth and Janson [25].

Table 4: Example Hydrocarbon Emission Rates (grams/veh-mi)

SPEED (mph)	Vehicle Type Light	Heavy
1.0	32.46	12.27
5.0	14.16	9.58
10.0	7.90	7.22
15.0	5.80	5.61
20.0	4.83	4.48
25.0	4.23	3.69
30.0	3.77	3.13
35.0	3.42	2.73
40.0	3.17	2.45
45.0	3.03	2.26
50.0	2.95	2.15
55.0	2.87	2.09
60.0	2.62	2.09
65.0	2.60	2.09

A similar table of rates must be specified, although default values are provided, for CO and NO with the COEMIS and NOEMIS templates. These rates have probably changed significantly since their time of estimation because of technological changes in automobiles. For this reason, the analyst may want to specify different rates based upon more recent data by using the spreadsheet templates to create new files.

Once the amount of pollution emitted per vehicle trip of each mode on each link has been calculated, the total pollution emitted by each mode is calculated as the product of fuel consumed per vehicle trip and the number of modal vehicle trips on each link. This summation, as shown by equation (17), is made in the same manner as was described earlier for auto and HOV fuel consumption.

$$E^{mp} = \Sigma_k \; E_k^{mp} \, V_k^m \quad \text{for each mode m and pollutant type p} \qquad (17)$$

where, V_k^m = volume of mode m vehicles assigned to link k,

E^{mp} = total emissions of pollutant p by all mode m vehicle trips.

The above summation of pollution emissions by mode over the entire network could alternatively be made over a subset of network links in order to examine the impacts of policies on pollution emissions over a particular subcomponent of the network.

Classifying buses as heavy duty vehicles, emissions by buses are approximated using the zone-to-zone travel times and distances. Average speeds between each pair of zones are calculated and used to obtain zone-to-zone average emission factors for each pollutant. The emissions calculations for buses are therefore performed in the same way as for autos and pools.

10 Structure of the Performance Evaluation Module (PERMOD)

The structure of the Performance Evaluation Module (PERMOD) is shown in Figure 5.

The following steps are executed by the the Performance Evaluation Module to calculate the impacts of HOV facilities based upon the results of Modules II-IV.

1. *Average Auto and HOV fuel consumption per vehicle trip on each link.* Using link speeds and distances from traffic assignment, fuel consumption per average auto and HOV vehicle trip on each link is computed.

2. *Total Auto and HOV fuel consumption for all trips on each link.* Person trips are divided by the average auto and HOV modal occupancies to obtain the modal vehicle trips on each link. These volumes are then multiplied by the average auto and HOV fuel consumption per vehicle trip on each link.

3. *Total Auto and HOV fuel consumption due to cold starts.* Zone-to-zone auto and pool vehicle trips are computed by dividing zone-to-zone modal person trips by their average modal occupancies, which are specific by origin zone. Zone-to-zone modal travel distances are multiplied by the zone-to-zone modal vehicle trips to obtain estimates of excess fuel consumption due to cold starts between each pair of zones.

4. *Total Auto and HOV direct energy consumption.* Steps 1 and 2 are repeated for every link. Then, modal link fuel consumption amounts for the auto and HOV modes are summed to yield total warm engine fuel consumptions for these modes on all links. Total excess fuel consumption for each of these modes due to cold starts is

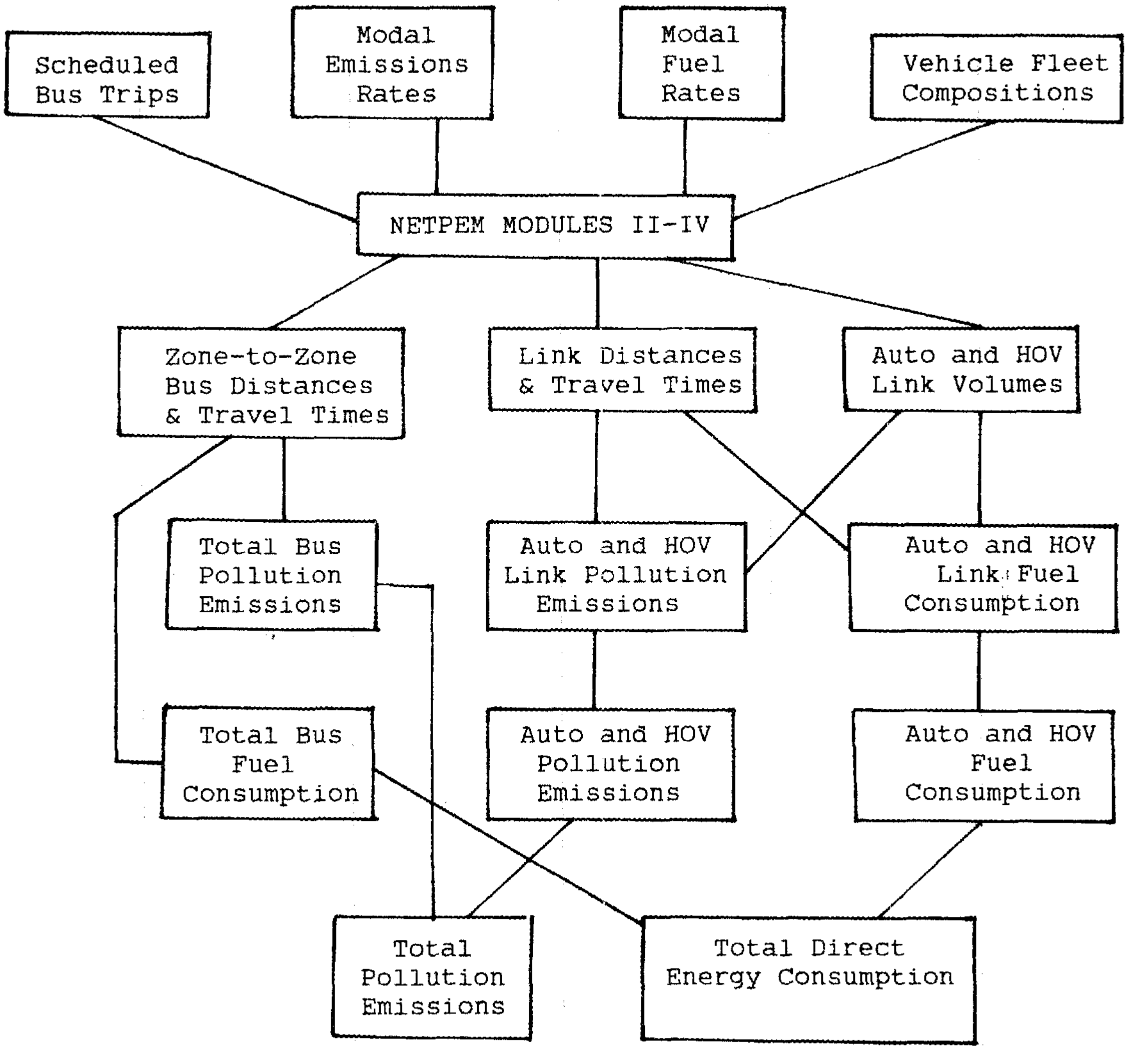

Figure 5: Structure of the Performance Evaluation Module (PERMOD)

then added to the warm engine modal fuel consumptions to yield total auto and HOV fuel consumptions in the network.

5. *Bus fuel consumption for trips between each pair of zones.*
   For each pair of zones, scheduled bus trips are multiplied by bus route distances between the zones to obtain the bus miles traveled. This quantity is multiplied by the average bus fuel consumption rate, which is not specific to speed in NETPEM, to obtain the bus fuel consumption for all trips between each pair of zones.

6. *Total bus direct energy consumption.*
   Zone-to-zone bus fuel consumptions are summed to obtain total bus fuel consumption in the entire network.

7. *Total direct energy consumption for all modes.*
   Total fuel consumption by each mode is converted to energy equivalent units and summed to yield total direct energy consumed in the network.

8. *Average Auto and HOV emissions per vehicle trip on each link.*
   Using link speeds and distances from the traffic assignment, emissions of pollutants HC, CO and NO per average auto and HOV vehicle trip on each link is computed.

9. *Total Auto and HOV emissions for all trips on each link.*
   Person trips are divided by the average auto and HOV modal occupancies to obtain the modal vehicle trips on each the link. These volumes are then multiplied by the average auto and HOV emissions per vehicle trip on each link.

10. *Total Auto and HOV pollution emissions.*
    Steps 8 and 9 are repeated for every link. Then, modal link emissions for the auto and HOV modes are summed to yield the total auto and HOV emissions for all links.

