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I am submitting herewith a dissertation written by Li-Yang Feng entitled "Traffic Assignment Procedures and The Impacts on Mobile Source Emission Estimates". I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

Frederick J. Wegmann, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the Council

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TRAFFIC ASSIGNMENT PROCEDURES AND THE IMPACTS ON MOBILE SOURCE EMISSION ESTIMATES

A Dissertation

Presented for the

Doctor of Philosophy

Degree

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Li-Yang Feng

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DEDICATION

This dissertation is dedicated to my parents

Mr. Feng, Zhifang and Ms. Wang, Yuchu

who have given me great encouragement toward my pursuit

for a better education and professional development.

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ABSTRACT

The assignment procedure is one of the major components of the urban transportation planning model. This research reviewed different commonly used assignment procedures, and examined the impacts of these distinctive procedures on vehicular emission estimates through a series of carefully designed experiments by using the Denver travel model as a case study. Three aspects of the traffic assignment procedures were studied: the algorithms, the volume-speed functions, and the time-of-day procedures. Several related issues, such as the definition of volume-speed functions at volume-to-capacity (v/c) ratio greater than 1.0 area, the assignment termination condition, the possibility of improvement of multi-period off peak period assignment, were also studied. It was concluded that different assignment procedures have relatively small differences on the Vehicle Miles Traveled (VMT) estimates and large differences on speed estimates. For the vehicle emission estimates, large variations (20%) were observed when the assignment procedures were altered. In addition to the speed, the research found that the VMT distribution among highway facilities varied considerably, and this was a major cause of the vehicle emission estimate differences. Recommendations were made for the application of different assignment procedures and future assignment procedural improvements.

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CHAPTER ONE

INTRODUCTION

1.1 Background

The Clean Air Act Amendments (CAAA) of 1990 have a great impact on the urban transportation planning (UTP) process. One requirement is to estimate vehicular emissions, a primary source of air pollution. The forecasting of vehicular emissions, called mobile source emissions, is based on projections from the urban transportation planning models. The Environmental Protection Agency (EPA) establishes standards for metropolitan areas with severe air quality problems. The metro area's transportation improvement program has to meet air quality requirements, otherwise, federal and state funds could be suspended for future Transportation Improvement Program (TIP) projects. In order to improve air quality, Transportation Control Measures (TCM) and Transportation System Management (TSM) strategies are often necessary as part of the improvements. All of these TIP, TCM and TSM activities have to be verified through the UTP modeling process.

The UTP modeling process was first developed during the 1950s for evaluating capital intensive projects such as major highway improvements. Its standard procedure contains four steps: trip generation, trip distribution, modal split, and traffic assignment. This procedure is also called travel demand forecasting. The UTP model outputs, specifically the estimated link speeds and systemwide vehicle miles traveled (VMT), are used as a primary input to a mobile source emission model for air quality analysis. In other words, the air quality analysis is very dependent on the UTP modeling process. However, due to the nature of the UTP modeling framework, it can be questioned if it is possible to produce speeds and VMT estimates that have the necessary precision for satisfying air quality requirements.

In the classic four-step UTP modeling process, one of the most important steps is the traffic assignment procedure. Several studies were reported on improving existing assignment procedures. Some of them used a post processor to adjust output speeds, while others focused on improving volume-delay relations in the capacity-restraint assignment procedure. The purpose of these studies was to explore improved assignment procedures to suite CAAA requirements. In practice, some metropolitan planning organizations (MPOs), cities, and state departments of transportation altered their traffic assignment procedure from using the traditional Bureau of Public Road (BPR) volume-delay function. Instead, they incorporated the 1985 Highway Capacity Manual (HCM85) defined volume-speed curves in order to get better assignment results.

There are several key elements in the assignment procedure. Among them, the volume-delay functions are the core of the traffic assignment algorithm under the capacity-restraint situation. The application of different assignment algorithms, the number of time periods in the assignment and the algorithm convergency status are additional criteria that affect the assignment outcome. Based on their experience and practice, transportation agencies around the country have used different combinations of these key elements in their assignment procedures. It is obvious that different assignment procedures do not produce the same speeds and link volumes on the network, and these changes in assignment procedures will have impacts on the air pollution forecasts. Naturally, several questions can be raised due to these differences:

1. How large are the differences in the estimated system VMT, vehicle travel time, and speeds due to different assignment conditions?
2. How can these differences affect the air quality analysis in terms of vehicular emission estimates?
3. What kind of guidelines should be developed to allow comparisons of results when different assignment procedures are used?

1.2 Study Objectives

Several studies already reviewed the deficiencies of the existing traffic assignment procedures and their relationship to air quality analysis[2][3]. Some of the studies referred to specific cases in order to develop their findings. Others used a descriptive approach to specify the problems without any quantitative comparison. This research reviewed commonly used traffic assignment procedures, as well as proposed procedures, to examine the outputs of different assignment procedures through a series of carefully designed experiments. Both qualitative and quantitative measures were used to ensure the test environments were identical. The study also compared and evaluated the impacts of these distinctive assignment procedures on vehicular emission estimates. The comparisons used the Denver metropolitan area as a case study. Guidelines were developed for the application of future traffic assignment procedural improvements. The conclusions derived from this research will assist both policy makers and practitioners to better understand the relationship between traffic assignment procedures and air quality analysis. Based on the nature and purpose of the study and the key elements of the traffic assignment process, three study objectives were specified.

1. Identify current assignment algorithms used in the UTP modeling process and apply these algorithms to Denver as a test case, and analyze the difference among the model outputs in terms of VMT, Vehicle Hours Traveled (VHT), speeds, and volume to capacity ratio (v/c ratio). MOBILE5A, a mobile source factor emission model, are used to evaluate emissions of major pollutants such as Hydrocarbons (HC), Carbon Monoxide (CO) and Nitrogen Oxides (NOx) for the different algorithms.
2. Examine different volume–delay functions for the same assignment algorithms. The purpose is to define how air quality analysis results would react to different volume–delay curves.
3. Investigate the impact of the time–of–day stratification, an intermediate step of the four–step UTP model, on three major vehicle emission pollutants: HC, CO and NOx.

In order to evaluate the performance of the various assignment procedures, a set of performance measures was used. These measures included some conventional items such as VMT, VHT, volume to capacity (v/c) ratio by highway facility types, etc. Additional measures were also developed.

The analysis was conducted by using the Denver metropolitan area as a case study. Based on the findings, recommendations were presented on the impacts of different algorithms, volume–speed curves, and time–of–day stratifications on the resulting air quality analysis.

CHAPTER TWO

LITERATURE REVIEW

Many studies were conducted that discuss the shortcomings of the current UTP modeling process and propose suggestions on how to improve the traffic assignment procedures and in turn, to achieve better vehicular emission estimates. However, no research was reported on the comparison of conventional traffic assignment procedures and their impact on the output from the vehicle emission model. Several references in related areas were reviewed.

In order to analyze the impact of the traffic assignment procedures, it was important to review the most current assignment practice used by major planning agencies around the country. The Institute of Transportation Engineers (ITE) Technical Council Committee 6Y-53 recently completed a report on the current status of UTP model applications in 10 large MPOs in the United States. The report indicated some variations in the application of traffic assignment techniques. Table 2.1 summarizes the techniques used in the assignment procedures. In the subsequent sections, the commentary focuses on the major aspects of the assignment model, such as the algorithm, volume-delay function, and time-of-day stratification.

2.1 Algorithms

Extensive research has been conducted on assignment algorithms, however, only a few are mature enough to be adopted in commercial UTP software packages. Instead of

Table 2.1 Summary of Traffic Assignment Procedures in Ten Large MPOs

City	Algorithm	Assignment Period(s)	Itera-tions	Volume-Speed Functions	Capacity	No. of TAZs
Atlanta GA	equilibrium	single period peak/all day	4	n/a	LOS E	670
Baltimore MD	incremental AON	single period peak/all day	4	n/a	n/a	631
Boston MA	equilibrium	five periods		modified BPR		775
Dallas Fort-worth TX	incremental	two periods all day peak hours		modified BPR for all day & peak	LOS E	800
Denver CO	equilibrium AON	three periods am peak (0.57) pm peak (0.35) off peak (0.1)	 7 4 2	standard BPR	LOS C	1530
Detroit MI	equilibrium	single period peak/all day	3	standard BPR	LOS C?	1548
Philadelphia PA	equilibrium	single period peak/all day	4	n/a	LOS E	1335
Pitttsburgh PA	equilibrium	three periods am peak 2 hrs pm peak 2 hrs off peak 20 hrs	 5 5 5	standard BPR w/ modified coefficients for freeways	LOS D	
St. Louis MO	equilibrium	single period peak/all day (0.10)	7	HCM85 w/ modified BPR base coefficients	LOS E	978
Washington DC	volume avg.	single period peak/all day	4	standard BPR	LOS C	1345

Notes:
1. The number in the ( ) represents the time-of-day factor
2. AON - All-or-nothing assignment
3. TAZ - traffic analysis zone

developing their own algorithms, most planning agencies use existing software packages to run the four-step UTP modeling process. Several software packages, such as MINUTP, TRANPLAN, EMME/2, TMODEL2, and QRSII, are widely used. For the larger metro areas, MINUTP, TRANPLAN and EMME/2 have a very large market share due to their computation capabilities. The all-or-nothing and equilibrium algorithms can be found in almost every software package, while multi-path algorithms including stochastic assignment seem less common. Among the 10 MPOs surveyed by ITE[4], seven of them used equilibrium or some combination of all-or-nothing and equilibrium algorithms. Denver's MPO, the Denver Regional Council of Governments, used an all-or-nothing algorithm for commercial vehicle assignments and an equilibrium algorithm for general purpose vehicle assignments. Two MPOs (Baltimore and Dallas-Fort Worth) used either an all-or-nothing or all-or-nothing incremental methods. For instance, the Baltimore MPO used an all-or-nothing assignment for through-vehicle trips and used an all-or-nothing incremental assignment method with a 40%+20%+20%+20% trip-loading distribution for all other vehicles. The Washington, DC, area MPO, the Metropolitan Washington Council of Governments, used an all-or-nothing volume averaging algorithm with four iterations for its traffic assignment. This was the only MPO identified as using a volume averaging assignment method. In general, the number of iterations used in the assignment process varied between two to seven for the equilibrium assignment.

The all-or-nothing or shortest path method[5] is the simplest and most basic assignment algorithm. This algorithm builds a shortest path tree for one zone to all other zones according to predefined travel time on each link in the network, and assigns all the trips onto the links along the tree. In the shortest path tree-building procedure, there could be several shortest paths that exist between a given origin zone and destination zone pair, but only one of these paths would be selected.

The equilibrium algorithm[5,6,7] was developed by using the all–or–nothing method as a basic algorithm. It requires several iterations to perform an assignment. Within each iteration, all the trips are assigned on the network to establish an initial set of link volumes, and the link impedances, usually the travel times, are re–calculated according to the volume–delay functions. Another all–or–nothing assignment is performed to obtain a second set of link volumes by using the impedances calculated in the previous assignment. Two sets of estimated link volumes are then combined with a fraction factor which is typically referred to as Lambda. This set of link volumes becomes the final result of current iteration. By using this newly combined third set of link volumes, another set of link impedances is obtained based on volume–delay function. This process continues until no shorter unused path exists in the entire network, or a specified algorithm termination condition is reached. During the iterative process, all selected interzonal highway trips are loaded on the minimum paths of the input highway network. The network parameter, time, is adjusted link by link according to a user specified volume–delay function time adjustment or the historic standard BPR capacity–restraint formula.

Instead of assigning all the trips along one shortest path, another algorithm[5,6], called multi–shortest–paths assignment algorithm, equally divides the trips according to the number of existing shortest paths, then assigns the trips accordingly. The stochastic assignment algorithm is an extension of multi–shortest–path assignment. It uses an exponential probability function to determine how trips should be distributed among several possible paths. The most efficient path will get the highest probability that implies a higher percentage of trips will be assigned and, on the other hand, the least efficient path will get the lowest percentage of assigned trips. The multi-shortest-path and stochastic assignments can be categorized as multi-path assignments. While not as conventionally utilized, some software packages, such as QRSII and TMODEL2, do not include the stochastic assignment option.

On calculating the link volume in a multi-iteration assignment, two methods, volume averaging and volume incremental, can be used[5]. For the volume averaging method, the algorithm assigns all the trips onto the network, then calculates a new link travel time according to the volume-delay function, builds new paths and assigns all the trips onto new paths. The final link volume is then taken as the average volume of all previous iterations. In the incremental method, each iteration of assignment only assigns certain percentages of the total trip table onto the network, and the link travel time is calculated based on the current link volume and the volume-delay function. After several iterations, all the trips are assigned. The final link volume is the sum of all previously assigned volumes.

2.2 Volume-Speed Functions

A capacity-restraint assignment requires a volume-delay function describing the relationship between the v/c ratio and network link travel times. The algorithm uses this function to adjust the link travel time for the next iteration. The most widely used volume-delay function in the traffic assignment can be expressed as the following:

$$t=t_0(1+\alpha(v/c)^{\beta}) \qquad (2.1)$$

where, t is link travel time, $t >= 0$

t_0 is the travel time under free flow traffic condition,

α and β are empirical parameters, or coefficients,

v/c is volume to capacity ratio, $v/c \in [0, 1]$

or, if speed is used as an dependent variable, then the expression is called volume-speed function:

$$s=s_0 / (1+\alpha(v/c)^\beta) \quad (2.2)$$

where, s is link travel speed, $s >= 0$,

s_0 is free flow speed.

When α=0.15 and β=4.0 are used, both expressions (2.1) and (2.2) are called the original BPR function because the Bureau of Public Roads first adopted this function in the 1950s[16]. Despite some deficiencies, the BPR function is still the most widely used function for capacity-restraint assignment.

In both the 1985 and 1994 Highway Capacity Manuals, the volume-delay relationship is expressed as a volume-speed relationship with volume/capacity ratio defined from 0 to 1. Since the speed has an inverse relationship to the time, the two definitions are interchangeable. The term 'volume-speed function' was used in this research.

Stopher[2] reported that the link volumes from the traditional assignment approach usually had reasonable accuracy (about 10% on average) when they were compared to actual traffic counts, although the speeds could exceed actual observation by as much as 35%. He pointed out two reasons that caused this phenomenon. First, the capacity-restraint formula did not degrade speeds properly at high network congestion levels. Second, the definition of capacity was inappropriate. Therefore, the speeds that were input to the vehicle emission model could result in significant errors in estimating emissions. To improve this weakness, he suggested recalculating link speeds according to field observations. But Stopher did not answer the question on how to recalculate the link speeds.

There are two ways to incorporate Stopher's idea. The HCM85 volume–speed curves were developed based on traffic engineering practice to give transportation planners a reference on estimating highway network speeds. Horowitz[8] developed a set of mathematical expressions based on the HCM85 volume–delay relationships by using least squared curve fitting techniques as the capacity–restraint formulas in the traffic assignment. Post-processing is another technique that can adjust the link speeds. Dowling[3] reported a study that used an improved BPR function that was very similar to the HCM85 freeway volume–speed curve, and employed a queuing theory based post–processor to refine the speeds when the v/c ratio exceeded 1.0. Due to the complexity of applying the post processor, only two highway links were verified by this study.

Many mathematical functions can be used as base functions to generate a HCM85 volume–speed curve expression. For example, the BPR function shown in expression (2.1) can be used as a base function by altering coefficients α and β. The coefficients α and β are sometimes called undetermined coefficients which mean values of the coefficients can be changed according to the least squared curve fitting technique. Horowitz[8] reviewed three base functions that included BPR's, Spiess's and Overgaard's, and independently developed three sets of coefficients for each of the base functions by using the HCM85 volume–speed curves. The base functions Horowitz summarized can be expressed as the following[8]:

1. BPR base function:

$$s = s_0/(1 + \alpha x^{\beta}) \tag{2.3}$$

2. Spiess's base function:

$$s = s_0 / \{2 + [\alpha^2(1-x)^2 + \beta^2]^{1/2} - \alpha(1-x) - \beta\}$$

$$\beta = (2\alpha-1)/(2\alpha-2) \tag{2.4}$$

3. Overgaard's base function:

$$s = s_0 / (s_0/s_c) \hat{} x^{\alpha} \tag{2.5}$$

where, s is link travel speed;

s_0 is the free flow speed;

s_c is the speed when volume reaches the capacity;

x is the v/c ratio;

α, β are undetermined coefficients

Planning agencies around the country use different forms of volume–speed functions in practices[4,9]. For example, the Boston and St. Louis MPOs adopted a BPR function with modified coefficients while the Dallas–Fort Worth MPO used its own expression to describe the volume–speed relationship. Pittsburgh's Southwestern Pennsylvania Regional Planning Commission used a modified BPR function for its freeway assignments, and for the rest of facilities, the original BPR function was used. Other MPOs mentioned in the ITE technical committee 6Y53 report included the Denver MPO which still used the original

BPR function. In recent years, planning agencies have given more attention to revising their volume-speed function according to HCM85 volume-speed curves.

2.3 Time-of-Day Stratification

Stopher[2] also pointed out that time-of-day stratification, a process that divided trip table(s) into several sub-tables according to different time periods (usually peak and off peak), was needed to obtain better assignment results. Furthermore, he suggested that separate highway assignments be made to the highway system for each peak and off peak period when applying time-of-day stratification. However, his report did not include a practical plan for implementation nor any analysis on the consequence of proposed changes.

At the 1995 Transportation Research Board (TRB) meeting, Crevd[10] reported that a practical approach to derive peak hour estimates from 24 hour travel demand models had been developed. This approach used Nationwide Personal Transportation Survey data to derive pm peak hour factors for work and non-work trips, used a Federal Highway Administration report[11] data to obtain a truck peak hour factor, and utilized the local traffic counts to determine the duration of the pm peak period. The study then used these pm peak hour factors to convert all-day trip tables to peak period trip tables by trip purposes. Finally, an assignment was made based on the factored trip tables to obtain pm peak period link volume for air quality analysis.

The time-of-day stratification used in the Pittsburgh, Boston and Denver travel models were far more advanced than Crevd reported[10]. For example, Denver's UTP models[9] used separated trip tables for work and non-work trips, commercial trips, HOV trips, internal-external trips and external-external trips by three periods: am peak, pm peak, and off peak. Trip table conversion factors were based on a 1985 origin-destination (O-D) survey. In addition, a peak period duration model was also developed to determine future year peak spreading according to system congestion level. The Denver Regional Council of Governments (DRCOG) also maintained a 30-minute resolution for the trip table conversion factors which meant the peak period durations were calculated both in one hour increments and in half hour increments. Boston's MPO went even further: it used five periods in the time-of-day stratification process. Besides these advanced practices, MPOs in other areas such as Atlanta, Baltimore, Detroit, etc., used single period traffic assignment which meant there was no formal time-of-day stratification involved. In this research, emphasis was placed on examining commonly used time-of-day stratification processes and their impacts on the air quality analysis.

2.4 The Vehicle Emission Estimate Procedure

MOBILE5A is the latest official mobile source emission factor model developed by the EPA[12]. The State of California also developed its own vehicle emission factor software called DTIM. MPOs and local air quality control agencies used mobile emission factor models to estimate HC, CO, and NOx. For example, the input of MOBILE5A consists of three types of information. The first part includes information on climate, the modeling year and season, the status of the vehicle inspection and maintenance program, fuel data, vehicle types, etc. The second part is VMT mix information that describes the VMT distribution by vehicle type, area type and highway facility type. This information is usually obtained through a separate field study. The third part is the speed information from the travel forecasting model. The output of MOBILE5A has emission rates for each of HC, CO and NOx, measured in grams per mile. These rates are processed together with the travel model VMT output in order to generate a regional vehicular pollutant estimation for the modeling year. Figure 2.1 shows an air quality analysis flow chart using MOBILE5A and its relationship to travel forecasting modeling process. In this research, MOBILE5A was used to estimate HC, CO, and NOx for different assignment results.

MOBILE5A requires the output of VMT and speeds from UTP model. In reality, there are several ways to transfer this output information into a mobile source emission model to establish emission inventory[13,14]. The simplest way is to use a single system average speed, overall VMT, a system average vehicle mix, and average percentage of cold start as input to produce three pollutant estimates. The second method uses more specific information from the travel model, such as speed, VMT, vehicle mix and percent cold start by area type, highway facility type and time period, to build an emission inventory. For TIP conformity and long range planning purposes, these two methods have very wide application. The third approach represents the highest resolution that extracts the network link level speed and VMTs to produce emission estimates. This method requires a very accurate geographic location description of the highway system in order to estimate emissions at grid level. This is commonly used for detailed air quality analysis like dispersion / photochemical models. In the Denver region, the speeds from the UTP model runs are only summarized by area type, facility type and three time periods for establishing an emission inventory[15]. The resultant speeds and VMT estimates from the assignment procedure are then input into MOBILE5A for air quality assessment.

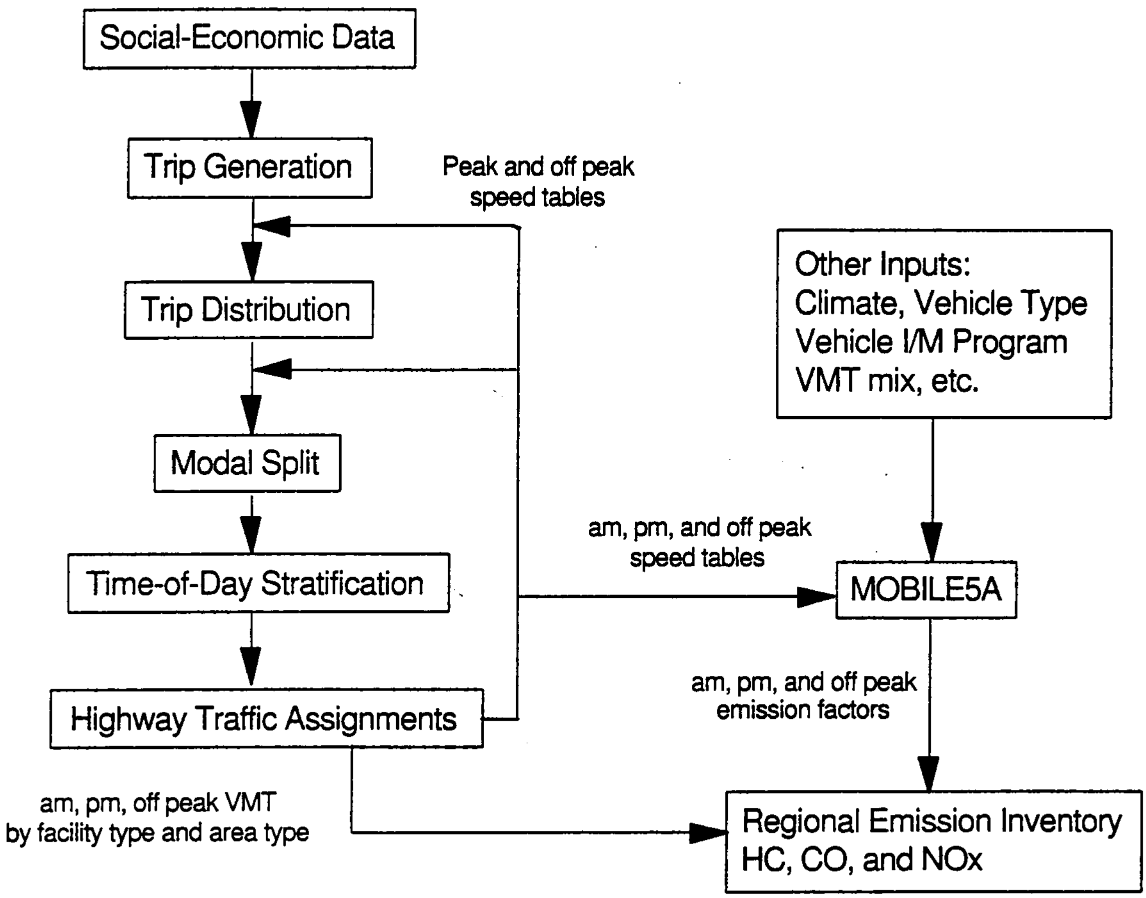

Figure 2.1 Transportation Model and Air Quality Analysis

2.5 Summary

As noted in the literature, there were different practices concerning the use of traffic assignment models among the large MPOs. Researches also suggested refined techniques to enhance assignment results and provide greater capability with air quality estimates. This research explored some of the advanced concepts to define the impact on the air quality models using Denver as a case study.

CHAPTER THREE

STUDY APPROACHES AND RESEARCH-RELATED MODELS

3.1 Study Approaches

As discussed in the study objectives, three groups of assignment-related procedures were evaluated: assignment algorithms, volume-speed functions and time-of-day stratifications. More than 20 different combinations of traffic assignments were conducted. Because of this, it was important to coordinate the tests through a well-designed plan in order to keep an uniform experimental environment.

The general approach of this research included two stages: the preparation stage and the test stage. The first stage contained the selection of test case models, the selection of the test alternatives, and the preparation of O-D tables. The second stage addressed the testing of the three assignment-related procedure groups: the algorithms, the volume-speed functions and the time-of-day stratifications. The approaches used in each comparison were similar.

3.2 The Test Models

3.2.1 Simplified Denver Travel Model

For presentation purposes, a simplified UTP model was constructed based on the Denver Regional Council of Governments (DRCOG) travel demand forecasting model as the test model. This regional model was calibrated based on 1985 Denver region household survey data, 1990 highway volume counts, and Colorado Highway Performance Monitoring

System (HPMS) data. The assignment performance on system VMT and link volume by facility type were exceeded Federal Highway Administration (FHWA) recommended standards. Figure 3.1 shows the Denver modeling area. The most current 1995 Denver regional demographic data set was utilized and the model was based on an origin-destination survey conducted in 1985. In the selected simplified Denver model, the modal split and transit assignment were omitted from the original regional model. Conversion factors were used to transform person trip tables to vehicle trip tables. Therefore, only two steps, trip generation and trip distribution, were needed to produce an O-D table. This simplified model contained 1,530 traffic analysis zones (TAZs), 9,500 nodes, and approximately 26,000 one way links.

Two major reasons made the Denver regional travel model an ideal test case to be used in this study. The first was the Denver model represents the state-of-practice and is typical of the technical level of travel demand models currently used in the United States for large metropolitan areas. Its trip generation, trip distribution, mode split and assignment modules were developed through generations of transportation planning efforts. The planning methodologies adopted in this model have applications to other cities. Secondly, Denver is a typical large city in the United States in terms of population, development density. Denver also has moderate air pollution problems. The estimated vehicle CO emission for year 1995 is 1,057,000 kilograms and the CO budget for year 2001 is 666,700 kilograms. The air quality conformity requires the estimated vehicle NOx emission should not exceed 98,400 kilograms for years 2005 and 2015. It will take a considerable effort, such as TCM, TSM and TDM, for the Denver region to control vehicle emissions under the budget. As a reference, Table 3.1 presents regional indicators for

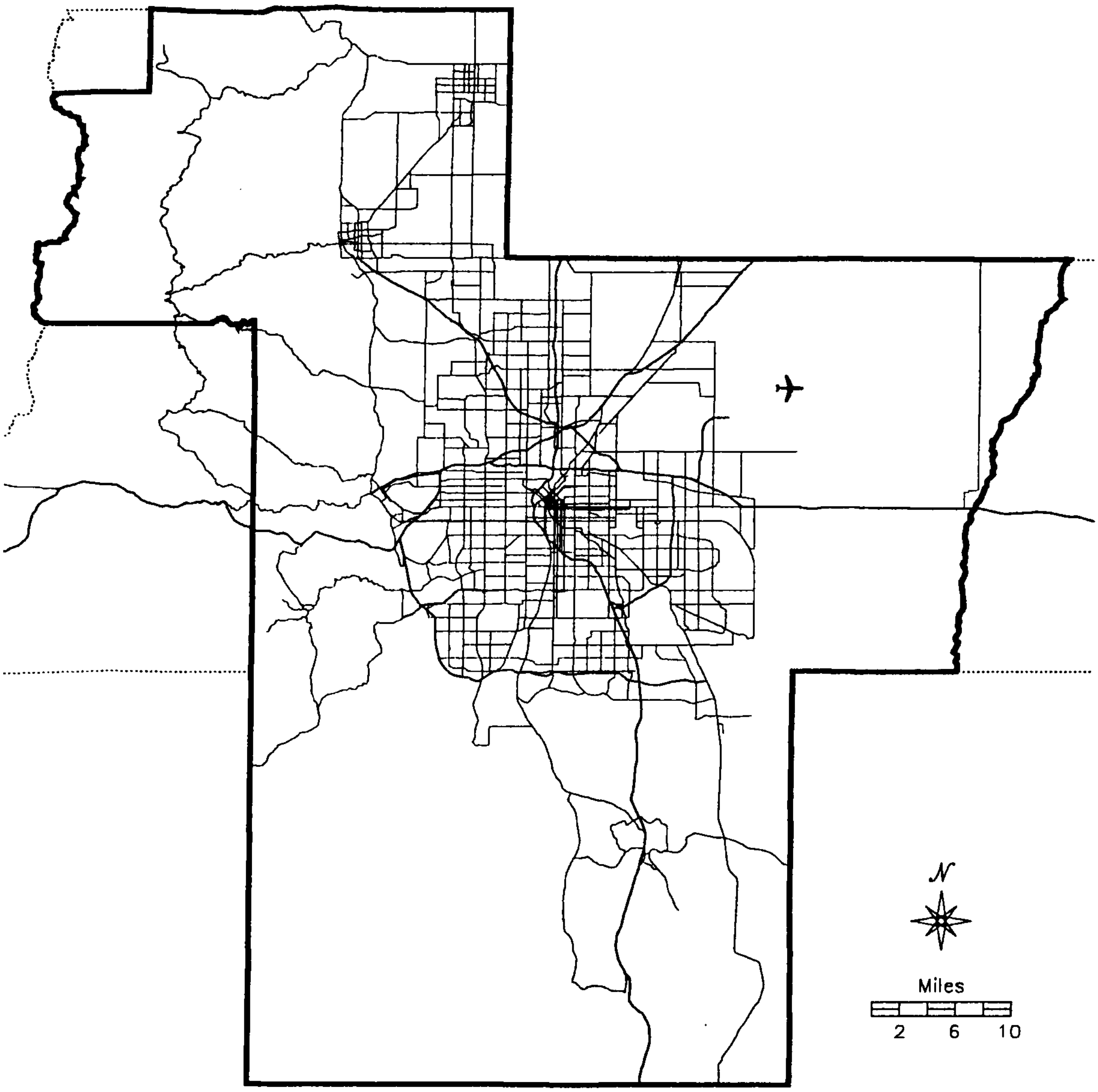

Figure 3.1 The Denver Transportation Modeling Area

Table 3.1 1990 Regional Indicators for Transportation, Density, and Air Quality

Urbanized Areas with over 1 Million Population

FEDERAL-AID URBANIZED AREA	*1990 POPULATION (1,000s)*	*PERSONS PER SQUARE MILE (1,000s)*	*FREEWAY LANE MILES PER CAPITA*	*FREEWAY MILES AS OF TOTAL ROADMILE*	*% DAILY VMT ON FREEWAY*	*VMT PER CAPITA*	*ANNUAL TRANSIT RIDERSHIP (Millions)*	*ANNUAL TRANSIT TRIPS/ CAPITA*	*AIR QUALITY OZONE*	*AIR QUALITY CO*
NEW YORK/NJ	15,780	4.97	0.36	2.9	36.0	14.3	2,808	175	Severe	Moderate
LA/LONG BCH/PMNA/ONT	11,428	5.44	0.41	2.4	42.6	21.9	515	45	Extreme	Serious
CHICAGO/NW INDIANA	7,303	3.73	0.33	2.1	27.9	16.9	697	103	Severe	
PHILADELPHIA	4,216	3.88	0.34	2.7	27.8	15.6	367	87	Severe	Moderate
DETROIT	3,905	3.14	0.45	2.2	34.1	20.0	95	26	Moderate	
SAN FRANCISCO/OAKLAND	3,676	4.50	0.58	3.8	54.5	20.9	414	114	Moderate	Moderate
WASHINGTON, D.C.	3,240	3.95	0.52	3.4	38.9	19.9	372	111	Serious	Moderate
DALLAS/FORT WORTH	3,030	2.16	0.84	2.3	41.3	26.5	57	18	Moderate	
BOSTON	2,803	2.71	0.52	2.8	43.0	18.3	324	117	Serious	Moderate
HOUSTON	2,798	1.81	0.70	1.8	39.5	25.6	91	31	Severe	
SAN DIEGO	**2,294**	**3.37**	**0.72**	**4.0**	**51.9**	**22.5**	**68**	**29**	**Severe**	**Moderate**
MINNEAPOLIS/ST. PAUL	2,055	2.06	0.71	3.2	39.0	21.0	70	33		Moderate
BALTIMORE	1,991	3.81	0.62	4.0	41.7	18.3	117	62	Severe	Moderate
ST. LOUIS	1,950	2.81	0.80	3.8	41.3	23.2	45	23	Moderate	
PHOENIX	1,920	1.98	0.30	0.9	17.8	20.7	32	16	Moderate	Moderate
ATLANTA	1,860	1.55	1.01	2.7	37.9	34.9	150	69	Serious	
MIAMI	1,800	4.07	0.36	1.9	30.4	18.6	78	41	Moderate	
CLEVELAND	1,752	2.79	0.67	4.0	40.9	18.4	75	45	Moderate	Moderate
SEATTLE/EVERETT	1,730	2.68	0.56	2.7	40.1	23.6	100	57	Marginal	Moderate
PITTSBURGH	1,708	2.40	0.50	2.8	22.1	19.0	89	53	Moderate	
DENVER	1,540	3.56	0.57	2.8	39.5	17.6	55	37		Moderate
SAN JOSE	1,410	4.33	0.71	4.5	47.9	23.0	46	32	Moderate	Moderate
KANSAS CITY	1,281	2.11	1.17	4.9	45.0	21.4	19	15	Marginal	
MILWAUKEE	1,220	2.22	0.47	2.2	26.2	23.5	66	54	Severe	
FT. LAUDERDALE/HOLLYWOOD	1,200	3.26	0.49	2.0	23.5	20.2	19	15	Moderate	
PORTLAND	**1,196**	**2.88**	**0.52**	**2.8**	**38.5**	**18.7**	**59**	**50**	**Moderate**	**Moderate**
SAN BERNARDINO/RIVERSIDE	1,169	2.44	0.63	3.2	47.6	21.4	10	8	Severe	
SAN ANTONIO	1,165	2.64	0.72	2.3	33.5	21.7	42	37		
CINCINNATI	1,136	2.01	0.77	4.2	46.1	20.8	35	29	Moderate	
SACRAMENTO	1,096	3.22	0.58	2.8	37.5	21.6	20	19	Serious	Moderate
NEW ORLEANS	1,080	2.99	0.31	2.0	23.2	15.5	85	82		
BUFFALO	1,064	2.63	0.61	4.0	31.6	16.0	30	32	Marginal	
ST. PETERSBURG	1,020	1.84	0.18	1.0	7.8	17.6	20	12	Marginal	
ORLANDO	917	2.14	0.39	2.1	20.9	20.9	8	9		
SALT LAKE CITY	872	2.18	0.64	3.2	33.5	19.3	24	30	Moderate	
WEST PALM BEACH	863	2.34	0.41	2.2	32.4	19.9	2	3	Moderate	

Source: The Urban Land Institute

transportation, land use, density, and air quality for the 36 largest U.S. cities as of 1990. As can be seen in the table, Denver had a population of 1.5 million with a density of 3,560 persons per square mile which placed it right in the middle of the 36 urbanized areas. The daily VMT per person was 17.6 miles which reflected the average value for large cities such as Washington DC, Cleveland, Baltimore, Portland etc. According to the Denver Regional Travel Model Documentation[9], the trip rates per person in the Denver region were very similar to other large cities like Seattle, Dallas, and Baltimore. Therefore, the research findings derived from the Denver case have general application in the UTP practice and air quality analysis.

3.2.2 Trip Generation, Trip Distribution and Modal Split

Trip generation determines how many trips will begin or end in each traffic analysis zone (TAZ). The Denver trip generation consists of six trip purposes: Home-Based Work (HBW), Home-Based Non-Work (HBNW), Non-Home-Based (NHB), Commercial/truck (COM), Internal-External (IE), and External-External (EE). The trip generation model has two sub-models: a production model and an attraction model. Both models use a cross-classification method.

The highway network path-building process serves as a pre-step to trip distribution. It develops the paths between zone pairs, determines zone-to-zone travel times and distances based on minimum impedance, and adds terminal time and intra-zonal travel times on developed paths for the trip distribution analysis. There are two types of files needed to build the highway paths: a highway network file and a set of speed tables describing peak and off peak highway speeds stratified by facility type and area type. The

Denver highway networks are divided into five area types: 1) central business district, 2) fringe, 3) urban, 4) suburban, and 5) rural, and seven facility types: 1) freeways, 2) expressways, 3) principal arterials, 4) minor arterials, 5) collectors, 6) ramps, and 7) centroid connectors.

Trip distribution establishes a linkage between zones. The gravity model, a widely used trip distribution model, is utilized by Denver travel model. Five trip purposes (HBW, HBNW, NHB, COM, and IE) are processed separately with different friction factor tables. The EE table is formed by using the Frater growth factor model based on base year O–D pattern estimates.

The modal split in the test case is simply a separate factor for each trip purpose to convert person trips to vehicle trips according to the Denver regional model modal split parameters.

3.2.3 Time–of–Day Stratification and Traffic Assignment

Time–of–day stratification process is closely related to the assignment procedure. In the early modeling practice, there was no formal time–of–day stratification. Eight to 12 percent of the all–day O–D table was assigned to the network and compared with hourly capacity; then the link volumes were converted back to all–day volumes. In the current Denver regional model, the time–of–day stratification process transposes the production–attraction (P–A) trip tables into the O–D tables, divides the O–D tables into three time period sub O–D tables (am peak, pm peak and off peak), and finally converts the person trips into vehicle trips.