11. *Bus pollution emissions for all trips between each pair of zones.*
    For each pair of zones, the average bus route distance is specified by the user to an input file based upon information obtained from the local transit authority. These average zone-to-zone bus route distances are divided by zone-to-zone bus travel times estimated in NETPEM to obtain the average bus travel speed between each pair of zones. Average zone-to-zone bus speeds are used to determine the corresponding emission rate of each pollutant type per bus-mile of travel. Then, the number of scheduled bus trips between each pair of zones is multiplied by the average bus route distance and emission rate to yield total emissions of each pollutant type for all bus trips between each pair of zones.

12. *Total Bus pollution emissions.*
    Zone-to-zone bus emissions are summed to obtain total bus emissions for the entire network.

13. *Total pollution emissions for all modes.*
    Total pollution emissions by each mode are summed to yield total emissions of each type in the entire network.

10.1 Energy and Emissions Data Specification Templates

Auto and HOV Fuel Consumption Rates

The FUECON template used to specify auto and HOV fuel consumption rates for each vehicle type is shown in Figure 6. The level of speed range detail that the analyst requires can be adjusted by changing the number and size of speed ranges.

```
"AUTO AND HOV FUEL CONSUMPTION RATES"
************************************

        (GAL/VEH-MILE)

        No.Speed Ranges          _______

 SPEED
 (mph)    Subcompact          Compact       Standard
--------------------------------------------------
_____    _________          ________      ________
_____    _________          ________      ________
_____    _________          ________      ________
```

Figure 6: FUECON Template - Auto and HOV Fuel Consumption Rates

Auto and HOV Excess Fuel Consumption Due to Cold Starts

Excess fuel consumption amounts per vehicle due to cold starts are specified in cumulative amounts for successively greater distances from the start of each vehicle trip. Figure 7 shows the COLDEX template used by the analyst to specify this information. The level of speed range detail that the analyst requires can be adjusted by changing the number and size of speed ranges.

```
"AUTO AND HOV CUMULATIVE EXCESS FUEL CONSUMPTION"
**************************************************

        No.Speed Ranges            ______

Total
Distance Cumulative Excess Fuel Consumption (gals)
  (mi)     Subcompact        Compact       Standard
--------------------------------------------------
 ______   __________     __________     _________
 ______   __________     __________     _________
 ______   __________     __________     _________
```

Figure 7: COLDEX Template - Cumulative Excess Fuel Consumption Amounts for Auto and HOV Trips Due to Cold Starts

Auto and HOV Fleet Compositions

The COMPOS template used to specify auto and HOV fleet compositions from which to calculate average auto and HOV vehicle fuel consumption and emission rates is shown in Figure 8.

```
"AUTO AND HOV FLEET COMPOSITION"
********************************

                Average     Average
      TYPE    Auto (%)    HOV (%)
--------------------------------
Subcompact |  ________    ________
   Compact |  ________    ________
  Standard |  ________    ________
```

Figure 8: COMPOS Template - Auto and HOV Fleet Compositions

Auto, HOV and Bus Pollution Emission Rates

Three templates similar to the one shown in Figure 9 are used to specify the emission factors for each pollutant: HC, CO and NO. Below is shown the HCEMIS template used to specify hydrocarbon (HC) emission rates for light and heavy duty vehicles. Templates named COEMIS and NOEMIS with which to specify CO and NO rates have the identical format. The level of speed range detail that the analyst desires can be adjusted by altering the number and size of speed ranges.

```
"HYDROCARBON EMISSION RATES"
****************************

       (GRAMS/VEH-MILE)

No.Speed Ranges      ______

 SPEED        Vehicle Type
 (mph)       Light      Heavy
-------------------------------

 ______     ______     _______
 ______     ______     _______
 ______     ______     _______
```

Figure 9: HCEMIS Template - Hydrocarbon Emission Rates

10.2 Summary of Impacts Reported by PERMOD

A summary table of travel impacts (or "measures of effectiveness") including modal totals of vehicle and person trips, vehicle and person miles, average speeds, travel times and travel distances, energy consumption and vehicle emissions is generated by PERMOD and written in ASCII format to disk in the form shown by Figure 10.

SUMMARY OF TRAVEL MODE IMPACTS
****

	AUTO	HOV	BUS	TOTAL
MODAL SPLIT				
Person Trips	____	____	____	____
Person Miles	____	____	____	____
Person Hours	____	____	____	____
Vehicle Trips	____	____	____	____
Vehicle Miles	____	____	____	____
Vehicle Hours	____	____	____	____
Avg.Hours/Trip	____	____	____	____
Avg.Miles/Trip	____	____	____	____
Avg. Speed	____	____	____	____
POLLUTANT EMISSIONS				
HC (000 gr)	____	____	____	____
CO (000 gr)	____	____	____	____
NO (000 gr)	____	____	____	____
DIRECT ENERGY CONSUMPTION				
Warm Eng.	____	____		
Cold Eng. __%	____	____		
T.Fuel(Gals.)	____	____	____	____
BTUs (000)	____	____	____	____

Figure 10: Summary Table of Travel Mode Impacts from PERMOD

This table contains modal performance measures and impacts for the entire network used in NETPEM although a similar table for a subset of links such as the HOV facility itself could be tabulated with adjustments to PERMOD's computations. The contents of this table are written to a file having whatever name is specified by the user at the start of PERMOD. This final table of statistics is imported directly to a spreadsheet template named COMBIN in which several such tables for alternative facilities can be examined.

11 Example Applications of NETPEM and PERMOD

This section presents several example applications of NETPEM to the Pittsburgh metropolitan area. NETPEM was used to simulate the impacts of five alternative HOV facilities on the Parkway East. These were:

1. A 3+ diamond lane with no changes to adjacent links.

2. A 3+ diamond lane with changes to adjacent links.

3. A 3+ diamond lane with no changes to adjacent links plus elastic demand.

4. A 4+ diamond lane with no changes to adjacent links.

5. A 3+ physically separated lane with no changes to adjacent links.

As explained earlier in Section 3, in creating a description file of an HOV facility with the HOVFAC template, the user can make adjustments to the free-flow travel times and capacities of adjacent auto (non-HOV) links. Adjustments to the performance characteristics of these links might need to be made if (1) the new HOV facility replaces one of the existing lanes, (2) if new HOV barriers affect the physical design of existing lanes in some way, or (3) if weaving and merging to and from a diamond lane or at entry and exit locations of a physically separated lane change the existing flow charcteristics of these links.

All of the examples described in this section were run on a small network of 11 zones, 17 nodes and 50 links. Although this network does not contain the level of detail required of a thorough transportation planning analysis, it does possess the characteristics needed to demonstrate the capabilities of NETPEM and PERMOD. Similar tests of NETPEM were performed on a DEC-20 computer with a larger network of 30 zones, 388 nodes and 847 links. Both networks represent the same eastern traffic corridor of Pittsburgh, which is the most heavily traveled corridor in the regional area. However, the results of the larger and smaller models are not directly comparable.

While the PC version of NETPEM is much simplier to use than its mainframe counterpart, the PC version is also quite slow for larger networks. With all the data files prepared, it requires roughly 10 minutes for the user to run this small example Pittsburgh network through enough iterations of assignment, modal split and elastic demand for the system to sufficiently converge. This time assumes a reasonable response rate of the user to interactive "yes/no" questions during execution. This approximate time was observed while using a PC/XT without a 8087 math co-processor. A math coprocessor would reduce the time to 6 or 7 minutes, and using an IBM AT would reduce this time even further to roughly 3 minutes. Of course, user response time becomes a larger portion of NETPEM "execution" time as the speed of the computer grows faster.

Although an IBM PC/XT with 640K of RAM will accept networks with up to 30 zones, 400 nodes and 1000 links, the execution time for such a network would be prohibitive. The current (July 86) version of NETPEM is only a prototype intended for testing on fairly small problems. Freeway corridors with perhaps 15-20 major traffic generating zones, 120 link intersection nodes and 300 links would exhibit acceptable execution times in NETPEM-PC. All examples described below using the smaller Pittsburgh network were run on an IBM PC/XT using Turbo Pascal 3.0[1] and only 320K of random access memory.

The next subsection reviews the procedure followed to run NETPEM and PERMOD in order to estimate the impacts of different HOV facilities, including assumptions adopted for these examples and details of the data specified to NETPEM for these runs. In the remaining subsections, results of the base case plus five different HOV facilities and/or lane use policies are presented.