The traffic assignment determines the routes that people would use when they make trips, determined from the trip distribution step. There are different algorithms to accomplish the trip routing. The unconstrained all-or-nothing and capacity-restraint equilibrium methods are the most popular. The assignment models used by the Denver MPO are discussed in more detail in chapters five and six.

3.3 Study-Related Models

3.3.1 MINUTP Programs

MINUTP is one of the three most widely used UTP software packages in the United States. MINUTP was originally developed as an microcomputer version of the Urban Transportation Planning System (UTPS), a federally produced software that is operated in a mainframe computer environment. MINUTP contains a set of programs which perform the various UTP modeling tasks. In order to run a MINUTP-based travel model, a control file (sometimes called a setup file) that contains a set of MINUTP program commands is required. The Colorado Department of Transportation (CDOT) has designated MINUTP as the official UTP modeling software used for microcomputer-based traffic forecasting within the state of Colorado. The assignments tested in this study used MINUTP as the primary UTP model software.

The two most important MINUTP modules in this study were the ASSIGN and MATRIX programs. The ASSIGN program provides a user option to select different algorithms, while the MATRIX program provides functions that manipulate matrices, such as addition, subtraction, division and multiplication, as well as converting matrix files between binary and American Standard Codes for Information Interchange (ASCII) formats. In the study, many control files were used to handle different functions and tasks. Appendix A is a sample of MINUTP control files used in this research.

Prior to version 93A, MINUTP did not provide the user with the option to alter the BPR volume–speed function in the capacity–restraint assignment method. Starting with version 93A, a new option was provided so that the user can change coefficients α and β in the volume–speed function. This gave the researcher an opportunity to test and compare the model performance under different coefficients. MINUTP Version 94B, the version used in this research, provides users even greater freedom so that they are able to specify their own volume–speed functions.

3.3.2 MOBILE5A, the Mobile Source Emission Factor Model

The MOBILE5A model was used as a post–processor to generate the vehicle emission estimates for all the assignment tests. After the traffic assignment, the link volumes and travel times were summarized as VMT and VHT by area types and facility types in a print file form. This print file was imported to a spreadsheet to generate speed estimates, then the output from the spreadsheet in ASCII was used as an input to MOBILE5A. The output of MOBILE5A contained three emission factors for HC, CO and NOx for each area type and facility type. A FORTRAN program was written to extract this information from MOBILE5A report file in ASCII format. These outputs were then imported into another spreadsheet to calculated pollutants in grams per vehicle mile and total emissions by area type and facility type. The Air Pollution Control Division of the Colorado Department of Public Health and Environment provided the other MOBILE5A required inputs, such as the VMT mix data, vehicle inspection and maintenance program status, climate information, estimated percentage cold start, etc. These data were based on several separated studies conducted by regional agencies including DRCOG. The VMT mix, the vehicle operating mode, such as percentage cold start and hot start, and temperature vary by highway facility, geographical location, and time period, Table 3.2 uses urban arterials and rural freeways as examples to illustrate how scenario parameters varied in the Denver regional MOBILE5A model. Appendix B presents a complete base control files used in this research for the vehicle emission factor modeling.

The next chapter discusses the overall study design and compares alternate assignment algorithms.

Table 3.2 Examples of Scenario Parameters in Denver Regional MOBILE5A Model

Facilty Type	Urban Major Arterials	Rural Freeways
Region	High-altitude	High-altitude
Calendar Year	1995	1995
Average Speed(mph)	31.6	57.4
Ambient Temperature (F)	47.9	47.9
Vehicle Operating Modes (%)		
Non-catalyst, Cold-start (PCCN)	22.3	19.3
Non-catalyst, Hot-start (PCHC)	14.9	7.7
Catalyst, Cold-start (PCCC)	31.7	25.0
VMT Mix (%)		
Light Duty Gas Vehicles (LDGV)	66.3	45.9
Light Duty Gas Trucks 1 (LDGT1)	19.0	21.0
Light Duty Gas Trucks 2 (LDGT2)	9.5	10.5
Heavy Duty Gas Vehicles (HDGV)	1.6	7.6
Light Duty Diesel Vehicles (LDDV)	0.4	0.3
Light Duty Diesel Trucks (LDDT)	0.2	0.2
Heavy Duty Diesel Trucks (HDDT)	3.0	14.5
Motorcycles (MC)	0.0	0.0
Total	100.0	100.0

CHAPTER FOUR

STUDY DESIGN AND COMPARISON OF ASSIGNMENT ALGORITHMS

4.1 Study Purpose

The major purpose of this chapter is to explore the impact of traffic assignment algorithms on the vehicle emission estimates through a series of tests and analyses. There were several issues to be considered as a part of this topic. The first was to compare overall assignment performance among different algorithms and their related estimates of vehicle emissions, and explore why and how these differences occurred. The second was to check if system performance measures such as VMT, VHT and speed, were distributed differently among the facility types for distinctly different assignment algorithms. If there were differences, then the degree of such a difference and its impact on corresponding emission estimates would be examined. Utilizing a fixed O-D pattern for the Denver area, a series of tests was designed to explore the assignment performance of different algorithms.

4.2 Test Design

Test design was an important step leading to a successful experiment. Four tasks were included in the test design stage of the study:

- Define assignment environment;
- Generate a uniform O-D table;
- Select test cases for different algorithm; and
- Determine test result summary method.

4.2.1 Assignment Environment

The definition of capacity is one of the critical factors that affect the capacity–restraint assignment. Capacity is defined as the maximum rate of flow at which vehicles can reasonably travel across one lane of roadway during a period of time. The commonly used unit is passenger cars per hour per lane (pcphpl). HCM85 defines a capacity range for each type of highway facility: freeway, urban arterial, and multi–lane highway. During the UTP model calibration stage, the capacities are adjusted to provide the best fit between model–produced link volumes and observed base year roadway counts. In the past, the practical capacity on a freeway was interpreted as 16,000 passenger cars per lane per day which was estimated as 1,500 passenger cars per hour per lane (pcphpl)[16]. The Denver regional travel model used practical capacity as equivalent to level of service (LOS) C. According to old traffic engineering practice[16], the capacity at the LOS C is similiar to "practical capacity", which means the traffic does not operate at either congested or free flow status. Many agencies are still using practical capacity in their assignment process. The LOS C capacity was selected to perform the test described in this chapter.

Many planning agencies use 9–10% of all–day O–D trip table to perform a single period all–day assignment with LOS C capacity. The factored O–D tables and hourly capacity of 1,500 pcphpl for freeways are used and the hourly assignment results are then converted back to all–day estimates of link volumes. The factored O–D table and hourly capacity are easy to implement with available software. It was tested in this research that the assignment results from using hourly capacity were the same as the assignment that used all–day capacity without a conversion factor. This hourly capacity approach is called single period all-day assignment. In this chapter, hourly capacity was used for all tested algorithms. A 9% factor was applied internally in the MINUTP ASSIGN module, and the all-day assignment result was automatically reported by the computer program.

As discussed in chapter two, the original BPR function was still a very popular volume-speed curve used around the country, and this function was selected for all the algorithms discussed in this chapter excepted for all-or-nothing assignment.

In summary, the algorithms tested in this chapter used:

- A 9% factor applied to the O-D table to make an all-day single period assignment;
- LOS C capacity (e.g. 1,500 pcphpl for freeways);
- The original BPR function for capacity-restraint assignment.

4.2.2 O-D Table Preparation

This task consisted of two sub-steps. The first was to define a set of appropriate speeds used to generate O-D trip distribution pattern, and the second was to generate an O-D table through trip generation and distribution modules.

To maintain an identical test environment, a uniform O-D table was required for all the assignment procedures tested in this research. Because link speed values have a great influence on the P-A tables and O-D trip tables, the selection of appropriate speeds to develop paths between zone pairs becomes important. HCM85 defines a rough relation between free flow speeds and practical capacity speeds for different highway facilities. For freeway sections, the practical capacity speeds are about 78%–82% of free flow speeds. For the arterials, the practical speeds are at 55%–72% of free flow speeds. Table 4.1 lists the relationship between the LOS C v/c ratio and speeds summarized from HCM85.

The speeds that correspond to practical capacity should be defined as practical speeds or level-of-service (LOS) C speeds. In this study, LOS C speeds were used in the trip distribution to determine an O-D table. For freeways, 0.8 of free flow speed was used. For expressways, since the operational characteristics are very similar to multi-lane highways in the suburban area, a ratio of 0.75 of free flow speed was used. For major arterials and minor arterials, the ratios of 0.6 and 0.55 of free flow speeds were used, respectively. Since there is no LOS and speed information provided in HCM85 for ramps and collectors, assumptions of 0.7 and 0.55 of free flow speeds were adopted for these facilities.

Table 4.1 LOS C Speed as a Percentages of Free Flow Speed

Freeways			
Free Flow Speed	v/c Ratio	LOS C Speed	% of Free Flow Speed
60 mph	< 0.77	54 - 57 mph	71% - 81%
55 mph	< 0.69	47 - 50 mph	78% - 83%
48 mph	< 0.67	> 43 mph	> 86%
Multi-lane Highways			
Free Flow Speed	v/c Ratio	LOS C Speed	% of Free Flow Speed
60 mph	< 0.71	50 - 53 mph	71% - 76%
55 mph	< 0.65	44 - 48 mph	73% - 80%
48 mph	< 0.60	39 - 42 mph	78% - 84%
Arterials			
Free Flow Speed	v/c Ratio	LOS C Speed	% of Free Flow Speed
I: Suburban 40 mph	-	22 - 28 mph	55% - 70%
II: Intermediate 33 mph	-	18 - 24 mph	54% - 72%
III: Urban 27 mph	-	13 - 19 mph	48% - 70%

After defining the speeds, trip generation module was performed to generate total trip productions and attractions for each TAZs based on 1995 Denver regional demographic data. Path trees were created by using level-of-service C speed for all highway links. Trip distribution and a simplified mode split were also performed to produce P–A vehicle trip tables for home-based trip purposes and O–D vehicle trip tables for non-based trip purposes. According to Denver region modeling practice, a time-of-day stratification process (This process is discussed in detail in chapter six) converted or transposed the trip tables generated from previous step into am peak, pm peak, and off peak three period O–D tables. These three table were then combined into one all-day O–D table. Four O–D tables were used in all the test cases discussed in this research. However, only one all-day O–D table was used to test the algorithms examined in this chapter.

4.2.3 The Test Cases

Considering the current practice and the software capability, three basic assignment algorithms were selected to be evaluated in this study: all-or-nothing, stochastic and equilibrium. Since there are different ways to calculate link volume for a multi-iteration assignment, the all-or-nothing and stochastic assignments can be further divided into different categories. Overall, six test cases were designed to test the impact of the different algorithms.

1. All-or-nothing
2. All-or-nothing volume averaging
3. All-or-nothing incremental
4. Stochastic volume averaging
5. Stochastic incremental

6. Equilibrium

All-or-nothing unconstrained assignment using free flow speeds is the simplest assignment algorithm adopted in the transportation network analysis. The all-or-nothing method assigns all the trips to the links that comprise the shortest path between two zones. The shortest path is determined by a set of pre-defined link travel times or speeds. Only one iteration of all-or-nothing assignment is needed, therefore, no capacity-restraint is applied. This research selected all-or-nothing as the first case to test.

The second algorithm tested was all-or-nothing volume averaging algorithm with capacity-restraint. Five iterations of all-or-nothing assignment were performed and the final resultant link volume was the arithmetic average of the five previous link volumes.

The third case used all-or-nothing incremental assignment in which each iteration was assigned a certain percentage of the O-D trips to the network by using the all-or-nothing method. The trip table was split into several sub-trip tables. After first iteration, the capacity-restraint formula was applied to recalculate the link travel time, and based on this recalculated link travel time, the second sub-trip table was loaded onto the same network with the first sub-trip table pre-loaded. This process continued until all the sub-trip tables were assigned onto the network. A 20+20+20+20+20 percentage split was used to form the total percentage of 100 and five iterations were selected for the test case.

The stochastic multi-path assignments with capacity-restraint are not currently conventionally applied, but, were included as tests. Test cases four and five referred to the stochastic volume averaging and stochastic incremental tests. Five iterations were adopted for each test case.

The last algorithm for testing was the equilibrium algorithm which currently has wide application in large metro areas. It is actually an improved version of shortest path method with capacity–restraint. In this algorithm, after traffic is assigned to a link, the travel time on each link is adjusted according to a volume–delay function that uses the link v/c ratio as an independent variable. Five iterations were used for this assignment, too. The number of iterations selected for all test cases in the study was five; this was based on the current modeling practices of large MPOs. Figure 4.1 is a summary of the test cases in the algorithm group.

4.2.4 Test Result Aggregation Scheme

After all six tests, the assignment performance measures, VMT, VHT, and speed, were summarized by area type and facility type. These desegregated speeds were then sent into a regional MOBILE5A model to produce emission rates for three pollutants: CO, HC and NOx. Finally, the generated emission rates, segregated by area type and facility type, were multiplied by their corresponding VMT to obtain vehicle emission estimates. Then these data were ready to be aggregated for further analysis. All the test results presented in this research, including this chapter, were summarized in a same manner to ensure the consistency of the analysis. For the convenience of analysis, qualitative words such as "small", "medium", and "large", were used to describe the test result difference in the text. The word "small" referred to the test measure difference below 5%, the word "medium" referred to the difference at 5%–15% level, while the word "large" implied the difference

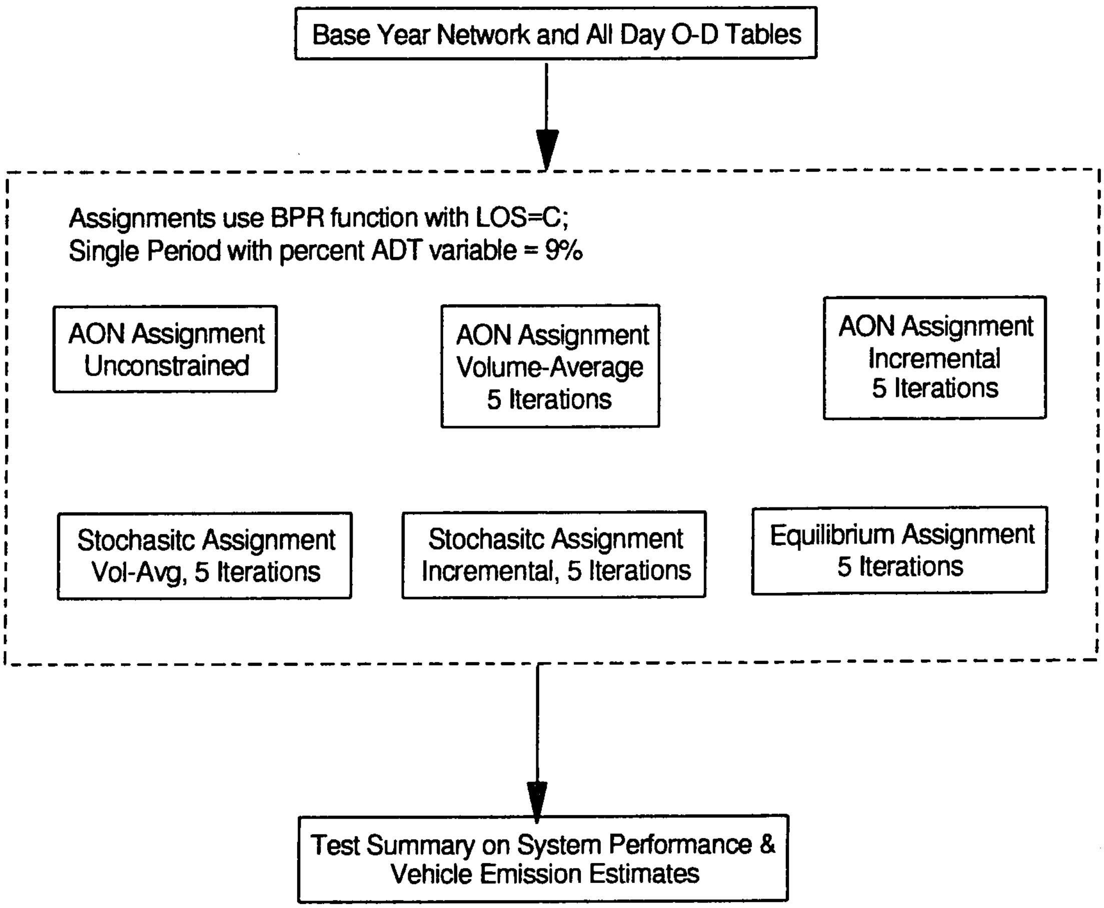

Figure 4.1 Summary of Test Plan on Algorithms

above 15%.

4.3 Test Result Analysis

4.3.1 Basic Speed–Vehicle Emission Rate Relationship

Since the estimation of vehicle emission factors depends on the input travel speeds produced by UTP model, it is useful to understand the general relationship between speed and emission factors. Based on the conclusions derived from a joint study conducted by APCD of CODOH and DRCOG, the VMT mix varied not only by highway facility type but area type as well. The same situation were also found on three vehicle operational statuses: old start, hot start, and stabilized. Therefore, different scenario data were adopted in the Denver MOBILE5A modeling process. As a case study, the Denver area data were applied to develop a family of curves to describe the relationship between network speeds and emission factors for three pollutants: HC, CO and NOx. Multiple MOBILE5A runs were made to produce the emission factor curve family under different VMT mix, vehicle operating mode, and highway facility conditions. For each area type, facility type and pollutant, a speed–emission curve was developed.

Figures 4.2 to 4.4 display typical relationships for an "urban area type" as an example of the curves developed by major highway facility types using the MOBILE5A model. The HC and CO emission rates had the same trends as a function of changes on vehicle operating speed. The HC and CO rates declined with the increase of vehicle operating speeds until speeds reached about 55 miles per hour (mph). After 55 mph, both emission rates started to increase, but the CO rate showed a higher rate of increase than HC. The test model indicated no significant variation on HC and CO emission rates between different highway facility types.

For NOx, the emission rate responded differently than the HC and CO rates. The test demonstrated a much flatter speed-emission rate when the speeds were in the ranges of 10 mph to 49 mph. After 49 mph, the emission rate increased rapidly. The test also showed a deviation on the NOx rate among the facility types. In general, the freeway showed the highest emission rate while the collector exhibited the lowest rate with a variation of around 10%. This deviation significantly influenced the system NOx emission estimates when there was a shift in VMT among facility types. For the HC and CO rates, there was very small influence due to shifting of VMT between facility types.