11.1 Review of the General Procedure for Using NETPEM

Figure 11 illustrates the general procedure followed when using NETPEM to assess the impacts of different HOV facilities.

The first step is to create the data files for the base case before any HOV facility is introduced. These files can be created using the spreadsheet templates provided and/or text editors that can produce standard ASCII files with no special control characters. These files are common to every execution of the model for the regional highway network and trip tables being used regardless of what HOV facility is being evaluated. Hence, once these files are created for the base case, they are available for all subsequent runs without any changes required.

Files required to execute NETPEM for a base case are:

- *Control file.*- Contains the number of nodes, zones and links in the network, and the maximum number of PARTAN iterations to be performed in each equilibrium traffic assignment.

- *Link file.*- Contains the list of all directed links in the network, as well as the link performance function for each. The data items listed for each link are its from-node, to-node, free-flow travel time (hours), practical capacity (vehicles/hour) and length (miles).

- *Modal Split Parameters file.*- Contains modal cost information and other parameters used in the multinomial logit model to split person trips among the travel modes. This file also contains the initial split of trips between modes by origin, and other origin zone data described earlier.

---

[1] Turbo Pascal is a trademark of Borland International, Inc.

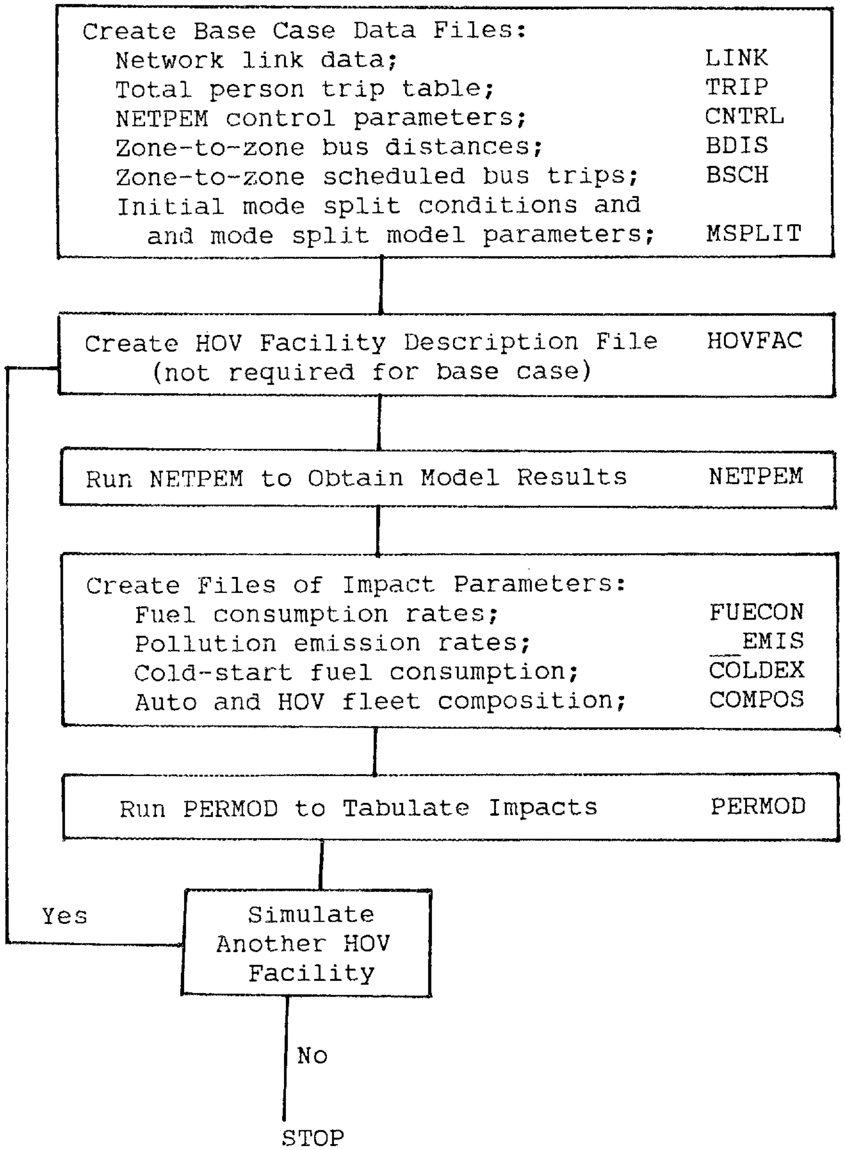

Figure 11: General Procedure for Using NETPEM

- *Scheduled Bus Trips file.-* Contains the number of scheduled bus trips between each pair of zones during the analysis period.

- *Bus Distances file.-* Contains an average zone-to-zone bus route distance (in miles) for each pair of zones connected by bus service.

- *Vehicle Mix file.-* Contains percentages of each vehicle type in the auto and pool fleets of vehicles.

Once the above data files have been created, all data required for a base case run of the model with no HOV facility added are complete. The logical course of attack at this point in the process would be to run the base case through NETPEM and PERMOD to check whether the network model is behaving as expected and whether the sequence of program routines and spreadsheets are functioning properly.

Running NETPEM creates five intermediate output files. These are:

1. A file of final auto link volumes and impedances.
2. A file of final pool link volumes and impedances.
3. A file of final zone-to-zone bus travel times.
4. A file of modal summary statistics for the network. This file contains total person and vehicle miles, total person and vehicle hours, and average speeds for the unloaded (i.e., free-flow) and loaded (i.e., equilibrium assigned) network.
5. A file of successive split and traffic assignment iterations. If the analyst wants to trace the results, the successive person trip tables and zone-to-zone travel times are stored in this file.

The first four files listed above are required for use in PERMOD to calculate the network performance impact measures and modal statistics. In addition to those four files, PERMOD also requires the rates of fuel consumption and emissions by vehicle types, and the assumed mixes of vehicle types. These files are:

- *Warm Engine Fuel Consumption Rates.-* Contains rates of energy consumption per mile for each vehicle type at each 5 mile-per-hour speed increment between 0 and 65 miles-per-hour for auto and pool vehicles.
- *Cold Start Excess Fuel Consumption.-* Contains the cumulative excess fuel consumed as a function of the total distance traveled for auto and pool vehicles.
- *Hydrocarbon Emissions Rates.-* Contains rates of HC emitted per mile by heavy and light vehicles at each 5 mile-per-hour speed increment between 0 and 65 miles-per-hour.
- *Carbon Monoxide Emissions Rates.-* Contains rates of CO emitted per mile by heavy and light vehicles at each 5 mile-per-hour speed increment between 0 and 65 miles-per-hour.
- *Nitrogen Oxide Emissions Rates.-* Contains rates of NO emitted per mile by heavy and light vehicles at each 5 mile-per-hour speed increment between 0 and 65 miles-per-hour.
- *Auto and HOV Vehicle Fleet Compositions.-* Contains percentages of subcompact, compact and standard size vehicles in the auto and HOV fleets.

By executing PERMOD separately from NETPEM in order to calculate the impacts of a particular HOV facility design, it is not necessary to rerun the network model to vary the impact coefficients such as the fuel consumption and pollution emission rates for sensitivity analyses.

Once the base case model has been successfully run and sufficiently tested, the next step is to create a file describing the HOV facility whose impacts are to be simulated. Again, this file can be created using the spreadsheet template HOVFAC provided or any suitable text editor. Data in the HOV facility file describes the facility by the end nodes of adjacent links already in the network, or as entirely new links, since each HOV link is not required to correspond to an adjacent auto link.

The final step is to calculate total fuel consumption and pollution emissions for each mode in the network with the new HOV facility by using PERMOD. The files output by NETPEM are input to PERMOD along with files of zone-to-zone bus route distances and scheduled bus trips. These datasets are used to calculate the summary tables of travel impacts that are written to disk as ASCII files. These files can then be entered into a spreadsheet template for examination and graphing.

When different HOV facilities are simulated, the base files do not have to be changed. Only one new file describing the new HOV facility needs to be created using the HOVFAC template, and then both NETPEM and PERMOD can be executed. The names of all output files are specified by the user for each run (unless the default names are selected instead) in order to avoid writing over output files from previous runs.

11.2 Some Assumptions Made in the Example Applications

For the example applications of NETPEM, the following assumptions were made regarding the modelling parameters used due to data availability.

1. *Base case modal split percentages by origin zone.*
   All the origin zones were assumed to have the same initial mode split of total person trips: 65% auto, 5% pool and 30% bus. In addition, all origin zones were assumed to have the same average household annual income of $22,500, the same zonal land area of 1 sq. mile and the same average pool occupancy of 5.5 driver/passengers per pool.

2. *Bus travel times are 35% greater than pool travel times.*
   Average zone-to-zone bus travel times depend on the alignment of bus routes and the number of passenger stops required. We did not

specifically obtain bus travel time information. Instead, each zone-to-zone bus travel time is estimated during NETPEM execution to be 35% greater than the corresponding zone-to-zone auto travel time, or 35% greater than the corresponding zone-to-zone pool travel time if a particular bus trip can make effective use of the HOV facility.

3. *Bus travel distances were calculated using the base case.*
   Average zone-to-zone bus travel distances depend on the alignment of bus routes between each pair of zones. We did not trace specific bus routes through the network in order to calculate these distances. Instead, a matrix of average zone-to-zone bus travel distances was estimated from regional road maps. These distances were needed to calculate the average zone-to-zone bus travel speed, which turned out to be roughly 12 mph for the base case.

4. *Scheduled bus trips were calculated using the initial split conditions.*
   The number of scheduled bus trips between each pair of zones over the analysis period is also needed to calculate total bus fuel consumption and vehicle emissions. We did not evaluate a complete bus schedule in order to determine this matrix. Instead, a matrix of zone-to-zone bus trips was estimated on the basis of what would be required to carry bus passengers at an average occupancy of approximately 20 passengers per bus using the initial modal split of the total person trip table.

5. *Modal split parameters β and γ were not calibrated on the basis of Pittsburgh data; they correspond to those reported by a study of Washington D.C.* [7].
   Traveler' modal choice preferences with respect to differences in the out-of-pocket costs and in-vehicle-travel times of alternative modes were assumed to be similar to those observed in Washington D.C. [7], in which the trip table utilized was for work trips during the morning peak period. Because the parameters from that study were intended for use with round trip travel costs and times, and since NETPEM models only one-way trips, the β and γ parameters from the Washington D.C. study were doubled for their use in our modelling runs:

   Beta = -57.6 dollars/cent
   Gamma = -0.0308 minutes^{-1} of travel time

The following data reported by Tsai [29] were used to specify out-of-pocket costs per vehicle or person trip by each mode:

Out-of-pocket cost per auto vehicle trip = 24.60 cents/mile
Out-of-pocket cost per pool person trip = 6.25 cents/mile
for pools with 3.5 passengers
Out-of-pocket cost per bus person trip = 100.25 cents (fare)

The assumptions mentioned above apply only to the data specified for these example applications and do not pertain to the the capabilities of the NETPEM program. The purpose of these examples is to illustrate the application of NETPEM rather than to obtain definitive results for a given metropolitan area. The model is likely to produce more realistic and reliable results if the accuracy of the input data is improved.

For all of the following example runs, a maximum number of 10 PARTAN iterations were performed for each equilibrium traffic assignment following each modal split of the total person trip table. Also, a maximum number of 5 modal split/assignment or elastic demand/modal split assignment iterations were performed. The convergence criteria for modal split and/or elastic demand between each iteration was set to 5% of total person trips. The convergence criteria of the golden section search used to combine successive traffic assignments was held to the same value for all runs.

11.3 Small Network Base Case with No HOV Facility

NETPEM was first applied to the "base case" network of 11 zones, 17 nodes and 50 links with no HOV facility as shown in Figure 12. A total person trip table with 11 zones for all modes was estimated from Pittsburgh survey data for the morning peak period. This trip table, and the other files specified for this run of NETPEM, are shown in the Appendix.

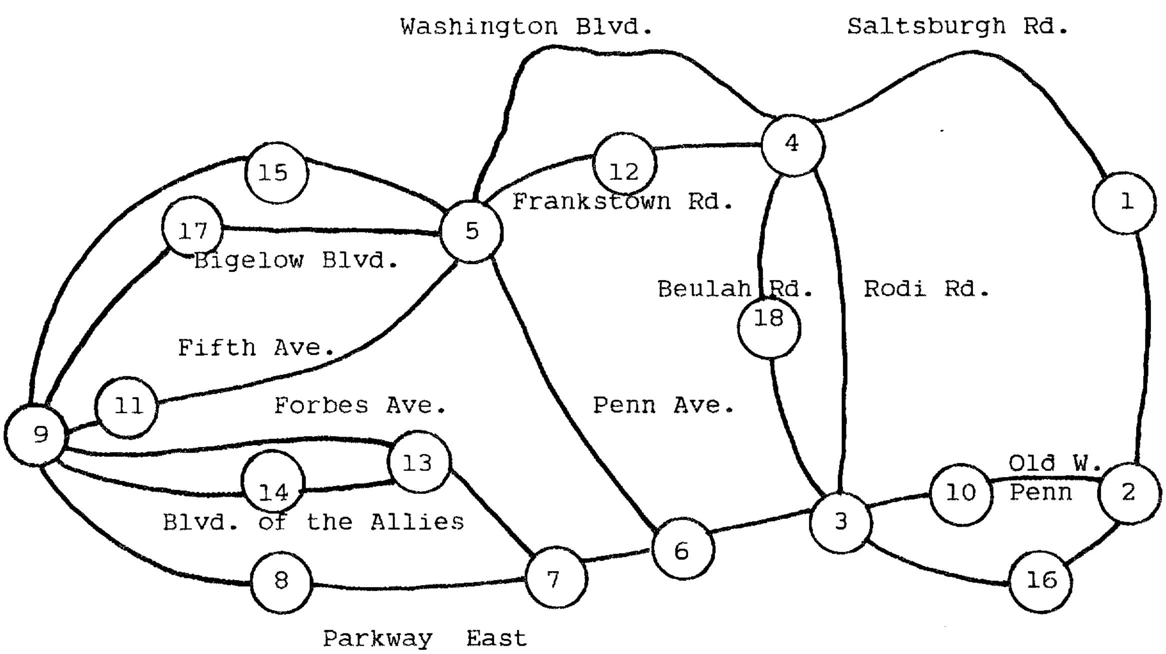

Figure 12: Small Network for Pittsburgh's Eastern Travel Corridor

The summary table of network performance statistics such as vehicle and person trips by mode, energy consumption and pollution emissions are shown in Table 5.

Table 5: Base Case Network Performance Statistics (No HOV Facility)

	AUTO	HOV	BUS	TOTAL
MODAL SPLIT				
Person Trips	6032	463	2781	9277
Person Miles	32380	2653	15731	50763
Person Hours	1879	193	1567	3639
Vehicle Trips	4640	84	135	4859
Vehicle Miles	24907.5	482.3	762.2	26152.1
Vehicle Hours	1445.2	35.1	75.5	1555.8
Avg.Hours/Trip	0.31	0.42	0.56	0.32
Avg.Miles/Trip	5.37	5.73	5.65	5.38
Avg. Speed	17.2	13.7	10.1	16.8
POLLUTANT EMISSIONS				
HC (000 gr)	135.2	2.4	5.5	143.1
CO (000 gr)	1501.9	26.8	38.7	1567.4
NO (000 gr)	56.4	1.1	21.4	78.9
DIRECT ENERGY CONSUMPTION				
Warm Eng.	2228	40		
Cold Eng. 35%	127	3		
T.Fuel(Gals.)	2355	43	231	2628
BTUs (000)	294373	5345	32014	331732

The first part of the table shows the final split values. For the base case, these quantities correspond to our initial assumption whereby person trips from every origin zone were initially split according to the same percentages -- 65% by auto, 5% by pool and 30% by bus. The following calculations show that these percentages are true of the person trips shown in the above table.

% persons trips by auto = 6032/9277 = 65 %
% persons trips by pool = 463/9277 = 5 %
% persons trips by bus = 2781/9277 = 30 %

Modal vehicle trips were obtained by dividing modal person trips by the average modal vehicle occupancies.

- For auto trips, the average vehicle occupancy was assumed to be 1.3; therefore, auto vehicle trips = 6032/1.3 = 4640.

- For pool trips, the average vehicle occupancy was assumed to be 5.5 driver/passengers per pool from every origin zone; therefore, pool vehicle trips = 463/5.5 = 84.

- Bus vehicle trips were read from the bus schedule file that assumed an average bus occupancy of approximately 20 passengers per bus. The value shown in the above table equals 2781/135 = 20.6 persons/bus.

Person miles, person hours and the corresponding vehicle miles and vehicle hours depend upon the equilibrium solution. These numbers can be used to compare the average modal travel times per trip.

When no HOV facility is introduced, the average pool travel time was 6.6 minutes greater than the average auto travel time due to the additional time required to pick-up passengers (assumed to be 1 minute per passenger) plus the additional travel time required to drive the additional distances between passenger pick-up locations.