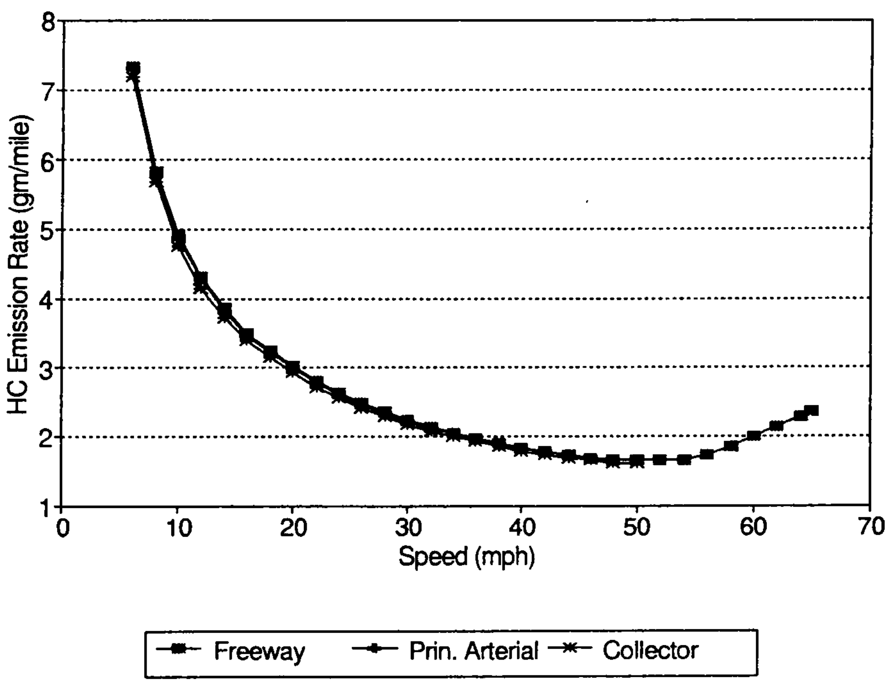

Figure 4.2 Urban Area Speed-HC Emission Factor Curves

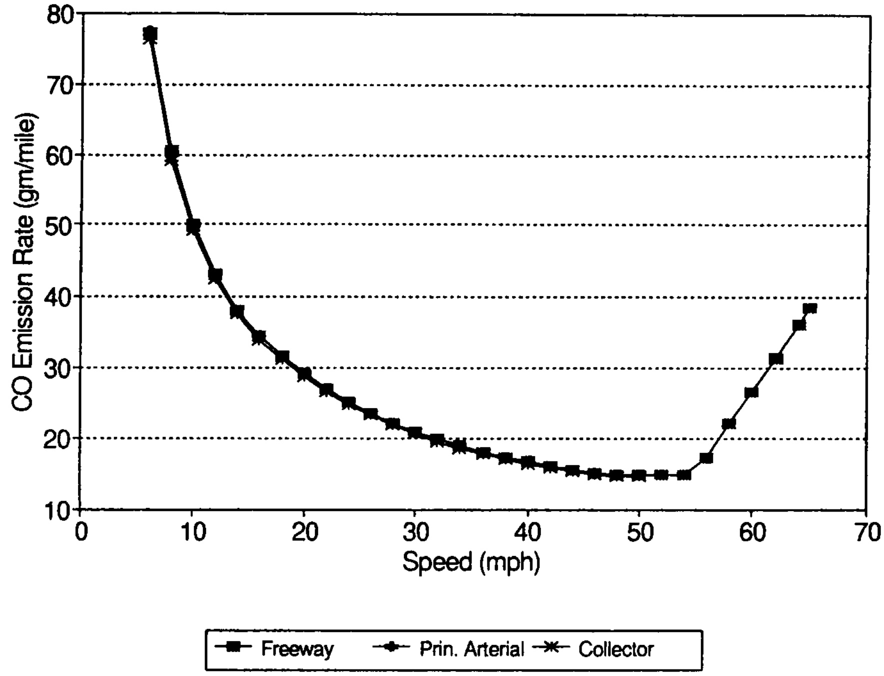

Figure 4.3 Urban Area Speed-CO Emission Factor Curves

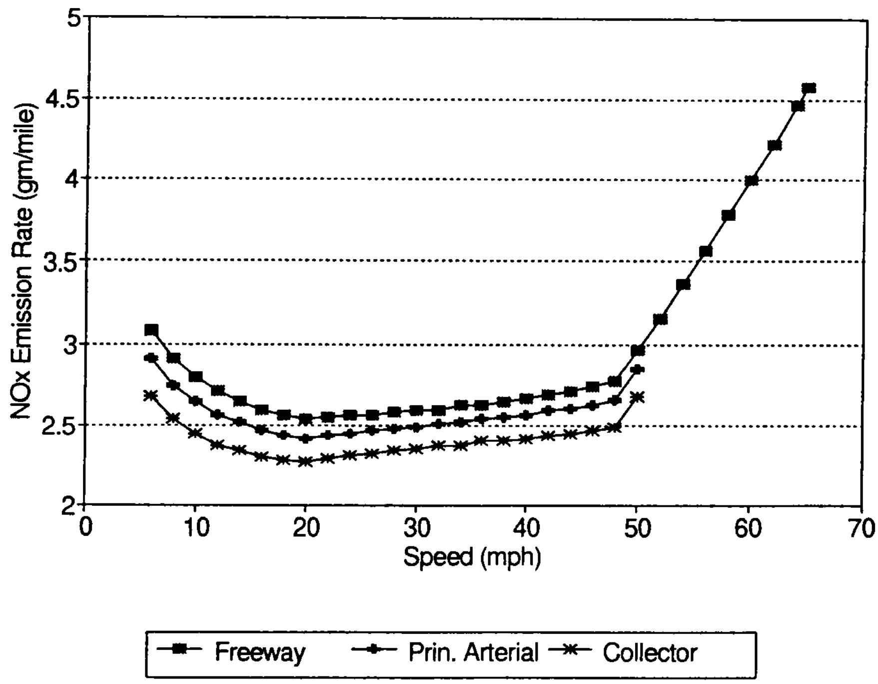

Figure 4.4 Urban Area Speed-NOx Emission Factor Curves

4.3.2 System Performance

Table 4.2 is a comparison of system performance measures and vehicle emission estimates of all six tested algorithms. Notice that both assignment performance and vehicle emission estimates were aggregated measures. Among six test cases, the first case, all–or–nothing unconstrained assignment, delivered the lowest VMT and speed, but the highest HC and CO estimates. In contrast, the equilibrium assignment (the sixth case) produced the highest average speed with the lowest estimates of HC and CO. For NOx, the all–or–nothing unconstrained assignment produced lowest kilograms while the equilibrium produced the highest. This indicated that speed played an important role in emission estimates. When comparing the speeds by facility type, the speed deviations among six different algorithms become very clear. Table 4.3 illustrates the speeds summarized by facility type for all six test cases. The speed deviations in the freeway and expressway facilities were much larger than the deviations in the arterials, and the collector speed changes were relatively small. The speed changes plus the VMT shifting, which is discussed in later sections, among the facility types, caused the discrepancy on vehicle emission estimation. The test also explored the emission differences between volume averaging methods and incremental methods. The volume averaging method always produced a higher average speed than the incremental method. As a result, the volume averaging method produced lower HC and CO estimates, but a higher NOx estimate.

The tests indicated that the algorithms had a large impact on vehicle emission estimates for the Denver region. The overall range of HC and CO emission differences produced among the algorithms was as large as 43% and NOx difference was as large as 10%. In

Table 4.2 A Comparison of Assignment Performance with Different Algorithms

System Performance	Test Cases					
	95A1	95A2	95A3	95A4	95A5	95A6
VMT (millions)	40.3	40.6	40.3	41.5	41.3	40.7
VHT (1,000 Hrs)	1,863	1,233	1,406	1,282	1,432	1,036
Speed (mph)	21.6	32.9	28.7	32.4	28.8	39.3
HC (1,000 kgs)	106.2	83.5	88.2	88.3	92.4	76.8
CO (1,000 kgs)	1,030.4	780.3	834.3	825.3	871.7	722.5
NOx (1,000 kgs)	109.9	113.4	109.8	116.2	112.4	121.3

Assignment Test Cases:
95A1: AON, Unconstrained
95A2: AON-Volume Average
95A3: AON-Incremental
95A4: Stochastic-Volume Average
95A5: Stochastic-Incremental
95A6: Equilibrium

Table 4.3 Speed Variation Among Tested Algorithms

	Speeds in Six Test Cases (mph)					
Facility Types	95A1	95A2	95A3	95A4	95A5	95A6
Freeway	22.5	39.0	29.4	40.7	31.2	49.1
Expressway	10.3	21.7	18.1	19.4	16.9	40.6
Major Arterial	24.5	31.6	30.5	32.3	31.9	35.3
Minor Arterial	23.5	29.1	30.9	29.4	29.6	33.6
Collector	20.0	23.8	23.5	20.6	19.3	25.8
System	21.6	32.9	28.7	32.4	28.8	39.3

Assignment Test Cases:
95A1: AON, Unconstrained
95A2: AON-Volume Average
95A3: AON-Incremental
95A4: Stochastic-Volume Average
95A5: Stochastic-Incremental
95A6: Equilibrium

all cases, the unconstrained all-or-nothing algorithm had the highest estimates. If only capacity constraint algorithms were considered, then the ranges of estimated HC, CO, and NOx differences were around 20%, 15%, and 10%, respectively. The capacity restraint assignments are very commonly used by planning agencies around country. Thus, only capacity-restraint assignment algorithms are discussed in following sections.

4.3.3 Impact of Assignment Iterations

The assignment algorithms attempt to assign for a fixed O-D table each trip to a minimum travel time path. As such, algorithms are able to achieve the lowest level of user cost in terms of travel time delay. However, this characteristic does not guarantee to make the algorithm produce the lowest estimates of VMT or VHT for the system. Each algorithm has its own capability to produce its best estimates on user travel time. Different estimates of CO, HC, and NOx estimates are expected, due to the performance differences of algorithms. In order to achieve a good performance level for each tested algorithm, the number of iterations for each algorithm must reach a steady state solution.

The number of iterations for each of the five algorithms was increased from five to 20 to explore the impacts. It was found that more iterations led to a slightly lower system VHT which meant the system reached a more efficient operation status. (A detailed discussion on assignment termination condition was conducted in chapter five for the equilibrium assignment.) The VMT, VHT and average speed are summarized in Figures 4.5 through 4.7. Noticed that the speeds displayed in Figure 4.5 are system average speed. As noticed in the figures, more iterations produced a slightly lower VMT and VHT estimates, but higher speed estimates. For the test cases, the percentage VHT changes between 20

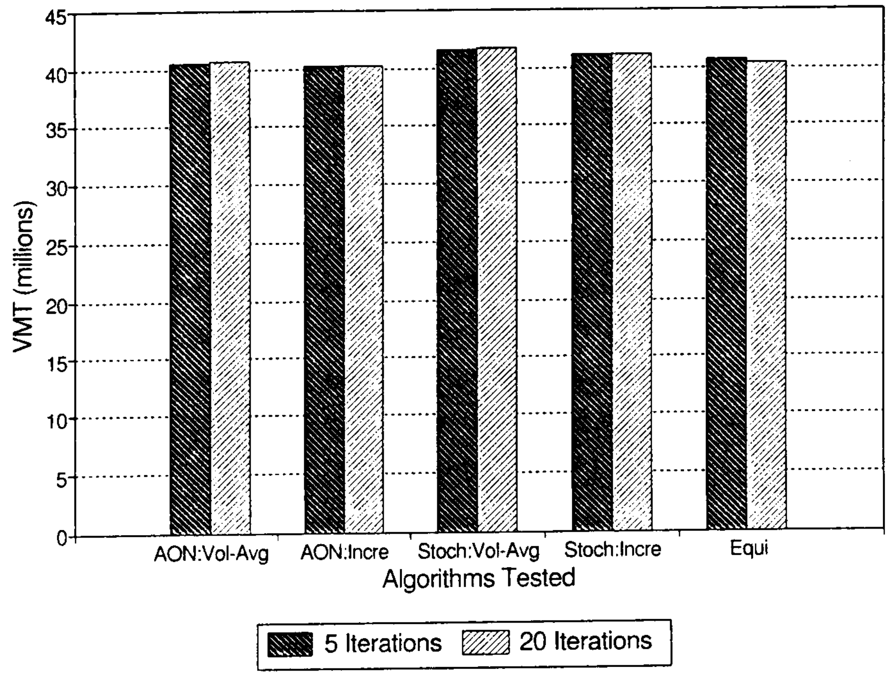

Figure 4.5 A Comparison on Assignment Algorithm Performances: VMT

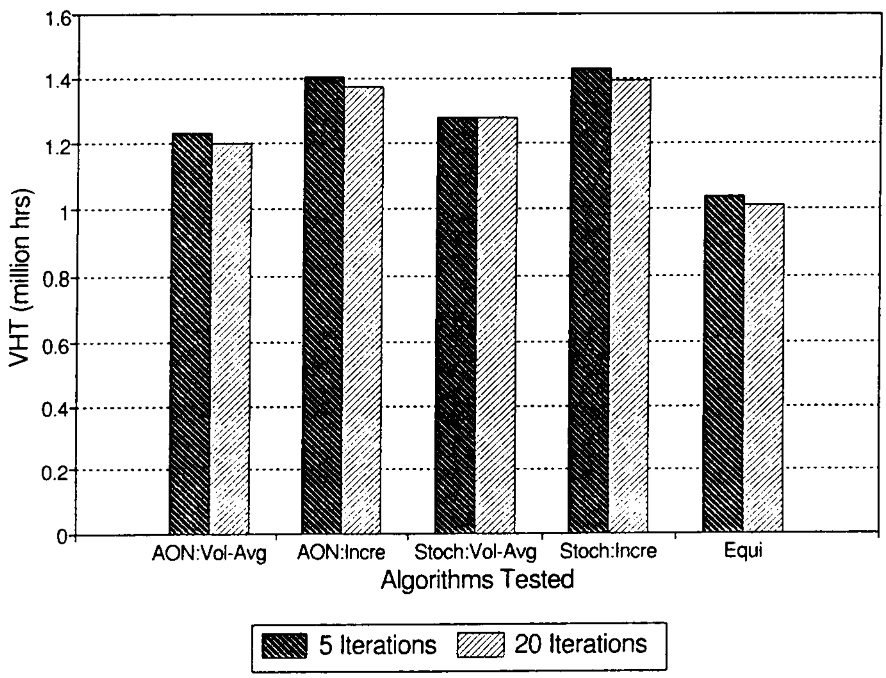

Figure 4.6 A Comparison on Assignment Algorithm Performances: VHT

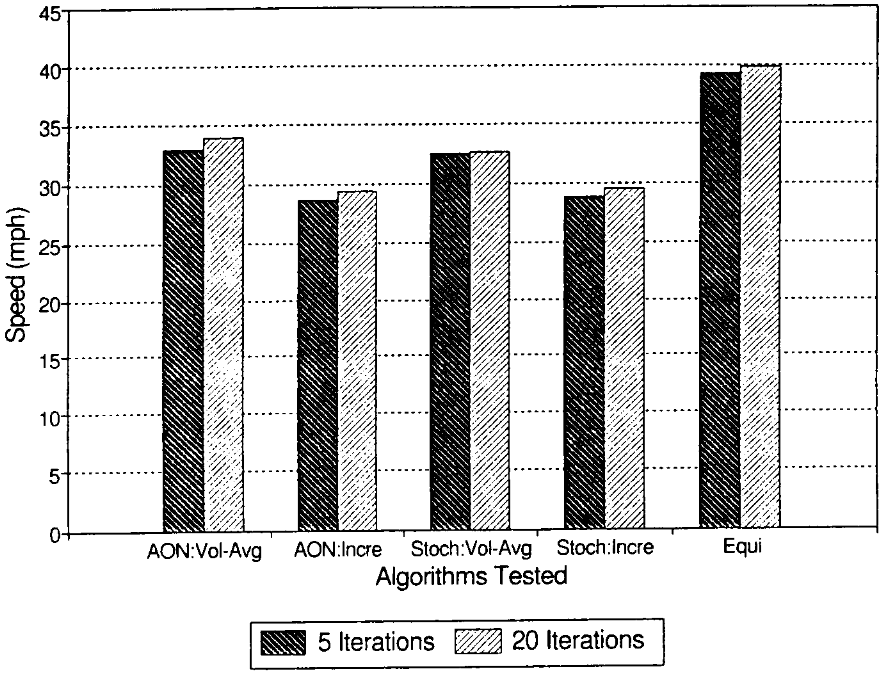

Figure 4.7 A Comparison on Assignment Algorithm Performances: Speed

iteration and 5 iteration cases were at the range of 0.1%–2.6%. The all–or–nothing volume averaging assignment had the highest difference. For the speed, the changes among tests were at the range of 0.6%–3.1%. For VMT, both stochastic and all–or–nothing incremental assignments showed almost no differences (<0.05%) when number of iterations increased. The equilibrium assignment indicated about 1% reduction in VMT when number of iterations increased from five to 20.

In summary, the equilibrium algorithm provided the lowest VHT and highest speed estimates among all five test cases. Both incremental algorithms provided the highest VHT and lowest speed estimates. In fact, during the 1990 Denver regional model calibration process, both equilibrium and AON volume averaging algorithms achieved very good highway volume distribution in terms of matching actual traffic counts. Based on the Denver case study, it could not be verified that the argument concluded by Horowitz that stochastic assignment reached the same level of travel time estimates as equilibrium assignment when the number of iterations were increased. The differences in multi-path selection criteria and in algorithm convergency rates between Horowitz's test algorithm and MINUTP's stochastic assignment could be two possible reasons that made the test result differ from his conclusions.

For the vehicle emission estimates, the results of assignments with 20 iterations were also different from the assignments with five iterations. For example, all five cases, with the exception of stochastic volume averaging algorithm, produced lower HC and CO estimates than the same cases with five iterations. It was also observed that the equilibrium assignment algorithm had the highest HC and CO reduction rates (2.5% and 2.9%) when 20 iterations of assignment were applied. For NOx, the changes between five iterations and 20 iterations were not as large as the differences in HC and CO estimates; the changes were at 0.1% to 1.4% levels. Figures 4.8 through 4.10 present the comparison of vehicle emission estimate changes between the five and 20 iteration assignments for all test cases.

4.3.4 Effect of Assignment on VMT and Speed Distribution

After each teat case was performed, the VMT, VHT and speed were summarized by five major highway facility type. To simplify the analysis, Figures 4.11 to 4.13 illustrate VMT, VHT and speed distribution changes between two groups of facility types: freeways and expressways versus major and minor arterials. When comparing the VMT distribution

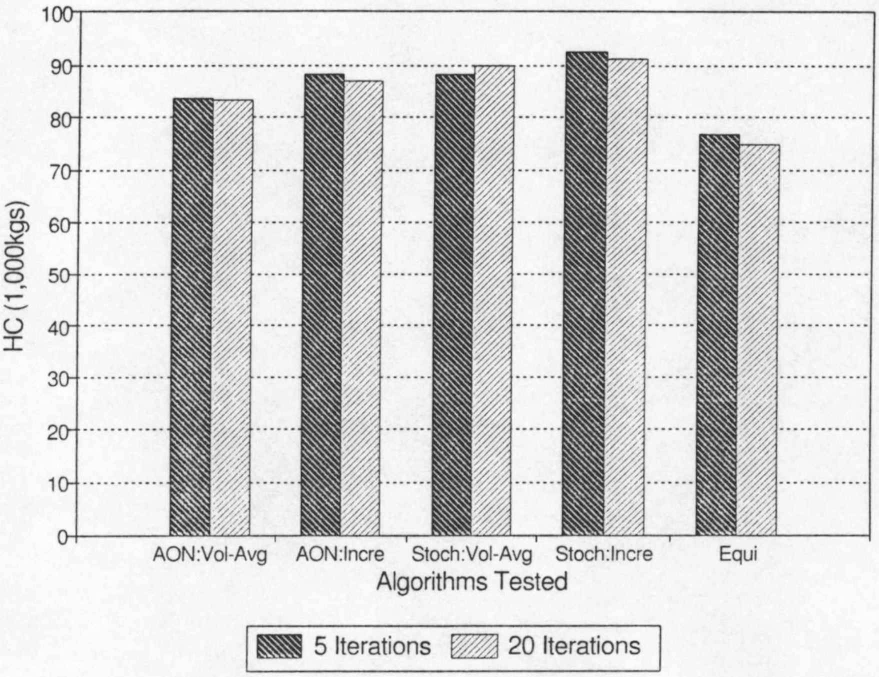

Figure 4.8 A Comparison on Assignment Algorithm Performances: HC

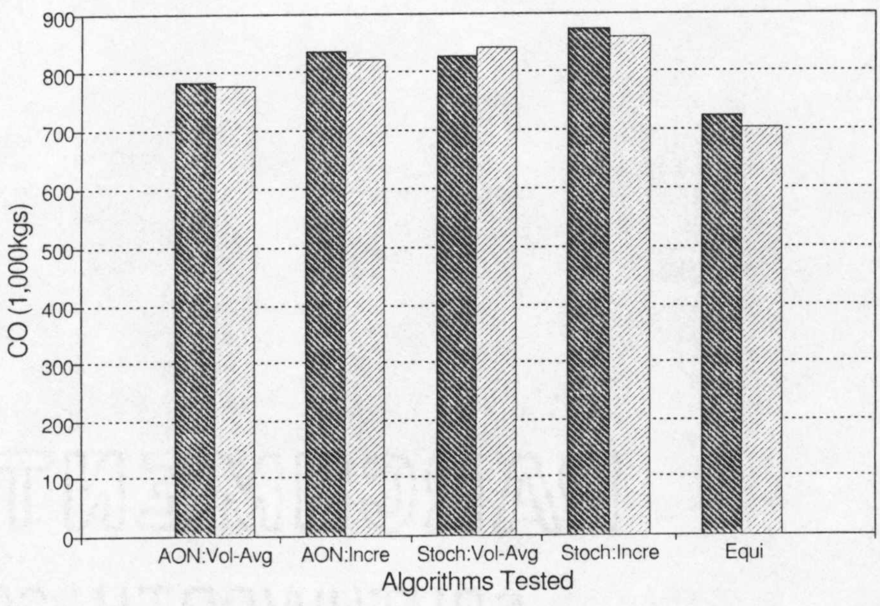

Figure 4.9 A Comparison on Assignment Algorithm Performances: CO

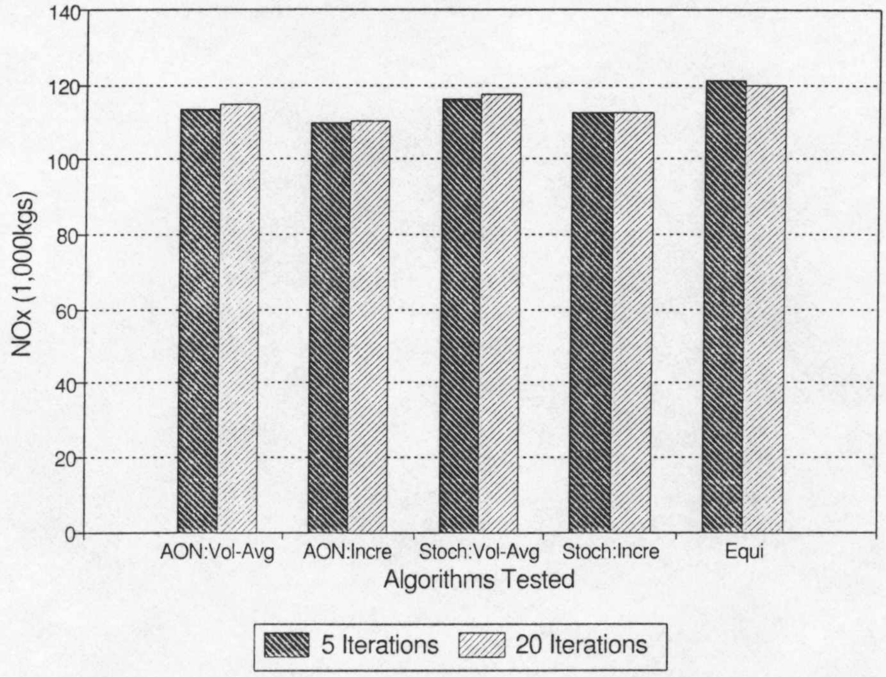

Figure 4.10 A Comparison on Assignment Algorithm Performances: NOx

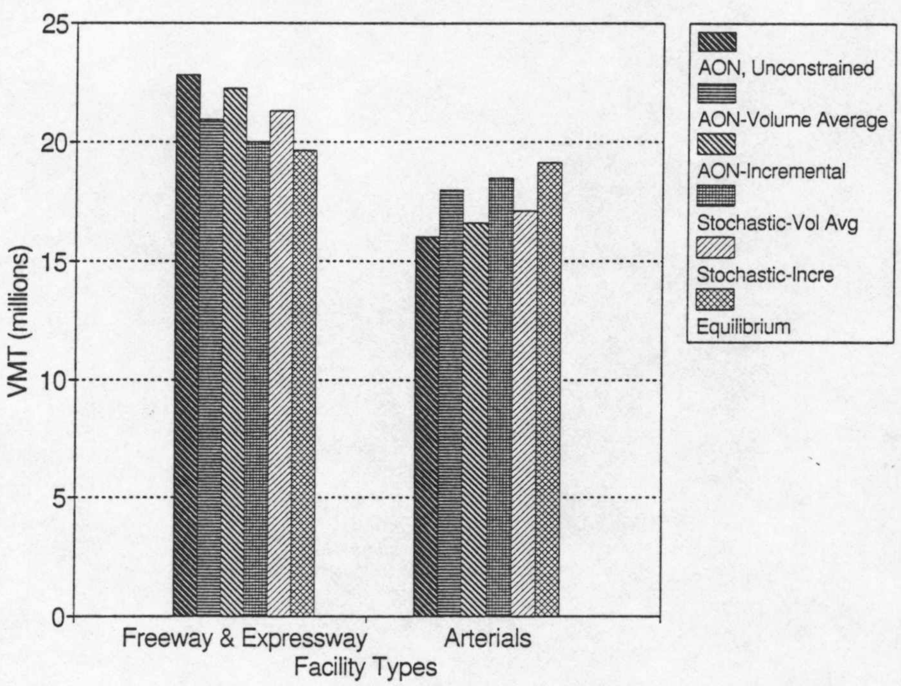

Figure 4.11 VMT Distribution Changes Between Highway Facilities

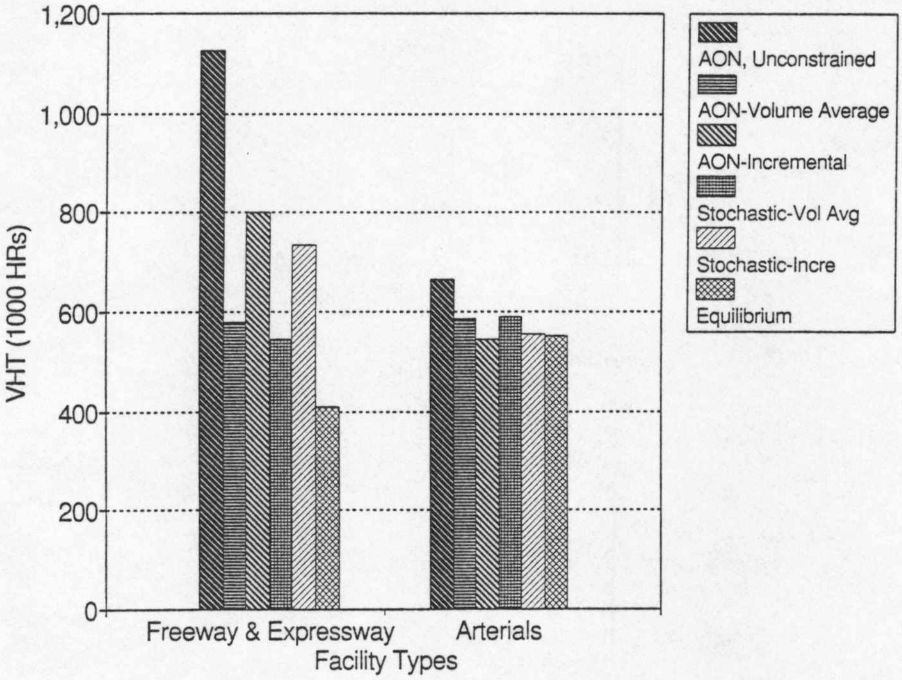

Figure 4.12 VHT Distribution Changes Between Highway Facilities

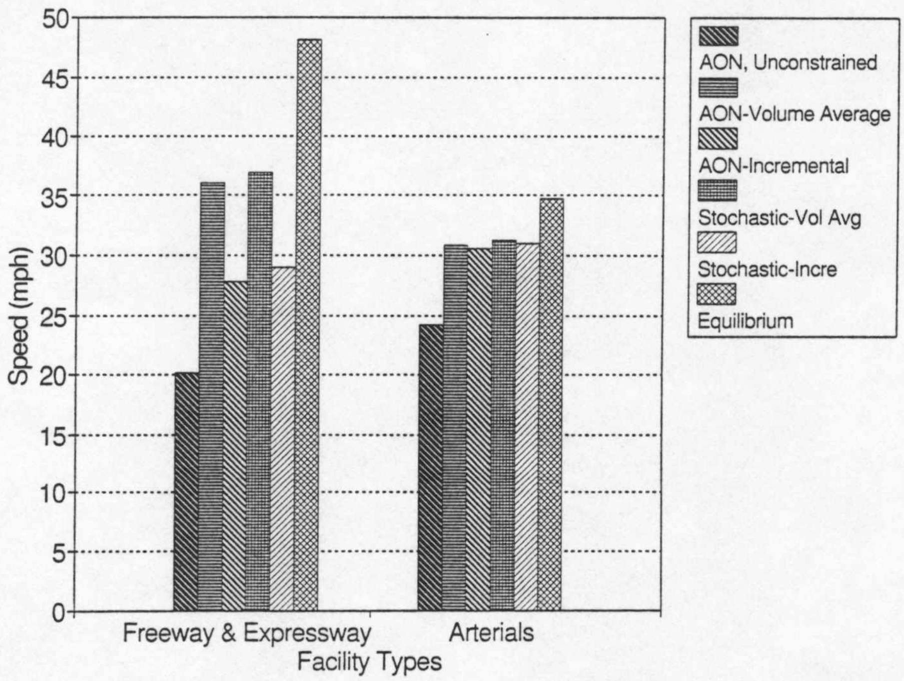

Figure 4.13 Speed Distribution Changes Between Highway Facilities

among facility types, the assignment algorithms showed relatively large variations. The unconstrained all–or–nothing case had the highest freeway VMT (22.8 million VMT) and lowest arterial VMT (16.1 million VMT) and the equilibrium case had an even VMT distribution (about 19 million VMT) between the two facility groups. Notice that the total VMT produced by different algorithms were within 1% in difference. For VHT, the tests indicated a very large VHT deviation (from 408,000 VHT to 1,126,000 VHT) among the various algorithms for the freeway group and smaller differences (from 542,000 VHT to 663,000 VHT) for the arterials. As a result, large deviation in speeds was found amongthe algorithms. This implied that the paths between O–D pairs selected by the different algorithms were very different. The all–or–nothing path assignment tended to select freeways since the shortest paths were determined by a set of predetermined speeds, while the equilibrium algorithm distributed trips more evenly to other facilities as a result of travel time equilibrium in the assignment.

4.3.5 Vehicle Emission Distribution Among Highway Facilities

The estimated vehicle emission distribution among highway facility types is closely related to the speed and VMT produced by the assignment algorithms. Figures 4.14 and 4.16 display the HC, CO and NOx distributions between two facility groups. The HC and CO followed the same trend as the speed: very large variations (about 50%) on freeways and relatively smaller variations (15%–20%) on arterials. The estimated CO range could be as low as 295,000 kilograms to as higher as 561,000 kilograms for freeway facility. The NOx estimates showed less fluctuation (about 10%) as seen in the comparison among the algorithms. Two major factors contributed to this vehicle emission variation. Firstly, the MOBILE5A model had different estimated VMT mix percentage and different cold and hot

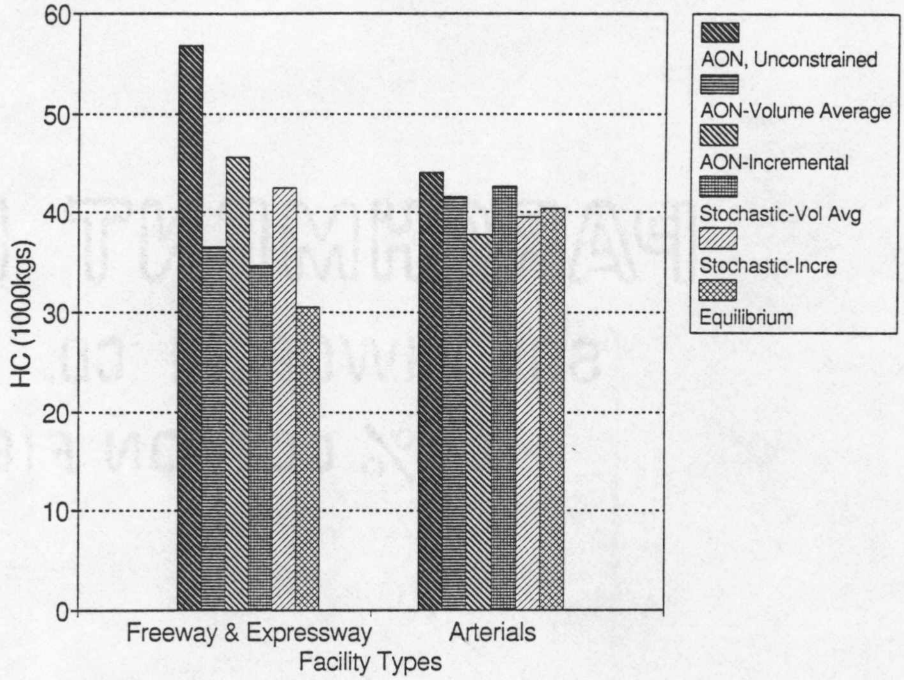

Figure 4.14 HC Distribution Changes Between Highway Facilities

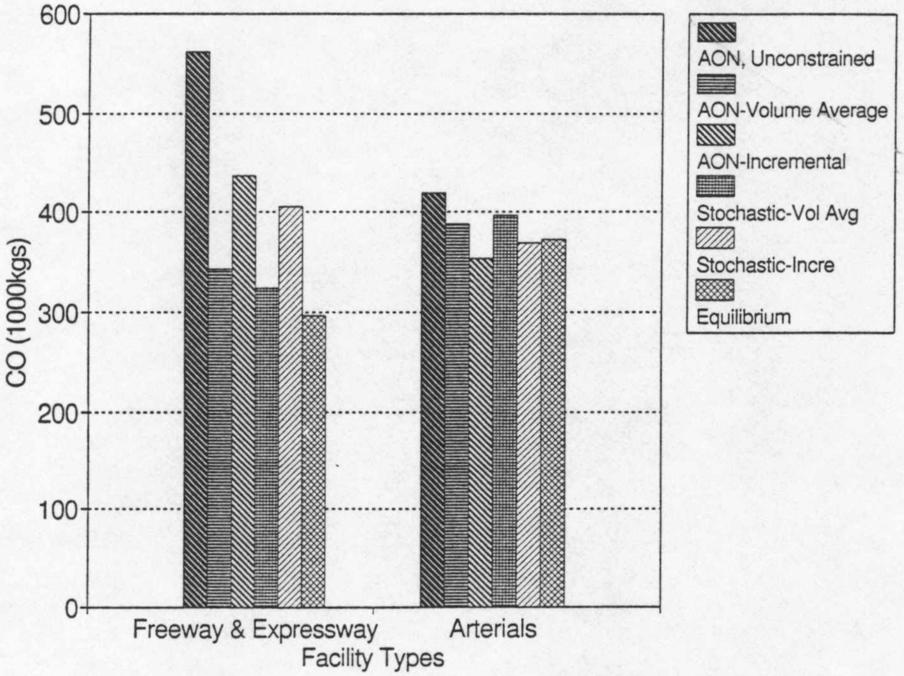

Figure 4.15 CO Distribution Changes Between Highway Facilities

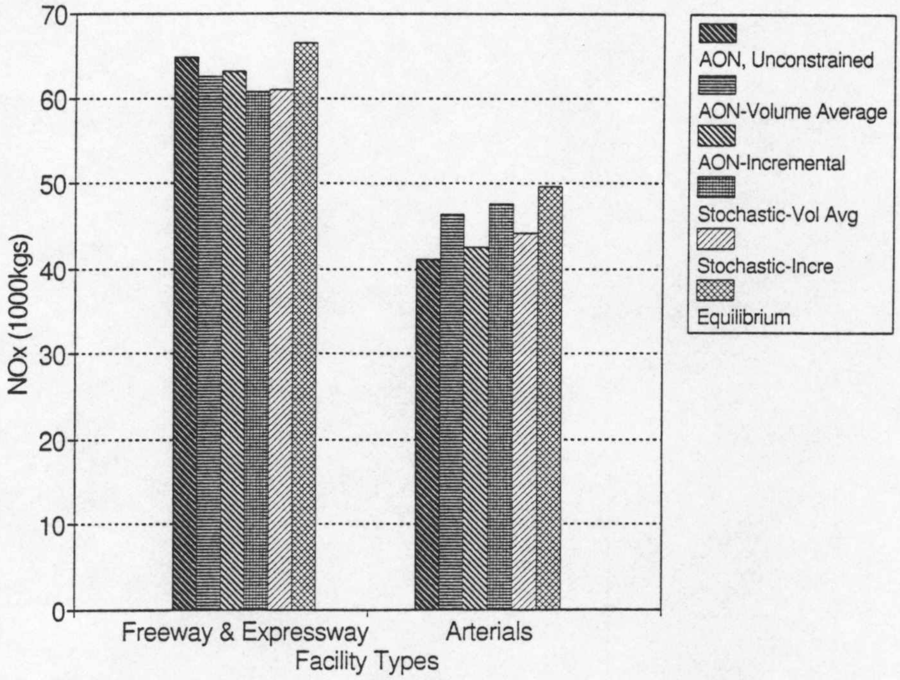

Figure 4.16 NOx Distribution Changes Between Highway Facilities

starts percentages for different facility types and area types, therefore, the emission rates were different even under the same speeds. Secondly, the VMT and speed distribution difference among tested algorithms also contributed a large portion of the differences. In summary, the analysis indicated that different algorithms produced not only different system level estimates of VMT, VHT and speed, but distinct distributions of performance measures among facility types as well. Therefore, for the Denver case study, the pollutant dispersal pattern varied with the algorithms studied.