Average modal travel speeds were calculated by dividing total modal vehicle miles by total modal vehicle hours. Average free-flow travel speeds were calculated similarly, except that total vehicle hours are calculated on the basis of free-flow travel times over the same routes to which these vehicles were assigned by the traffic assignment module.

The second part of Table 5 shows total pollution emissions for each mode. Auto and pools are light vehicles, and their emission rates per mile are obtained from the emissions rate tables in the Appendix. For example, the average HC emission rate for an auto trip with an average speed of 17.2 mph equals 135200/24907.5 = 5.4 grams/mile. For buses, an average HC emission rate of 5500/762.2 = 7.21 grams/mile corresponds to an average speed of 10.1 mph as shown by the HC emission rates listed for heavy-duty vehicles.

The third part of Table 5 shows the modal fuel consumptions. Equilibrium travel speeds on most links were within the 15 to 40 mph speed range for which GMRL estimated a linear relationship between fuel consumption per mile of travel and vehicle speed. A gross approximation auto fuel consumption based upon total vehicle miles of travel and the average auto speed would equal 0.085 gal/mile * 24907.3 miles = 2117 gallons. Note that this approximation is only 5% smaller than the value corresponding to the fuel consumption of warm engines. For buses, a fixed factor of 42,000 BTU/mile was used to estimate a total bus fuel consumption of 762 * 42,000 = 32 million BTU's.

11.4 A 3+ Diamond Lane (No Changes to Adjacent Auto Links)

The first HOV facility to be evaluated using the small network was an additional diamond lane to the Parkway East. Since this facility was to be a completely new lane, rather than the use of an existing lane, the free-flow travel times and capacities of the adjacent auto lanes were not altered, as indicated by a value of 1.0 for each of the two special capacity and time factors. The default (or no-effect) value for each of these factors is 1. The diamond lane being simulated here is permitted for use by pools with 3 or more passengers. This facility was added to the small network as shown in Table 6.

Table 6: Description of a 3+ Diamond Lane (No Changes to Adjacent Links)

```
Number of Links     6                                 For Entry & Exit:
                                                          1 = Yes
Minimum Number of                                         2 = No
Passengers per Pool    3.0
```

From Node	Entry (1/2)	To Node	Exit (1/2)	Free Flow Time (hrs)	Factor Cap.	Factor Time	Length (mi)
2	1	16	1	0.01167	1.0	1.0	0.2333
16	1	3	1	0.10000	1.0	1.0	2.0000
3	1	6	1	0.04333	1.0	1.0	0.8666
6	1	7	1	0.03000	1.0	1.0	0.6000
7	1	8	1	0.10167	1.0	1.0	2.0333
8	1	9	1	0.09500	1.0	1.0	1.9000

The facility was described node-by-node in order to allow pools to enter or exit the HOV lane at each node. A more precise description of a diamond lane would be to use smaller links to represent pool merging at more points. However, equilibrium results would be the same, unless additional auto links were connected to the new nodes.

Table 7 shows the impacts caused by the addition of this diamond lane to the small network. When compared to the modal split of the base-case, 138 auto person trips changed to the other modes. However, only eleven of these trips changed to pools while 127 of these trips changed to bus. (The program works with real numbers, but only integer person and vehicle trips are reported.)

The average auto travel time per person trip decreased from 0.31 hours in the base case to 0.3 hours in this case because of fewer vehicles on the network. The average person trip travel time by pool decreased from 0.42 hours to 0.38 hours,

Table 7: Impacts of a 3+ Diamond Lane (No Changes to Adjacent Links)

	AUTO	HOV	BUS	TOTAL
MODAL SPLIT				
Person Trips	5894	474	2909	9277
Person Miles	29705	2634	16497	48836
Person Hours	1785	181	1503	3470
Vehicle Trips	4534	86	135	4755
Vehicle Miles	22849.9	479.0	762.2	24091.2
Vehicle Hours	1373.3	32.9	69.2	1475.4
Avg.Hours/Trip	0.30	0.38	0.51	0.31
Avg.Miles/Trip	5.04	5.56	5.65	5.07
Avg. Speed	16.6	14.5	11.0	16.3
POLLUTANT EMISSIONS				
HC (000 gr)	128.7	1.2	5.2	135.2
CO (000 gr)	1427.6	15.1	36.4	1479.1
NO (000 gr)	54.2	0.3	20.6	75.1
DIRECT ENERGY CONSUMPTION				
Warm Eng.	2124	27		
Cold Eng. 35%	123	3		
T.Fuel(Gals.)	2247	30	231	2508
BTUs (000)	280888	3722	32014	316624

and the average person trip travel time by bus decreased from 0.56 hours to 0.51 hours. Even though the average auto travel time decreased, the average auto travel speed also decreased. The reason why this occurred is that total auto vehicle miles decreased by a larger percentage than total auto vehicle hours. Total auto vehicle miles decreased by 8% from 24907 to 22850 while total auto vehicle hours decreased by only 5% from 1445 to 1373.

This occurrence can be explained by noting that travel time is not only proportional to trip length, but also to the level of congestion on the links. Therefore, long distance trips do not always correspond to long travel time trips. If use of the HOV facility results in a greater percentage decrease in long distance trips than in long travel time trips, both the average travel time and speed of all trips can decrease.

Pollution emissions and energy consumption decreased significantly for both the auto and pool modes. Since the bus schedule and the bus travel distances remained fixed, bus fuel consumption did not change and bus emissions were almost unchanged -- they decreased slightly because of the zone-to-zone bus travel speed increasing slightly.

11.5 A 3+ Diamond Lane with Changes to Adjacent Auto Links

The second HOV facility to be evaluated using the small network was a diamond lane partially installed onto the existing lanes of the Parkway East. Because of competition with the other vehicular traffic for existing roadway capacity, the addition of this facility to the network did include some changes to the free-flow travel times and capacities of the base-case auto links.

This second test facility is described in Table 8. Since the diamond lane occupies only a portion of the existing roadway width, the capacities of adjacent auto links were reduced to 70% of their base-case values. Additionally, in order to partially simulate the additional congestion caused by the merging and weaving of traffic in and out of the diamond lane, the free-flow travel times of the auto links were each increased by 20% of their base-case values.

Table 8: Description of a 3+ Diamond Lane with Changes to Adjacent Links

Number of Links 6

Minimum Number of
Passengers per Pool 3.0

For Entry & Exit:
1 = Yes
2 = No

From Node	Entry (1/2)	To Node	Exit (1/2)	Free Flow Time (hrs)	Factor Cap.	Factor Time	Length (mi)
2	1	16	1	0.01167	0.7	1.2	0.2333
16	1	3	1	0.10000	0.7	1.2	2.0000
3	1	6	1	0.04333	0.7	1.2	0.8666
6	1	7	1	0.03000	0.7	1.2	0.6000
7	1	8	1	0.10167	0.7	1.2	2.0333
8	1	9	1	0.09500	0.7	1.2	1.9000

Table 9 shows the impacts caused by this diamond lane implementation in the small network. It can be seen by comparing the results of this simulation to those shown previously that the network with this HOV facility out performs the base-case network with respect to all impact measures. However, it generally performs worse than the network in which changes to the supply characteristics of the adjacent links auto links were not made at the time that the HOV lane was added. While this result might be expected, it shows that the impact changes estimated by the model for these examples do agree with their logical directions of change.

As can be seen in Table 9, total energy consumption increased to 334 million BTU's, which is even higher than in the base case. Reductions in the capacity of

Table 9: Impacts of a 3+ Diamond Lane with Changes to Adjacent Links

	AUTO	HOV	BUS	TOTAL
MODAL SPLIT				
Person Trips	5725	498	3054	9277
Person Miles	28728	2831	17366	48925
Person Hours	1990	193	1598	3781
Vehicle Trips	4404	91	135	4629
Vehicle Miles	22098.4	514.7	762.2	23375.3
Vehicle Hours	1531.1	35.1	69.9	1636.1
Avg.Hours/Trip	0.35	0.39	0.52	0.35
Avg.Miles/Trip	5.02	5.69	5.65	5.05
Avg. Speed	14.4	14.7	10.9	14.3
POLLUTANT EMISSIONS				
HC (000 gr)	140.0	1.3	5.3	146.5
CO (000 gr)	1579.2	16.0	36.7	1631.8
NO (000 gr)	53.4	0.4	20.7	74.5
DIRECT ENERGY CONSUMPTION				
Warm Eng.	2265	28		
Cold Eng. 35%	119	3		
T.Fuel(Gals.)	2385	32	231	2647
BTUs (000)	298063	3943	32014	334021

adjacent auto links lead to an overall worse situation. The shift of person trips towards HOV and buses (5725 auto drivers versus 5894 auto drivers for the case in which auto links are not affected) did not compensate for the extra fuel consumed due to congestion in the auto links.