4.3.6 Emission Sensitivity to VMT and Speed

Although the VMT distribution changed widely (15%–17%) between freeways and arterials, the total system VMT experienced only a moderate deviation among the algorithms. Table

4.4 compares five test cases to the equilibrium algorithm case which is currently used by Denver and most other large MPOs. The equilibrium algorithm produced the lowest system travel time and the highest system average speed. The sensitivities of the three major pollutants to the change of VMT and speed are also displayed in the Table 4.4 by tested algorithms. The speed played a more critical role than VMT in influencing the pollutant estimates. Among five test cases, the VMT differences were at 1% level. As a result, only 0.4%–2.0% changes in CO and HC estimates were attributed to the change of VMT. For speed estimates, the differences ranged from 17%–45% which caused 8%–40% differences in CO and HC estimates. NOx was less sensitive to speed change, the estimated variations were not as quite, but still resulted in 5%–10% variations among test cases.

4.4 Chapter Summary

In this chapter, six typical traffic assignment algorithms and their impacts on the vehicle emission estimates for Denver case study were examined. This chapter also discussed several study design related issues such as defining capacity, preparing a test O–D table, as well as preparing basic speed–emission rate relationships for HC, CO and NOx. Based on the results from the Denver case study and analysis, the following are the major findings of this chapter:

1. The equilibrium assignment algorithm achieved the lowest overall system travel time among all the tested algorithms. It produced lowest system estimates of HC and CO and highest estimate of NOx.

Table 4.4 Vehicle Emission Estimates Sensitivity to the Assignment Performance

Table 4.4A
AON vs Equilibrium

	VMT	Speed
% Difference	-1.0%	-45.0%

Changes	HC % Diff	HC Emission (1000kgs)	CO % Diff	CO Emission (1000kgs)	NOx % Diff	NOx Emission (1000kgs)
Due to VMT	-1.0%	-0.8	-1.0%	-7.1	-1.0%	-1.2
Due to speed	39.3%	30.2	43.6%	315.0	-8.4%	-10.2
Total	38.3%	29.4	42.6%	307.9	-9.4%	-11.4

Table 4.4B
AON Volume Average vs Equilibrium

	VMT	Speed
% Difference	-0.4%	-16.3%

Changes	HC % Diff	HC Emission (1000kgs)	CO % Diff	CO Emission (1000kgs)	NOx % Diff	NOx Emission (1000kgs)
Due to VMT	-0.4%	-0.3	-0.4%	-2.8	-0.4%	-0.5
Due to speed	9.1%	7.0	8.4%	60.6	-6.1%	-7.4
Total	8.7%	6.7	8.0%	57.8	-6.5%	-7.9

Table 4.4C
AON Incremental vs Equilibrium

	VMT	Speed
% Difference	-1.0%	-27.1%

Changes	HC % Diff	HC Emission (1000kgs)	CO % Diff	CO Emission (1000kgs)	NOx % Diff	NOx Emission (1000kgs)
Due to VMT	-1.0%	-0.8	-1.0%	-7.4	-1.0%	-1.2
Due to speed	15.9%	12.2	16.5%	119.3	-8.5%	-10.3
Total	14.9%	11.5	15.5%	111.8	-9.5%	-11.5

Table 4.4D
Stochastic Volume Average vs Equilibrium

	VMT	Speed
% Difference	1.9%	-17.7%

Changes	HC % Diff	HC Emission (1000kgs)	CO % Diff	CO Emission (1000kgs)	NOx % Diff	NOx Emission (1000kgs)
Due to VMT	1.9%	1.5	1.9%	13.9	1.9%	2.3
Due to speed	13.1%	10.0	12.3%	88.9	-6.1%	-7.4
Total	15.0%	11.5	14.2%	102.8	-4.2%	-5.1

Table 4.4E
AON Volume Average vs Equilibrium

	VMT	Speed
% Difference	1.3%	-26.7%

Changes	HC % Diff	HC Emission (1000kgs)	CO % Diff	CO Emission (1000kgs)	NOx % Diff	NOx Emission (1000kgs)
Due to VMT	1.3%	1.0	1.3%	9.0	1.3%	1.5
Due to speed	19.1%	14.7	19.4%	140.2	-8.6%	-10.4
Total	20.4%	15.7	20.7%	149.2	-7.3%	-8.9

Notes:
1. All comparisons used equilibrium assignment results as a base.
2. The percentage difference was calculated as:
(selected algorithm result - equilibrium result)/equilibrium result * 100
3. The absolute difference was calculated as:
selected algorithm result - equilibrium result

2. There were small to moderate system VMT changes (1.0%–1.9%), but very large VHT and speed variations (27%–45%) among six algorithms. This caused large variations on the HC and CO estimates (up to 22%). The smaller variation in NOx estimates (up to 10%) was due to a flatter speed–emission rate curve for NOx.

3. The sensitivity analysis showed that the major impact on emission estimates among the tested algorithms comes from the estimates of overall speed which contributed up to 19%, 19% and 10% changes in estimating HC, CO and NOx, while VMT differences were less pronounced.

4. Although system VMT had changes of 1.0%–1.9% among the tested algorithms, the VMT distribution changes between the two major facility groups, freeways and arterials, were as high as 15%–18%. This caused vehicle emission distribution among facilities to fluctuate greatly. For freeways, the unconstrained all–or–nothing and incremental assignments had the highest estimates of HC and CO, while the equilibrium algorithm and volume averaging algorithms had the lowest estimates of HC and CO.

5. Due to the flatter speed–emission rate curve, the NOx estimation change was relatively small among the test algorithms.

CHAPTER FIVE

IMPACTS OF VOLUME-SPEED FUNCTIONS ON TRAFFIC ASSIGNMENT

5.1 Study Purpose and Research Questions

In the previous chapter, the variation in system performance and related air quality estimates attributed to using different algorithms were examined. This chapter discusses various volume-speed functions, explores their impacts on system performance and air quality estimates under a capacity-restraint assignment procedure. The analysis uses the assignment results and their related emission estimates to evaluate the performance of different volume-speed curves. In the study, a series of tests was conducted reflecting three major considerations.

1. The first was to investigate the characteristics of different volume-speed functions and explore the linkage between volume-speed functions and system performance measures. Besides the BPR curve, the Highway Capacity Manual of 1985 and 1994 (HCM85 and HCM94) can be used to define volume-speed relationships. These curves are used in the assignment procedures by different planning agencies. Since the HCM based volume-speed functions are based on traffic engineering experimental observations, it was anticipated the curve would produce a more reasonable volume-speed relationship than the BPR functions. It was unclear to what degree the system performance measures would change and, as a result, the vehicle emission estimates would be influenced.
2. The vehicle emission rate is a function of assignment speeds and the system VMT estimates. This research investigated the relative contribution of VMT and speed

to the estimation of HC, CO, and NOx for different volume-speed relationships.

3. The third consideration was the definition of the volume-speed beyond a v/c ratio of one. In the traffic engineering field, there were many studies on the characteristics of volume-speed functions. However, most of the studies were based on traffic flow theory and discussed the volume-speed functions at v/c ratios less than 1.0[17]. Therefore, the volume-speed relationship up to a v/c ratio of 1.0 was relatively well defined. But because the volume-speed function used in transportation planning models as part of a capacity-restraint assignment algorithm must be continuous, a definition for the volume-speed function beyond a v/c ratio of 1 is necessary. The volume-speed function at v/c ratios greater than 1.0 could potentially have a large impact on the system performance measures, and have a large implication on determining VMT and VHT. Therefore, it was expected that vehicle emission factor model would be sensitive to the shape of the volume-speed function in the v/c ratio > 1.0 area.

5.2 Volume-Speed Curves and Mathematical Expressions

5.2.1 Approach

Besides the BPR volume-speed curves, other curves, such as HCM85 and HCM94 curves, were also developed since the 1950s[1,18]. Increasing attention is focused on the HCM85 curves presented in the TRB Special Report 209: Highway Capacity Manual in 1985. Three types of curves were developed for freeways, multi-lane highways, and urban arterials.

The Highway Capacity Manual presents only the graphic expression of the volume-speed relationship. However, a mathematical expression in a form of volume-speed function has to be adopted for the capacity-restraint assignment procedure. The mathematical expression is usually developed through a curve fitting procedure with the following mathematical expression as an objective function:

$$\min \Sigma [f_2(x_i)-f_1(x_i)]^2 \qquad x_i \in [0, 1.0] \qquad (5.1)$$

where, f_1 is a dependent variable of the HCM volume-speed curve,

f_2 is the dependent variable of the function to be produced,

x_i is the ith common independent variable, v/c ratio, in functions f_1 and f_2,

Function(5.1) is a least squared function. Before the curve fitting, a base function with undetermined coefficient(s) must be selected, then the least squared function is used to monitor how close the values of the base function fit the original curve, and to select the coefficient(s) when the objective function reaches its minimum value.

Horowitz[8] reviewed three base functions, the BPR, the Spiess's and the Overgarrd's, to develop HCM curve mathematical expressions. Two of these, the BPR and the Overgarrd's, were selected in this study as samples to verify research assumptions. The reason not to consider the Spiess's base function was that the value of this function is between the BPR and Overgarrd's function values when the v/c ratio is greater than one. It should be adequate to select the BPR and Overgarrd's functions as upper and lower boundaries to study the characteristics of the volume-speed functions. For the purpose of this study, a spreadsheet was developed to search for the best fit of the undetermined coefficients in the base functions. A 'Hill Climbing' algorithm was simulated with a spreadsheet. The absolute errors of the estimated coefficients were all at 0.01 level which meant the difference between estimated value and the true value was less than 0.01. Considering the search boundary and the number of undetermined coefficients, this method was sufficiently accurate for use in this study. Again, the BPR and Overgarrd's base functions are displayed as the following:

The BPR base function:

$$s = s_0/(1 + \alpha x^{\beta}) \qquad (5.2)$$

The Overgarrd's base function:

$$s = s_0 \,/\, (s_0/s_c) \,\hat{}\; x^{\alpha} \qquad (5.3)$$

where, s is link travel speed;

s_0 is the free flow speed;

s_c is the speed when volume reaches the capacity;

x is the v/c ratio;

α, β are undetermined coefficients

Note that the Overgarrd's function only has one coefficient α.

5.2.2 HCM85 Curves

Many mathematical functions with undetermined coefficients can serve as base functions to satisfy expression(5.1) and generate a HCM85 volume-speed function expression. For example, the BPR function shown in expression(5.2) can be used as a base function by altering coefficients α and β.

Table 5.1 displays a table listing two sets of coefficients developed for the modified BPR

Table 5.1 Mathematical Expressions of HCM85 Volume–Speed Curves

Volume-Speed Functions	Coefficient(s) α	Coefficient(s) ß	R Squared	Objective Function
Freeways				
Original BPR	0.15	4.0	0.904	79.58
Modified BPR	0.66	7.2	0.944	53.79
Overgarrd's	7.9	-	0.956	59.54
Arterials				
Original BPR	0.15	4.0	0.959	14.43
Modified BPR	0.76	5.9	0.986	2.28
Overgarrd's	5.7	-	0.993	2.00
Multi-lane Highways				
Original BPR	0.15	4.0	0.951	392.73
Modified BPR	0.73	2.1	0.981	19.71
Overgarrd's	2.0	-	0.988	17.40

function and Overgarrd's function, the achieved correlation coefficients (R^2) and minimum objective function values. The original BPR function and its performance are also listed. Note that the original BPR function only has one set of coefficients for all facility types. Figures 5.1 to 5.3 show the plots of the functions developed for HCM85 freeway, urban arterial and multi–lane highways.

The volume–speed relationship is very complicated for signalized arterial facilities. The intersection delay, the space between adjacent signals, the variation of signal timing, and highway geometry are some of the factors that change the volume–speed relationship. Since the main purpose of this study was to survey the impact of different shaped curves and their implication to the UTP modeling and air quality analysis, a typical volume–speed situation was introduced with an effective green time to signal cycle length ratio set to

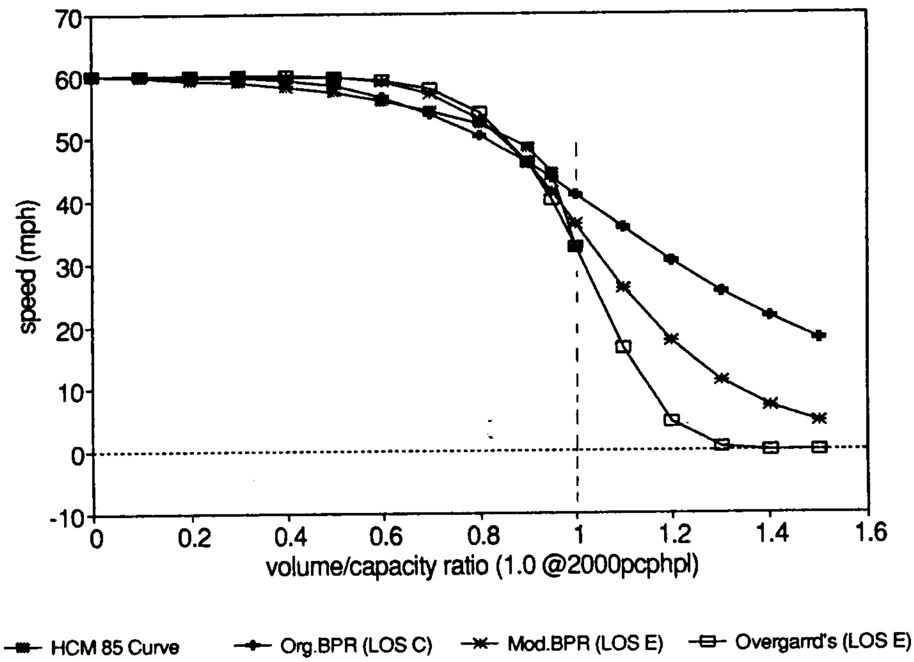

Figure 5.1 HCM85 Based Volume-Speed Functions for Freeways

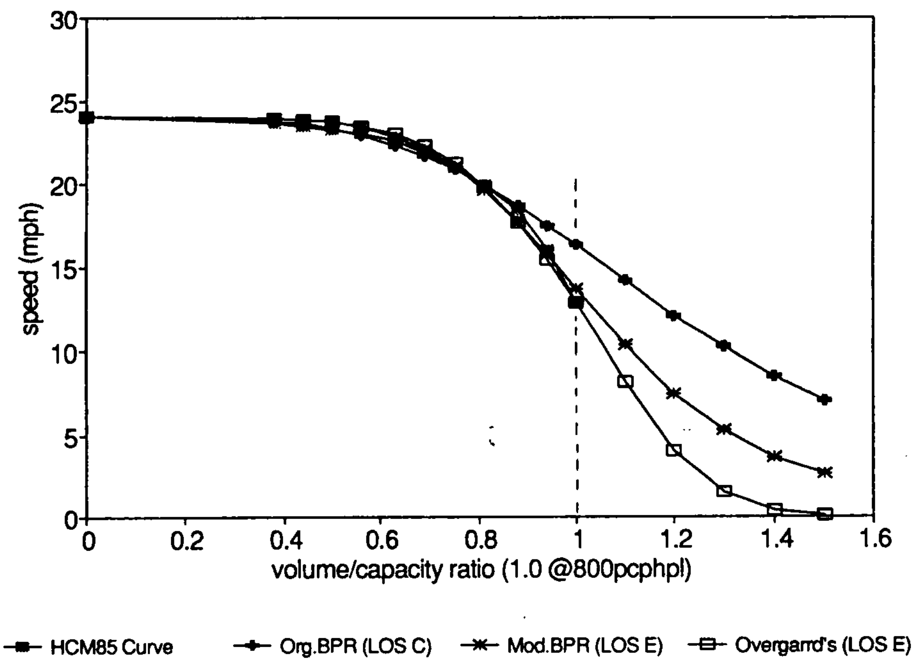

Figure 5.2 HCM85 Based Volume-Speed Functions for Urban Arterials

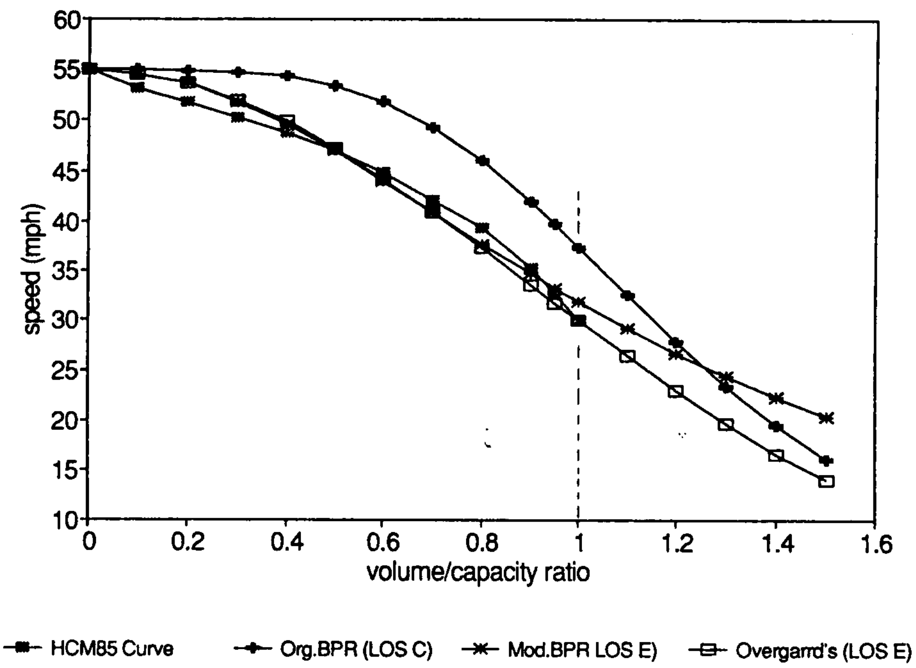

Figure 5.3 HCM85 Based Volume-Speed Functions for Multi-Lane Highways

50%. This condition corresponded to the arterial sample calculation presented in the 1985 and 1994 Highway Capacity Manuals.

5.2.3 HCM94 Curves

In recent years, the HCM85 curves were revised due to concerns about replicating traffic flow condition and air quality analysis requirements. The new volume-speed curves, named as HCM94 curves in this research, were released in December 1994[18]. There were two major revisions. One was the capacity increased on freeways from 2,000 pcphpl to 2,300 pcphpl and multi-lane highways from 1,900 to 2,000 pcphpl to 2,000-2,300 pcphpl. The second was the change in the shape of the volume-speed relationships on highway facilities. The new relationship showed a slower drop in the speed when the v/c ratio is under 0.8 and a sharper reduction when speed is at 0.8–1.0 of the capacity. Figures 5.4 and 5.5 display the comparison of freeway volume-speed curve changes between HCM85 and HCM94 as an example. It was anticipated that these modifications would produce reasonable estimates of highway speed and, in turn, produce better vehicle emission estimates. Similar to the HCM85 curves, two sets of volume-speed functions were developed for the HCM94 curves as shown in Table 5.2. By comparing it to Table 5.1, notice that the coefficients in both the modified BPR functions and Overgarrd's functions changed. Same as in the HCM85 volume-speed function development, the coefficients of the original BPR function, α and β, are set to 4.0 and 0.15 for all facility types. Figure 5.6 plots the freeway volume-speed functions using the original BPR, modified BPR and Overgarrd's base functions generated from HCM94 volume-speed curve. Figures 5.7 and 5.8 plot urban arterial and multi-lane highway volume-speed functions produced based on HCM94.