11.6 A 3+ Diamond Lane with Elastic Demand (No Changes to Adjacent Auto Links)

For some travel environments, it may not be appropriate to model travel demand as being fixed. Some degree of elasticity has to be considered. The effects of allowing total travel demand to be elastic are presented here by using the same HOV facility file as is shown above in Table 6. The only difference in running the model is that the user responds with "y" instead of "n" to a question as to whether elastic demand is to be allowed. Table 10 shows the impacts of adding this diamond lane in which no changes were made to the adjacent auto links and demand is made elastic. For this example, three iterations of elastic demand, modal split and equilibrium assignment were performed. The results show that total person trips for the entire network increased by 4.5 percent over the base case observed trip table.

Table 10: Impacts of a 3+ Diamond Lane with Elastic Demand (No Changes to Adjacent Links)

	AUTO	HOV	BUS	TOTAL
MODAL SPLIT				
Person Trips	6121	500	3079	9700
Person Miles	31057	2846	17505	51408
Person Hours	1913	192	1594	3699
Vehicle Trips	4709	91	135	4935
Vehicle Miles	23889.7	517.5	762.2	25169.4
Vehicle Hours	1471.8	34.9	69.1	1575.7
Avg.Hours/Trip	0.31	0.38	0.51	0.32
Avg.Miles/Trip	5.07	5.69	5.65	5.10
Avg. Speed	16.2	14.8	11.0	16.0
POLLUTANT EMISSIONS				
HC (000 gr)	139.4	1.3	5.2	145.9
CO (000 gr)	1555.0	15.8	36.4	1607.2
NO (000 gr)	56.7	0.4	20.6	77.6
DIRECT ENERGY CONSUMPTION				
Warm Eng.	2285	28		
Cold Eng. 35%	128	3		
T.Fuel(Gals.)	2413	31	231	2675
BTUs (000)	301637	3931	32014	337582

Total energy consumption and pollution emissions increased with respect to the base case. The reason for this is that the additional transportation supply was accompanied by a cooresponding increase in demand reflected by an increase in total person trips from 9277 to 9700. These additional trips offset the energy savings shown in Table 6 that would otherwise have resulted from the use of more efficient modes. The elastic demand option also resulted in the auto mode having a 63.38% share of total person trips as compared to a 63.84% share in the inelastic case.

The impacts shown in Table 10 were obtained with the demand factor described in Section 7 and shown in equation (13) set to 1.0. A less dramatic change in total person trips would be obtained if a factor less than 1.0 were used. (DF equal to zero corresponds to inelastic demand.)

11.7 A 4+ Diamond Lane (No Changes to Adjacent Auto Links)

The following example was run in order to compare the impacts of adding a 4+ diamond lane (versus the 3+ lane added earlier) to the Parkway East. In this example the demand was assumed to be inelastic, and no changes were made to the adjacent auto links. Implimenting this lane use policy is accomplished very simply by changing a single factor within the HOVFAC template. For this example, the same HOV facility file was used as was shown earlier in Table 6, except the very first parameter in the template was set to 4. Table 11 shows the impacts of adding this 4+ diamond lane in which no changes were made to adjacent auto links.

Results in Table 11 show that the impacts of the 4+ lane use policy are worse than those of the same HOV facility operated with a 3+ policy. The reason is that 3 person pools prohibited from using the HOV facility have to use the auto links, which creates addtional congestion for a larger number of travelers.

Table 11: Impacts of a 4+ Diamond Lane (No Changes to Adjacent Links)

	AUTO	HOV	BUS	TOTAL
MODAL SPLIT				
Person Trips	5934	471	2872	9277
Person Miles	29929	2585	16276	48790
Person Hours	1815	185	1522	3522
Vehicle Trips	4565	86	135	4785
Vehicle Miles	23022.1	470.0	762.2	24254.3
Vehicle Hours	1396.3	33.6	70.9	1500.8
Avg.Hours/Trip	0.31	0.39	0.53	0.31
Avg.Miles/Trip	5.04	5.49	5.65	5.07
Avg. Speed	16.5	14.0	10.8	16.2
POLLUTANT EMISSIONS				
HC (000 gr)	131.0	1.9	5.3	138.2
CO (000 gr)	1454.5	21.7	37.0	1513.1
NO (000 gr)	54.7	0.7	20.8	76.2
DIRECT ENERGY CONSUMPTION				
Warm Eng.	2159	34		
Cold Eng. 35%	124	3		
T.Fuel(Gals.)	2282	37	231	2550
BTUs (000)	285310	4624	32014	321948

11.8 A 3+ Physically Separated Lane (No Changes to Adjacent Auto Links)

The final HOV facility whose impacts were simulated with NETPEM is a physically separated lane. In this type of facility, access to the HOV lane is limited to some ramps only. The effects of changing the lane from diamond to physically separated are presented here in Table 13. These results were obtained by using the same HOV facility file as was shown earlier in Table 6, except that users of the HOV lane are only able to enter the lane in a suburban location where it begins, and exit the lane at its downtown terminus as indicated by the entry/exit column in Table 12. This situation represents a reversible lane that is only used by inbound traffic flows during the morning peak period.

Table 12: Description of a 3+ Separated Lane (No Changes to Adjacent Links)

```
Number of Links    6                                For Entry & Exit:
                                                         1 = Yes
Minimum Number of                                        2 = No
Passengers per Pool   3.0
```

From Node	Entry (1/2)	To Node	Exit (1/2)	Free Flow Time (hrs)	Factor Cap.	Factor Time	Length (mi)
2	1	16	2	0.01167	1.0	1.0	0.2333
16	2	3	2	0.10000	1.0	1.0	2.0000
3	2	6	2	0.04333	1.0	1.0	0.8667
6	2	7	2	0.03000	1.0	1.0	0.6000
7	2	8	2	0.10167	1.0	1.0	2.0333
8	2	9	1	0.09500	1.0	1.0	1.9000

Table 13 shows the impacts of adding this physically separated lane in which no changes were made to the adjacent auto links and demand is kept to be inelastic. The results suggest that a very small benefit is obtained because only trips that can effectively use the HOV facility for its entire length are in a better situation. In the case of diamond lanes, pools were allowed to enter the HOV facility at almost any point.

12 Modelling Other Types of HOV Lane/Ramp Facilities with NETPEM

The design of NETPEM is intended to provide sufficient flexibility for modelling many different types of HOV lane/ramp facility design and use policies, and other transportation system management (TSM) strategies as well. In this final subsection, we present some examples of how NETPEM can be used to evaluate other types of HOV facilities and lane use policies.

Table 13: Impacts of 3+ Separated Lane (No Changes to Adjacent Links)

	AUTO	HOV	BUS	TOTAL
MODAL SPLIT				
Person Trips	5947	471	2859	9277
Person Miles	32484	2717	16248	51449
Person Hours	1843	190	1559	3592
Vehicle Trips	4575	86	135	4795
Vehicle Miles	24987.8	494.0	762.2	26244.0
Vehicle Hours	1418.0	34.5	73.1	1525.7
Avg.Hours/Trip	0.31	0.40	0.54	0.32
Avg.Miles/Trip	5.46	5.77	5.65	5.47
Avg. Speed	17.6	14.3	10.4	17.2
POLLUTANT EMISSIONS				
HC (000 gr)	134.3	1.8	5.4	141.5
CO (000 gr)	1495.8	20.7	37.7	1554.3
NO (000 gr)	55.2	0.7	21.1	76.9
DIRECT ENERGY CONSUMPTION				
Warm Eng.	2207	33		
Cold Eng. 35%	126	3		
T.Fuel(Gals.)	2333	36	231	2599
BTUs (000)	291569	4514	32014	328097

12.1 Multiple HOV Facilities

NETPEM does not require an unbroken node-by-node description of the HOV facility to follow only one existing highway when added to the network. HOV facilities are described node-by-node, and this information is enough for the shortest path algorithm. Therefore, multiple HOV facilities can be considered as a *single* HOV facility and described in the same file. This option allows the user to add multiple HOV facilities to the network such as those shown in Figure 13.

12.2 Physically Separated HOV Lane with No Intermediate Entrances or Exits

If the supply characteristics of adjacent auto links are unaffected, the HOV facility can be specified by only indicating the starting and ending nodes. Both facilities in Figure 13 correspond to this case. For example, for the facility connecting node 1 to node 6, it is not required to specify the segments 1-2,2-4,4-6, but only the entire link 1-6.

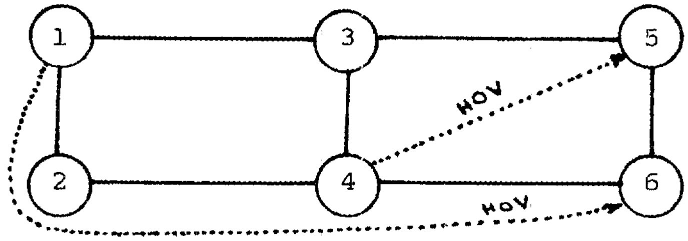

Figure 13: Network Representation of Multiple HOV Facilities in NETPEM

12.3 Contraflow HOV Lanes

No restriction is applied to the direction of HOV links. Contraflow lanes are specified in a manner similar to concurrent-flow lanes. The only difference is that, if modifications to the auto links are desired, these have to be done by the analyst directly in the link file because the algorithm cannot find the corresponding link if the head and/or the tail node do not match.

12.4 Ramp Metering with Traffic Signals

A typical form of ramp metering is to install a special traffic signal on the entrance link to an expressway that is intended to limit the total number of non-HOV vehicles that enter to the facility per hour, while allowing HOV's unimpeded access to the freeway. This type of ramp metering technique can be modelled in NETPEM by coding a HOV link in parallel to the existing non-HOV ramp link, and then modifying the performance function of the non-HOV ramp link to account for the phase delay of the traffic signal installed there, where total travel time on the link is equal to time in the queue plus the service time (link impedance). The capacities of both the HOV and non-HOV ramps links could be made very large to nullify congestion effects on the entrance ramp after passing the signal. A network schematic representation of how such a link could be modelled is shown in Figure 14.

12.5 Discontinuous HOV Facilities

Suppose that an extra diamond lane is going to be introduced to the network, but that for some reason, such as a tunnel or bridge, it is impossible to add an additional lane to some segments of the expressway. The HOV facility will have to occupy the normal auto links in these segments, or not exist at all on these

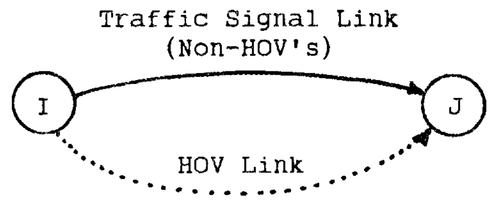

Figure 14: Network Representation of Ramp Metering with a Traffic Signal

segments. Figure 15 illustrates the case of a tunnel along the expressway where the HOV facility is the added.

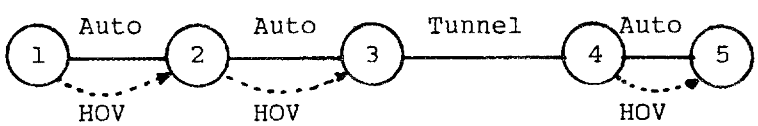

Figure 15: Discontinuous HOV facilities

This case is similar to the situation in which multiple HOV facilities are to be added to a network. There is no requirement that an HOV facility be continuous. Therefore, the facility can be described in a file as a series of links just as any other HOV facility, except that the node numbering of this particular facility will not represent a unbroken path.

13 Summary

A model to assess the impacts of major high-occupancy vehicle (HOV) facilities on regional levels of energy consumption and vehicle air pollution emissions in urban areas was described and applied in this report. The Network Performance Evaluation Model combines several urban transportation planning models into a multi-modal network equilibrium framework including elastic demand. The NETPEM program itself contains only the urban traffic modelling routines. Calculations of modal fuel consumption and vehicle emissions based upon link volumes and travel times from NETPEM are accomplished by running the results of NETPEM through the Performance Evaluation Module called PERMOD. This two-stage process allows the user of NETPEM and PERMOD to vary the impact parameters required for PERMOD such as fuel consumption and pollution emission rates to see how such changes affect the magnitude of impacts without having to rerun the travel models themselves. It also streamlines the execution of NETPEM by not having these data and calculations required within it.

NETPEM and PERMOD can be used to forecast and compare the impacts of alternative network design and supply configurations on area traffic patterns, travel costs, mode choice, travel demand, energy consumption and vehicle missions. Several important modelling options such as the multinomial modal split model and elastic demand make it possible to compare different planning scenarios. Spreadsheet templates are used to define input paramaters and impact coefficients, and to examine tables and graphs of the model's impact estimates. Lastly, since NETPEM is programmed in standard Pascal, its code can be executed on mainframe or microcomputers with only minor coversions required.

The software and User's Manual provided with this report is for NETPEM-PC. Screen and cursor control made possible through the use of microcomputer software make this version of NETPEM easiest to use. NETPEM-PC can be run on IBM PC, XT or AT computers. Networks having a maximum of 30 zones, 400 nodes and 1000 links can be run on these computers with 640K of RAM, while slightly smaller networks can be run on computers with less addressable memory.

For example applications of NETPEM-PC, the potential impacts of five different HOV lane/ramp facilities, when added to a major expressway in the Pittsburgh metropolitan area, were simulated as described in this report. These example applications demonstrated the flexible use of NETPEM for modelling many different types of HOV facility operations on a highway network. The results of these example runs were discussed, and techniques for modelling other types of HOV lane/ramp facilities within NETPEM were suggested. These examples, and the description of the model, were also intended to show that NETPEM is applicable to modelling other types transportation network supply changes in addition to HOV facilities for which is was created. Other types of supply changes may require direct adjustments to the network link file, however, rather than by using a spreadsheet template as was done for HOV facilities.

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Appendix A. Datasets Used in Example Applications

Table A-1: Network Link File for the 11 Zone Pittsburgh Network (11 zones, 17 nodes, 50 links)

From Node	To Node	Free-Flow Travel Time (hours)	Capacity (veh/hr)	Length (mi)
1	4	0.226	600.0	4.533
1	2	0.195	600.0	3.900
2	10	0.070	600.0	1.400
2	16	0.011	600.0	0.233
2	1	0.195	600.0	3.900
3	4	0.056	600.0	1.133
3	6	0.043	2000.0	0.866
3	10	0.005	600.0	0.100
3	16	0.100	600.0	2.000
4	12	0.116	500.0	2.333
4	5	0.176	600.0	3.533
4	1	0.226	600.0	4.533
4	3	0.056	600.0	1.133
5	6	0.096	500.0	1.933
5	11	0.101	900.0	2.033
5	17	0.116	500.0	2.333
5	15	0.015	500.0	0.300
5	12	0.015	500.0	0.300
5	4	0.176	600.0	3.533
6	7	0.030	2000.0	0.600
6	3	0.043	2000.0	0.866
6	5	0.096	500.0	1.933
7	8	0.101	1500.0	2.033
7	13	0.066	500.0	1.333
7	6	0.030	2000.0	0.600
8	9	0.095	2000.0	1.900
8	7	0.035	1500.0	0.700
9	11	0.008	900.0	0.166
9	17	0.116	500.0	2.333
9	13	0.206	500.0	4.133
9	8	0.061	2000.0	1.233
9	14	0.133	1000.0	2.666
9	15	0.116	500.0	2.333
10	3	0.038	600.0	0.766
10	2	0.070	600.0	1.400
11	9	0.008	900.0	0.166
11	5	0.101	900.0	2.033
12	5	0.015	500.0	0.300
12	4	0.116	500.0	2.333
13	9	0.140	500.0	2.800
13	14	0.006	1000.0	0.133
13	7	0.066	500.0	1.333
14	9	0.133	1000.0	2.666
14	13	0.006	1000.0	0.133
15	9	0.116	500.0	2.333
15	5	0.015	500.0	0.300
16	3	0.100	600.0	2.000
16	2	0.011	600.0	0.233
17	9	0.015	500.0	0.300
17	5	0.015	500.0	0.300

Table A-2: Total Person Trips File for the 11 Zone Pittsburgh Network

TOTAL PERSON TRIPS FOR THE 11 ZONE PITTSBURGH NETWORK
****
(trips from each origin zone listed in rows)

1	2	3	4	5	6	7	8	9	10	11
0	0	579	0	542	0	316	796	1569	0	0
0	0	0	0	314	0	0	2154	7825	0	0
0	0	0	0	546	0	0	465	1866	0	0
0	0	0	0	0	1192	497	1093	2947	0	0
0	0	0	0	0	0	0	0	3946	0	0
0	0	0	0	0	0	0	585	8516	0	929
0	0	0	0	0	0	0	0	430	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0