The five sets of volume-speed functions of HCM85, HCM94, and the original BPR function were incorporated into all test cases to detect their influence on the assignment procedure:

1. The original BPR function, for all facility types;
2. Three modified BPR-HCM85 functions, for freeway, arterial and multi-lane highway facilities;
3. Three HCM85 Overgarrd's HCM85 functions, for freeway, arterial and multi-lane highway facilities;
4. Three modified BPR-HCM94 functions, for freeway, arterial and multi-lane highway facilities; and

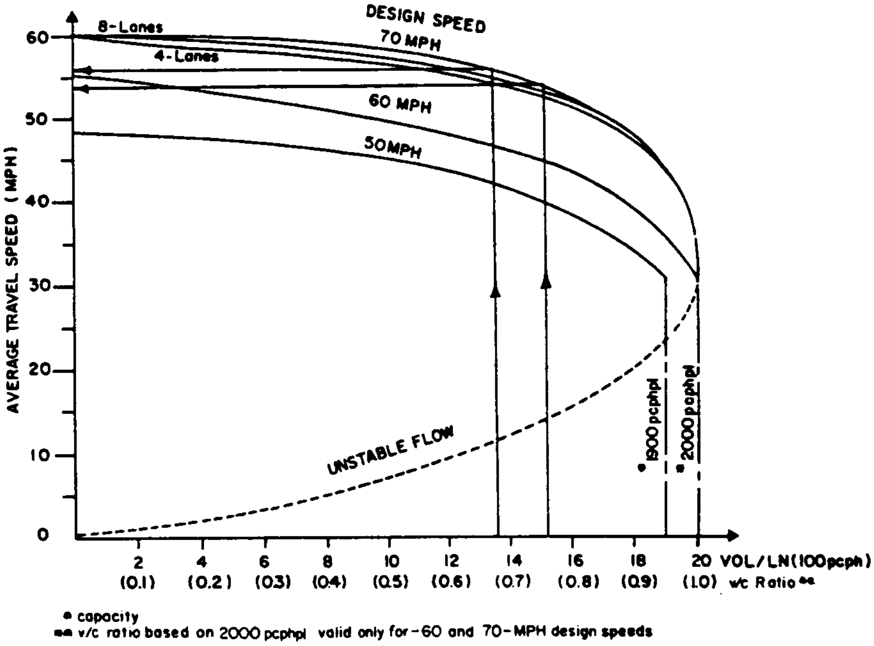

Figure 5.4 HCM85 Freeway Volume-Speed Curves[1]

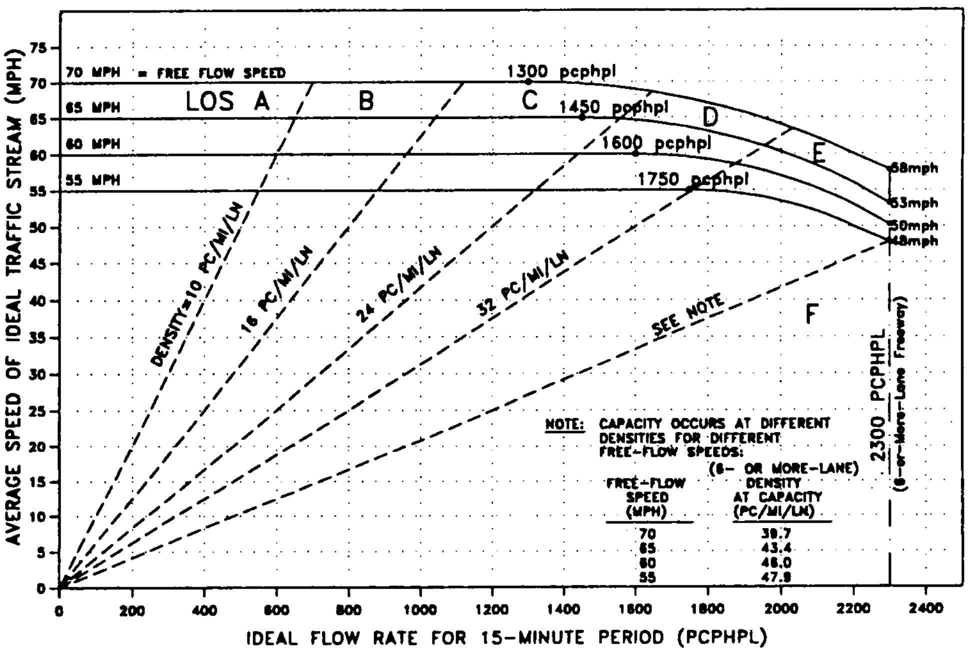

Figure 5.5 HCM94 Freeway Volume-Speed Curves[18]

Table 5.2 Mathematical Expressions of HCM94 Volume-Speed Curves

Volume-Speed Functions	Coefficient(s) α	Coefficient(s) β	R Squared	Objective Function
Freeways				
Original BPR	0.15	4.0	0.883	376.32
Modified BPR	0.81	2.3	0.998	0.52
Overgarrd's	7.6	-	0.997	0.74
Arterials				
Original BPR	0.15	4.0	0.860	20.97
Modified BPR	0.57	9.2	0.980	2.32
Overgarrd's	8.7	-	0.986	2.06
Multi-lane Highways				
Original BPR	0.15	4.0	0.951	593.98
Modified BPR	0.08	5.5	0.986	0.35
Overgarrd's	5.3	-	0.986	0.36

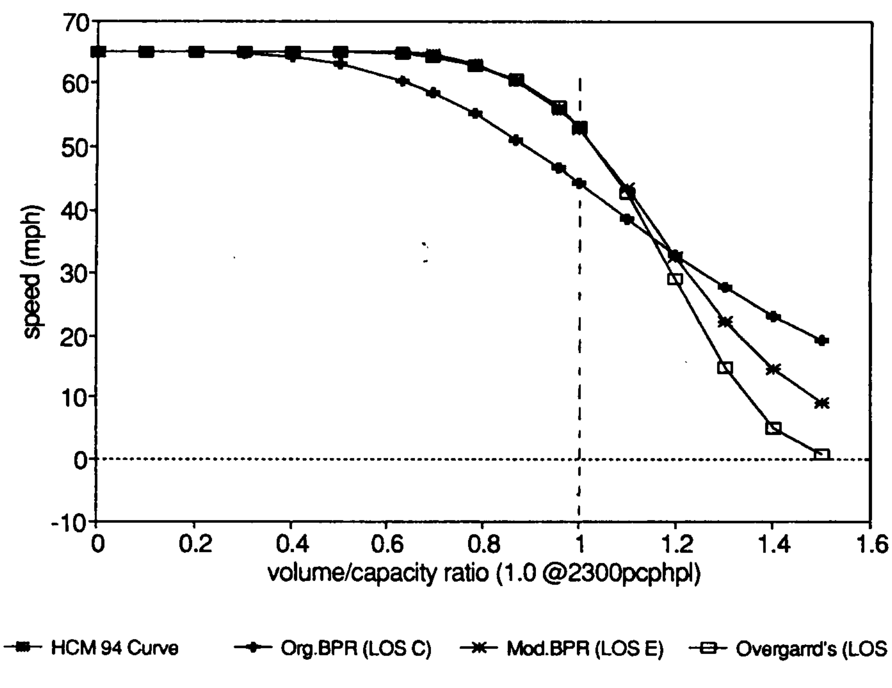

Figure 5.6 HCM94 Based Volume-Speed Functions for Freeways

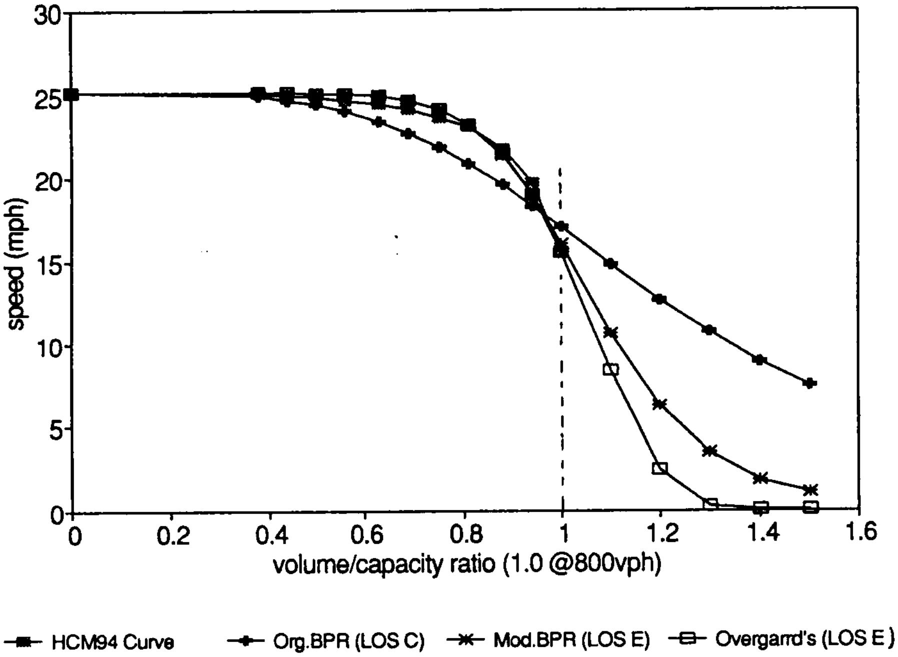

Figure 5.7 HCM94 Based Volume-Speed Functions for Urban Arterials

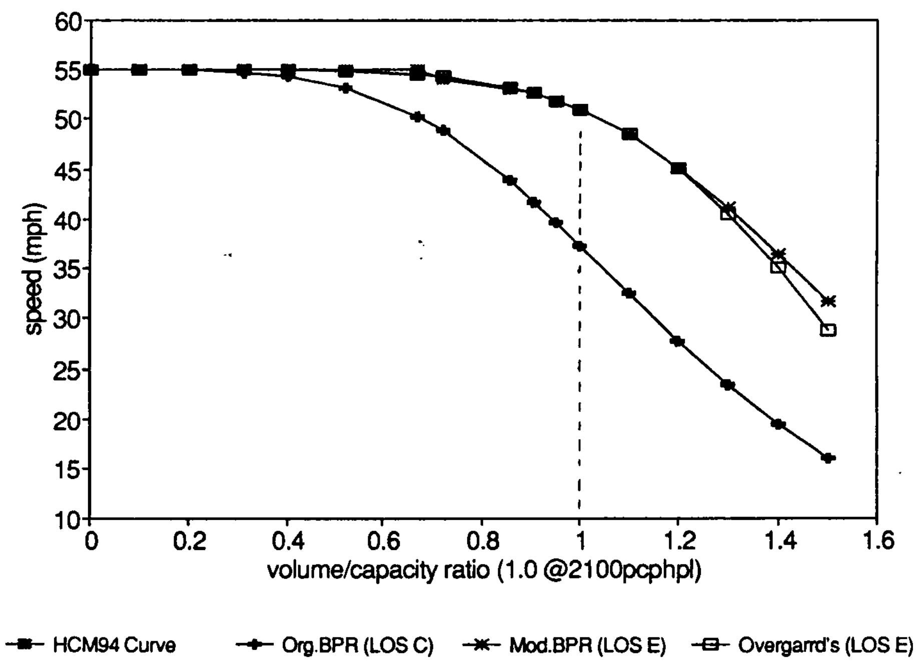

Figure 5.8 HCM94 Based Volume-Speed Functions for Multi-Lane Highways

5. Three HCM85 Overgarrd's HCM94 functions, for freeway, arterial and multi-lane highway facilities.

5.3 Volume-Speed Function Integral Value (VSFIV)

5.3.1 The Concept

The v/c ratio > 1.0 is an undefined area of the volume-speed function in practice, but the function must be extended beyond a v/c ratio of 1.0 in the capacity-restraint assignment algorithm. Therefore, the characteristics of the volume-speed function, where the volume is greater than the capacity, need to be discussed. As shown in Figure 5.1, the different HCM85 freeway volume-speed functions, the original BPR, the modified BPR, and the Overgarrd's functions have a similar curve shape when the v/c ratio falls in the [0, 1] interval. This is controlled by the least squared objective function. When the v/c ratio exceeds the [0, 1] interval, the function curves start to display larger differences. Because of this phenomenon, it was hypothesized that the assignment system performance measures depend on the characteristics of the curve where the v/c ratio is greater than 1.0. However, no study was conducted to evaluate this phenomenon.

A new concept was introduced to evaluate the volume-speed function performance where the v/c ratio is greater than 1.0. Recall that in finite calculus, the function:

$$F(x) = \int_{x2}^{x1} f(x)dx \qquad (5.4)$$

represents the size of the area bounded by functions y = 0, x = x1, x = x2, and y = f(x) where x and f(x) are all defined in Quadrant I. By utilizing the same concept, the integral function:

$$F(x) = \int_{0}^{\infty} f(x)dx \qquad (5.5)$$

where, $f(x)$ is a volume-speed function,

x is the v/c ratio, $x \in [0, \infty)$,

can be used to represent the integral value of a function $f(x)$ which is the size of the area bounded by the function $f(x)$ with v/c ratio from zero to infinity. If $f(x)$ is a volume-speed function, the function $F(x)$ specified in expression(5.5) can be named as the Volume-Speed Function Integral Value (VSFIV). The inter-relationship between VSFIV and system performance measures can be explored through applying VSFIV at different intervals, such as $x \in [0, 1)$ and $x \in [1, \infty)$.

Since different volume-speed functions lead to different integral values, the change in free flow speed defined in the volume-speed function also changes the integral value. Therefore, a normalized volume-speed function must be used to eliminate effect of the difference in free flow speeds in the volume-speed functions. This integral value is here called the Normalized Volume-Speed Function Integral Value (NVSFIV). Note that the speed in the integrand is always 1. For example, the NVSFIV can be expressed as

$$V = \int_{x1}^{x2} s_0/(1 + \alpha x^{\beta})dx \qquad (5.6)$$

where, $s_0 = 1$

x is v/c ratio, $x \in [0, \infty)$,

for a volume-speed function that uses the BPR function format as a base.

5.3.2 The Numerical Solution of NVSFIV

In calculus, only a very limited number of functions, called elementary functions (such as x^2, x^3, $1+x^2$), can be integrated analytically. In most situations, numerical computational methods are required to find approximate integral values. Since the volume-speed functions are derived from field data, and rational numbers are often involved, the numerical solution of NVSFIV becomes appropriate and feasible.

The basic principle of numerical solution to an integral problem is to divide the integral area into very small pieces, then use a simple method to calculate the size of each piece. The final integral value is the sum of all the pieces. Several methods, such as the trapezoidal method, the Simpson method, the Romberg method, etc., were developed to calculate the integral values. Among these methods, the trapezoidal method is one of the oldest. However, almost no one still uses this method due to its inaccuracy and inefficiency. Instead, the composite trapezoidal closed formula is commonly used today. The composite trapezoidal is less efficient than the Composite Simpson formula and Romberg formula, but it is easy to program. Considering the programming effort, the calculation time, and the precision required, the composite trapezoidal method was adopted in this study. A PASCAL program was written to calculate the NVSFIV. It required less than one minute to finish the calculation on the test machine, a 486DX33 based computer, and produced a satisfactory solution with an error margin less than < 0.00001. The source code of the program is attached as Appendix C.

In the study, the NVSFIVs for five volume-speed function sets, the modified BPR and the Overgarrd's functions for HCM85 and HCM94, plus the original BPR function, represented the area integrated by the volume-speed function at v/c ratio from zero to infinity. This area can be divided into two sub-areas: v/c ratios are greater than 1.0 and less than 1.0. For the purpose of this research, emphasis was placed on exploring the volume-speed relationship at v/c ratio greater than 1.0 and on its impact on assignment performance.

Unless it is specified, the NVSFIVs discussed in this chapter are defined at v/c ratios from 1.0 to infinity. This can be expressed as:

$$\text{NVSFIV} = \int_{1.0}^{\infty} f(x)dx \qquad (5.7)$$

where, f(x) is a normalized volume-speed function,

x is v/c ratio, $x \in [1, \infty)$

Table 5.3 presents the calculated NVSFIVs for all the volume-speed functions used in the test cases. Since there is only one original BPR function, the coefficients and NVSFIVs are the same for both HCM85 and HCM94 curves regardless of facility type.

5.3.3. Capacity and Maximum Assignable Volume

Due to the nature of the assignment volume-speed function, the NVSFIV was defined to characterize the volume-speed function where the v/c ratio is greater than 1.0. The volume-speed function, on the other hand, determined the assignment performance at

Table 5.3 NVSFIVs for the Volume-Speed Functions Used in the Tests

HCM85	NVSFIV			HCM94	NVSFIV		
Vol-Speed Functions	v/c < 1	v/c > 1	Total	Vol-Speed Functions	v/c < 1	v/c > 1	Total
Freeways				Freeways			
Orginal BPR	0.97	0.81	1.78	Orginal BPR	0.97	0.81	1.78
Mod. BPR-HCM85	0.94	0.15	1.09	Mod. BPR-HCM94	0.98	0.25	1.23
Overgarrd's-HCM85	0.94	0.07	1.01	Overgarrd's-HCM94	0.98	0.18	1.16
Arterials				Arterials			
Orginal BPR	0.97	0.81	1.78	Orginal BPR	0.97	0.81	1.78
Mod. BPR-HCM85	0.92	0.18	1.10	Mod. BPR-HCM94	0.96	0.13	1.08
Overgarrd's-HCM85	0.92	0.08	1.00	Overgarrd's-HCM94	0.96	0.07	1.03
Multi-lane Highways				Multi-lane Highways			
Orginal BPR	0.97	0.81	1.78	Orginal BPR	0.97	0.81	1.78
Mod. BPR-HCM85	0.83	0.90	1.73	Mod. BPR-HCM94	0.99	0.68	1.67
Overgarrd's-HCM85	0.83	0.31	1.14	Overgarrd's-HCM94	0.99	0.51	1.50

both the v/c ratio > 1.0 and the v/c ratio < 1.0. Since the assignment algorithm frequently operated under conditions with the v/c ratio greater than 1.0, the actual maximum volume assigned on a network link was not subject to the HCM defined capacity. Therefore, in traffic assignment, the maximum volume assigned to, for example a freeway link, could be far greater than 2,000 pcphpl on the freeway.