Table A-3: Scheduled Bus Trips for the 11 Zone Pittsburgh Network

SCHEDULED BUS TRIPS FOR THE 11 ZONE PITTSBURGH NETWORK
****
(trips from each origin zone listed in rows)

1	2	3	4	5	6	7	8	9	10	11
0	0	2	0	2	0	1	3	6	0	0
0	0	0	0	1	0	0	6	26	0	0
0	0	0	0	2	0	0	2	7	0	0
0	0	0	0	0	4	2	4	11	0	0
0	0	0	0	0	0	0	0	14	0	0
0	0	0	0	0	0	0	2	34	0	4
0	0	0	0	0	0	0	0	2	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0

Table A-4: Initial Conditions File for the 11 Zone Pittsburgh Network

INITIAL CONDITIONS FILE FOR THE 11 ZONE PIITSBURGH NETWORK
****

Constants for the Network
****

Beta = - 57.6
Gamma = - 0.0308

Ratio street/air distance = 1.25
Average pick up dwell time = 1.0 minutes
Average Auto Occupancy = 1.3

Out-of-Pocket Costs
****

Auto	=	24.60	(cents/mile)
Pool	=	6.25	(cents/mile) for
		3.5	passenger pools
Bus	=	100.25	(cents)

Initial Split Conditions
****

Avg. Inc. per year	No. Auto Drivers	No. Pool Commuters	No. Bus Riders	Area Zone	Avg. Riders	% Poolers in 3 Pools
22500	2471	190	1141	1.0	5.5	0.30
22500	6690	515	3088	1.0	5.5	0.30
22500	1870	1	863	1.0	5.5	0.30
22500	3724	286	1719	1.0	5.5	0.30
22500	2565	197	1184	1.0	5.5	0.30
22500	6519	501	3009	1.0	5.5	0.30
22500	279	21	129	1.0	5.5	0.30
22500	0	0	0	1.0	5.5	0.30
22500	0	0	0	1.0	5.5	0.30
22500	0	0	0	1.0	5.5	0.30
22500	0	0	0	1.0	5.5	0.30

Table A-5: Auto and HOV Fuel Consumption Rates

AUTO AND HOV FUEL CONSUMPTION RATES (GAL/VEH-MILE)
****

Number of Ranges 14

SPEED	Subcompact	Compact	Standard
1.0	0.4564	0.7552	0.9522
5.0	0.1220	0.1800	0.2226
10.0	0.0802	0.1081	0.1314
15.0	0.0663	0.0841	0.1010
20.0	0.0593	0.0722	0.0858
25.0	0.0551	0.0650	0.0767
30.0	0.0523	0.0602	0.0706
35.0	0.0503	0.0567	0.0663
40.0	0.0371	0.0498	0.0616
45.0	0.0379	0.0504	0.0623
50.0	0.0395	0.0531	0.0656
55.0	0.0420	0.0563	0.0696
60.0	0.0453	0.0608	0.0752
65.0	0.0497	0.0667	0.0825

Table A-6: Cumulative Excess Fuel Consumption for Auto and HOV Trips Due to Cold Starts

AUTO AND HOV CUMULATIVE EXCESS FUEL CONSUMPTION (GAL/VEH)
****

Number of Distance Ranges 16

Distance from Start of Trip (miles)	Cumulative Excess Fuel Consumption (gal) by Vehicle Type Subcompact	Compact	Standard
0.6	0.0506	0.0586	0.0799
1.2	0.0559	0.0706	0.0932
1.9	0.0613	0.0826	0.1039
2.5	0.0666	0.0892	0.1119
3.1	0.0719	0.0946	0.1172
3.7	0.0746	0.0999	0.1225
4.4	0.0773	0.1039	0.1279
5.0	0.0799	0.1079	0.1332
5.6	0.0812	0.1105	0.1359
6.2	0.0826	0.1119	0.1385
6.8	0.0826	0.1119	0.1412
7.5	0.0826	0.1119	0.1438
8.1	0.0826	0.1119	0.1452
8.7	0.0826	0.1119	0.1465
9.3	0.0826	0.1119	0.1478
9.9	0.0826	0.1119	0.1484

Table A-7: Hydrocarbon Emission Rates

HYDROCARBON EMISSION RATES (GRAMS/VEH-MILE)
****

Number of Speed Ranges 14

Speed	Vehicle Type Light	Heavy
1.0	32.46	12.27
5.0	14.16	9.58
10.0	7.90	7.22
15.0	5.80	5.61
20.0	4.83	4.48
25.0	4.23	3.69
30.0	3.77	3.13
35.0	3.42	2.73
40.0	3.17	2.45
45.0	3.03	2.26
50.0	2.95	2.15
55.0	2.87	2.09
60.0	2.62	2.09
65.0	2.60	2.09

Table A-8: Carbon Monoxide Emission Rates

CARBON MONOXIDE EMISSION RATES (GRAMS/VEH-MILE)
****

Number of Speed Ranges 14

Speed	Vehicle Type Light	Heavy
1.0	444.55	100.03
5.0	179.50	72.81
10.0	93.23	50.72
15.0	65.25	36.72
20.0	52.40	27.63
25.0	44.22	21.60
30.0	37.93	17.54
35.0	33.11	14.79
40.0	29.85	12.96
45.0	28.10	11.79
50.0	27.29	11.15
55.0	25.91	10.97
60.0	21.63	11.23
65.0	21.63	11.23

Table A-9: Nitrogen Monoxide Emission Rates

NITROGEN OXIDE EMISSION RATES (GRAMS/VEH-MILE)
****

Number of Speed Ranges 14

Speed	Vehicle Type Light	Heavy
1.0	3.01	45.73
5.0	2.49	36.00
10.0	2.21	28.07
15.0	2.20	23.12
20.0	2.34	20.08
25.0	2.53	18.40
30.0	2.71	17.76
35.0	2.85	18.08
40.0	2.93	19.40
45.0	3.02	21.95
50.0	3.13	26.21
55.0	3.37	33.07
60.0	3.85	44.10
65.0	3.85	44.10

Table A-10: Auto and HOV Vehicle Fleet Compositions

AUTO AND HOV FLEET COMPOSITION PERCENTAGES
****

Vehicle Type	Avg. Auto (%)	Avg. HOV (%)
Subcompact	0.12	0.05
Compact	0.30	0.20
Standard	0.58	0.75

Table A-11: Fuel Economy (MPG) at Various Speeds for Selected Vehicles[a]

Vehicle Type	Speed (mph) 15	25	35	45	55	65
'81 Buick Century (6-cylinder)	23.5	29.4	30.2	31.3	29.2	27.6
'81 Chevrolet Caprice-Diesel (8-cylinder)	21.2	31.3	33.7	36.5	33.0	27.7
'82 Chevrolet Caprice Wagon (8-cylinder)	17.5	20.1	24.6	30.6	23.3	21.4
'82 Chevrolet Chevette-Diesel (4-cylinder)	57.3	70.7	49.0	47.2	39.7	27.6
'82 Chevrolet Citation (4-cylinder)	15.1	25.2	32.6	36.4	33.7	23.6
'83 Chevrolet Monte-Carlo (6-cylinder)	20.9	28.6	31.4	31.9	29.5	26.1
'83 Chevrolet Pickup-Diesel (8-cylinder)	18.2	24.7	24.7	23.8	22.9	18.9
'84 Chevrolet S-10 Pickup (4-cylinder)	22.0	28.4	33.6	34.1	26.5	21.8
'82 Datsun 210 (4-cylinder)	44.0	55.5	54.7	43.0	37.7	33.5
'83 Ford Escort (4-cylinder)	28.9	45.1	45.7	39.0	36.3	29.6
'82 Ford Fairmont (4-cylinder)	21.4	30.9	32.2	32.2	27.6	23.0
'82 Ford Futura (6-cylinder)	24.6	33.5	33.6	31.8	28.0	23.6
'83 Pontiac Firebird (6-cylinder)	21.3	29.2	38.0	34.2	33.6	30.6
'83 Plymouth Reliant (4-cylinder)	21.6	32.4	32.5	29.9	28.1	23.8
'82 Toyota Corolla (4-cylinder)	37.0	35.0	36.3	32.8	30.3	27.4

[a] Cruise (zero acceleration) speeds.

Source: McGill R.N., Hooker J.N. and Hodgson J.W., Vehicle Testing Project. Oak Ridge National Laboratory, Oak Ridge, TN. September 1984.

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