Different volume-speed functions have different NVSFIVs associated with different maximum v/c ratios. Corresponding to this maximum v/c ratio, the maximum assignable volume can be defined as the volume reaching the point where the speed is zero. At this point, the link impedance or travel time should be infinite, so that no more traffic can be assigned on it. In practice, this condition is hard to satisfy. So the maximum assignable volume can defined as the volume where the speed reaches a considerably low point, such as 1 to 3 mph or 1%–3% of the free flow speed. Based on the maximum assignable volume concept, another measure, the extended assignable volume, can also be defined:

$$\text{Extended assignable volume} = \text{Maximum assignable volume} - \text{Capacity} \qquad (5.8)$$

The expression(5.8) shows that the extended assignable volume is the difference between the maximum assignable volume and the capacity. Using the original BPR function and the Overgarrd's HCM85 freeway functions as examples, Figures 5.9 and 5.10 display the concepts of maximum assignable volume, extended assignable volume, and their relationship to the NVSFIV. Note that the area under the volume-speed functions with v/c ratio from 1.0 to infinity. It is clear that the area under the volume-speed function will vary with the maximum assigned v/c ratio. For example, if the maximum assigned v/c ratio is

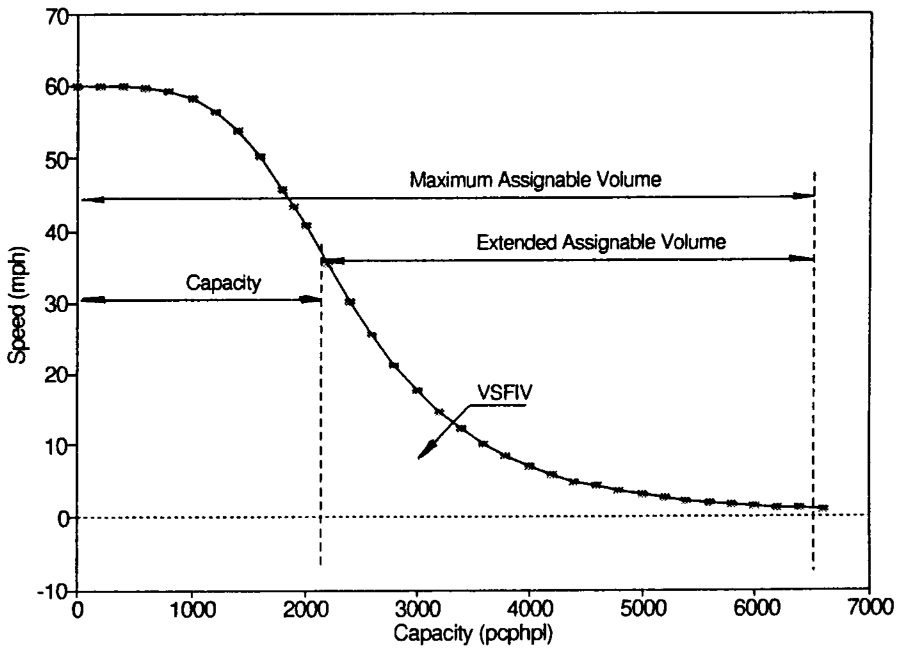

Figure 5.9 Maximum and Extended Assignable Volumes

for Original BPR Function

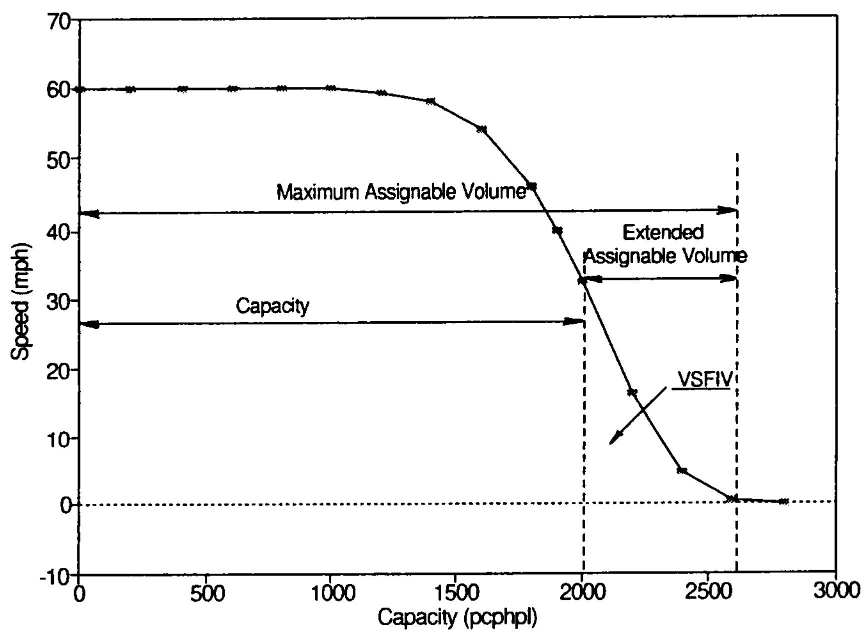

Figure 5.10 Maximum and Extended Assignable Volumes

for Overgarrd's HCM85 Function

four to five for the original BPR function and 1.2 for Overgarrd's HCM85 function, the area under the v/c > 1.0 portion of the curve will vary extensively.

5.4 Assignment Termination Condition

From the tests concluded in Chapter Four, it was found that the system VHT decreased and the speed increased gradually as number of iterations in the assignment increased. In the equilibrium assignment procedure, at least two iterations are required. Different numbers of iterations will result in different levels of system performance. The question then becomes how many iterations are needed. From a system viewpoint, two different assignment objectives can be achieved[25]. One is system optimum which seeks to minimize system travel time and maximize average speed. Another is so called user equilibrium which is designed to minimize individual traveller's travel time form origin to destination. Under this objective, "a stable condition is reached only when no traveller can improve his travel time by unilaterally changing routes". It has been proved that these two objectives can not be achieved at the same time unless the network link travel time is not a function of traffic volume in the assignment[26]. In the capacity restraint assignment, the second objective is commonly used. However, the true equilibrium condition is very difficult to reach. In commercial UTPS software packages including MINUTP, a tolerance level, which defines an acceptable equilibrium status to terminate the assignment process, is defaulted. The assignment program will terminate when either the tolerance level is satisfied or a user defined number of iterations is reached. However, it was observed in this research that the termination condition was not easy to satisfy with default tolerance levels under congested network conditions. In the practice, the question becomes when such an iterative process should be terminated since the true equilibrium status is unknown.

Several tests were carried out to find the number of iterations required to reach a stable system performance for each volume-speed function set used in the various assignments. A base year (1995) O-D table was loaded to the same network with different volume-speed functions. Figures 5.11 to 5.13 display the general trends on how the system performance measures change as a function of the number of iterations. Three conclusions were drawn from the tests:

1. After 20-25 iterations, all three performance measures reached a stable condition which indicated that 25 iterations were appropriate as an approximate termination condition.

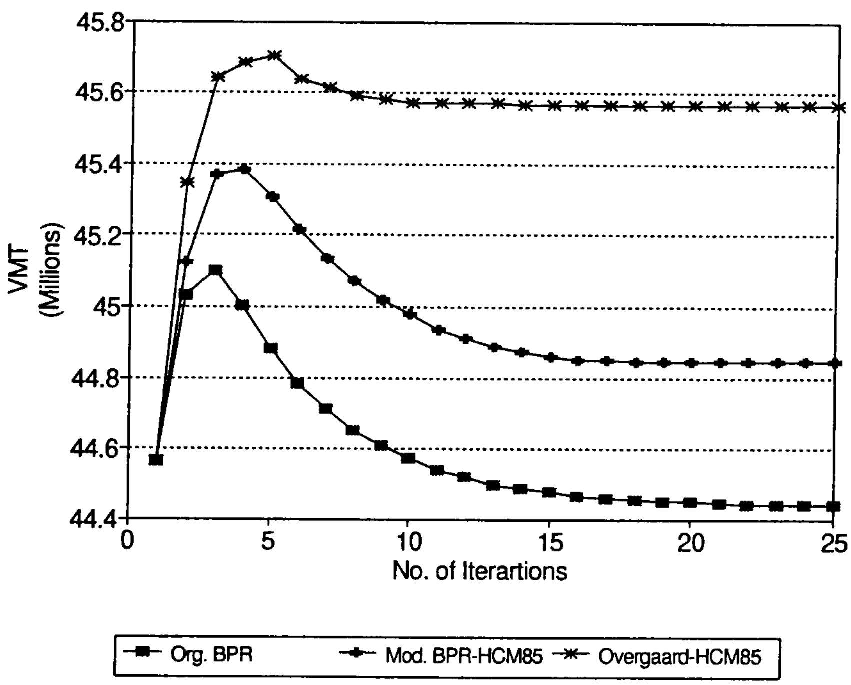

Figure 5.11 Number of Iterations and Assignment Performance: VMT

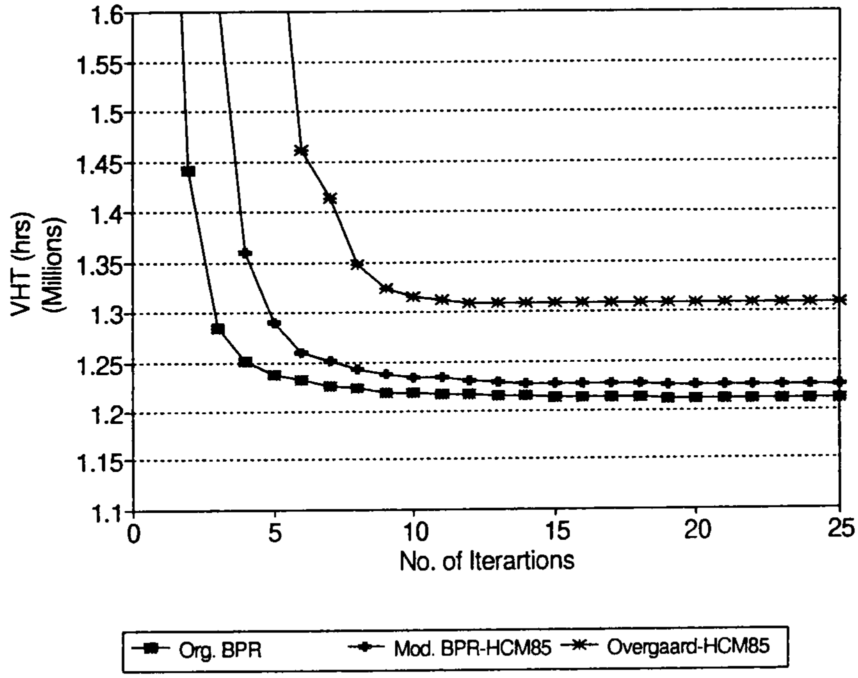

Figure 5.12 Number of Iterations and Assignment Performance: VHT

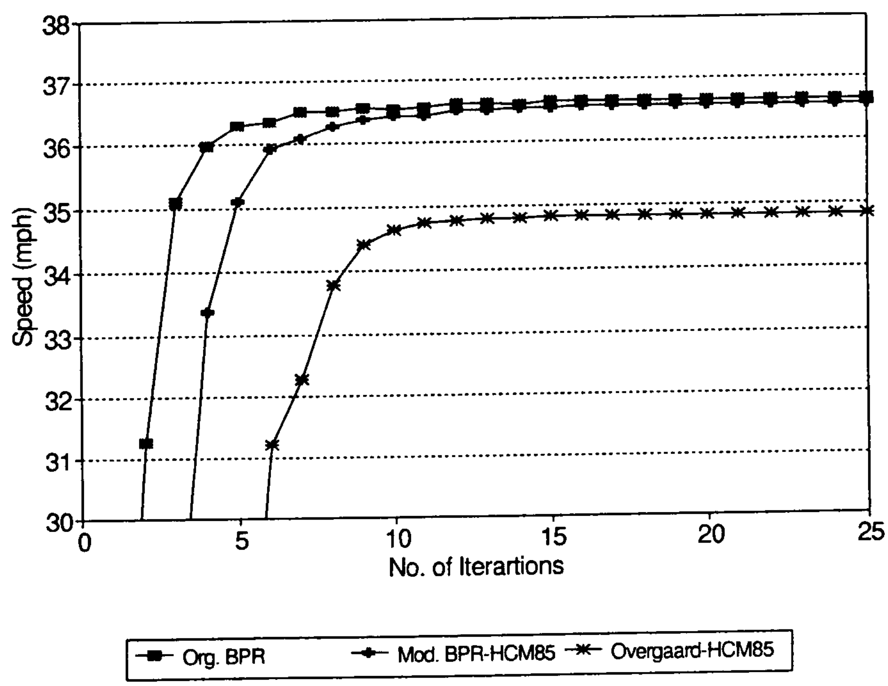

Figure 5.13 Number of Iterations and Assignment Performance: Speed

2. The VMT displays a faster convergency rate than other two measures: the VHT and the speed.
3. The performance measures had large variations when the number of iterations was less than 10. Fewer than five iterations should be considered unacceptable.

A relative percentage error (RPE) was introduced to help to determine a realistic number of iterations and to minimize the computing time:

$$RPE = |(x^* - x_i)/x^*| \tag{5.9}$$

where, x^* is the performance measure when assignment reaches 'true' equilibrium. In the study case, it is the performance measure at iteration 25.

x_i is the performance measure at iteration i.

i is number of iterations.

Since there were three major performance measures (VMT, VHT and speed) in the assignment, then the number of iterations should be determined by the measure with the largest RPE, that is

$$\max \{|(x^* - x_i)/x^*|, |(y^* - y_i)/y^*|, |(z^* - z_i)/z^*|\} <= e \tag{5.10}$$

where, x_i, y_i, and z_i are the VMT, the VHT and the speed at iteration i

x^*, y^*, and z^* are the VMT, the VHT and the speed when the number of iterations reaches infinity.

e is a predetermined error margin or tolerance level to control the number of iterations.

The expression(5.10) ensures that the maximum error among the performance measures does not exceed a predetermined margin. The error tolerance e was determined as 0.5% according to experience. Similar to any convergency process, the test proved that a higher error margin led to a smaller number of iterations, while a lower error margin resulted in a higher number of iterations. Table 5.4 shows the number of iterations needed to satisfy different error margins using different volume-speed functions.

The test results (shown in Table 5.4) indicated that assignments using Overgarrd's volume-speed function required the largest number of iterations while the original BPR function needed the least. The reason lies in the shape of the volume-speed curve and the extended assignable volume. The smaller extended assignable volume made it more difficulty for the algorithm to find a better path in a congested network. The tests also showed that the number of iterations should be between 10 and 15 for large cities like Denver, where moderate levels of congestion are experienced. Comparing this conclusion to current assignment practice in large MPOs, it was recommended that the number of

Table 5.4 Number of Iterations and Assignment Error Margins

Absolute % Error	Volume-Speed Functions		
	Original BPR	Modified BPR-HCM85	Overgarrd's HCM85
0.10%	16	14	13
0.30%	13	12	13
0.50%	11	12	13

iterations be raised in order to obtain a stable assignment condition. Fifteen iterations were used for all volume-speed function test cases presented in this chapter.

Since different volume-speed functions affected the number of iterations in the assignment, it is recommended that the number of iterations used in a capacity-restraint assignment be checked in the modeling process when a new volume-speed function is adopted.

5.4 Test Environment

5.4.1 General Information

As stated before, the major purpose of this chapter was to explore the impacts of different volume-speed functions used in the assignment procedure and their implication to the UTP forecasting of VMT, VHT and speed, and estimation of vehicle emissions. Similar to the tests described in the Chapter Four, a uniform test background was maintained. Again, the Denver region's transportation planning data were used as a sample to carry out the tests. These background conditions are summarized as the following:

- 1995 base year O-D table initialized by using LOS C speeds;
- Base year highway network;
- Single period all-day equilibrium assignment;

The mathematical expressions of volume-speed curves with their corresponding coefficients derived from HCM85 and HCM94 curves were used in the MINUTP ASSIGN program to execute the tests.

5.4.2 The Test Cases

Five test cases were conducted. This included:

1. The original BPR function;
2. The modified BPR function with HCM85;
3. The Overgarrd's function with HCM85;
4. The modified BPR function with HCM94; and
5. The Overgarrd's function with HCM94.

The first case used the BPR function's original coefficients with α=0.15 and β=4 and used practical capacity (LOS C) which was similar to the equilibrium assignment used in Chapter Four. The purpose of selecting this case was that the original BPR function with practical capacity is still the most popular volume-speed function used in the assignment procedure, and it provided a convenient base of comparison with other cases tested. The second and third cases both used the HCM85 defined volume-speed relationship with LOS E capacity. Case two used the BPR base function with altered coefficients while case three used Overgarrd's base function. It was expected that these two functions would generate different results. The fourth and the fifth HCM94 test cases used the HCM94 curves which represent the future applications of volume-speed curves. They were parallel to test cases two and three. For cases four and five, the HCM94 freeway, arterial, and multi-lane curves were employed to replace the HCM85 curves used in the case 2 and 3. The performance difference between the HCM85 and HCM94 curves and their impacts on air quality analysis were explored through these five test cases.

5.5 Test Results: Original BPR and HCM85 Curve Analysis

5.5.1 System Performance Measures and Vehicle Emissions

The VMT and the speed estimates from the tests were the most important performance measures, since the MOBILE5A model used speed to determine the emission rates and VMT to determine the overall emission level. Three models, including the original BPR case, the modified BPR–HCM85 case and the Overgarrd's HCM85, were run to determine the impacts of using HCM85 based volume–speed functions. The overall system performance measures as well as their respective vehicle emission estimates are listed in Table 5.5. The three cases produced slightly different VMT estimates. A relatively larger VHT difference (28%–31%), especially when comparing Overgarrd's HCM85 to the

Table 5.5 HCM85 Curve Assignment Performance and Vehicle Emission Estimates

V-S Functions	VMT in 1000s	VHT in 1000s	Speed (mph)	Emission Estimates (1000 kgs) HC	CO	NOx
Original BPR	40,346	1,013	39.8	74.9	701.3	119.6
Mod. BPR-HCM85	40,779	1,031	39.6	76.6	725.1	121.5
Difference	433	17	-0.2	1.7	23.8	1.9
Percent Change	1.1%	1.7%	-0.6%	2.3%	3.4%	1.6%
V-S Functions	**VMT in 1000s**	**VHT in 1000s**	**Speed (mph)**	**Emission Estimates (1000 kgs) HC**	**CO**	**NOx**
Original BPR	40,346	1,013	39.8	74.9	701.3	119.6
Overgarrd's-HCM85	40,953	1,324	30.9	88.0	825.8	112.8
Difference	607	311	-8.9	13.1	124.5	-6.8
Percent Change	1.5%	30.7%	-22.3%	17.6%	17.8%	-5.7%
V-S Functions	**VMT in 1000s**	**VHT in 1000s**	**Speed (mph)**	**Emission Estimates (1000 kgs) HC**	**CO**	**NOx**
Mod. BPR-HCM85	40,779	1,031	39.6	76.6	725.1	121.5
Overgarrd's-HCM85	40,953	1,324	30.9	88.0	825.8	112.8
Difference	174	294	-8.6	11.4	100.7	-8.7
Percent Change	0.4%	28.5%	-21.9%	14.9%	13.9%	-7.2%

Original BPR, was observed. Recall that in Figure 5.1, the freeway volume–speed curves, the speed on the Overgarrd's HCM85 had the highest rate of decline when the v/c ratio approached the capacity and thereafter. As a result, the Overgarrd's HCM85 case produced about a 9 mph overall lower speed than the original BPR case. The modified BPR–HCM85 and original BPR cases produced similar average speeds. The maximum differences on the performance measures appeared between the Overgarrd's HCM85 and the original BPR cases. Table 5.5 also displays the vehicle emission estimates produced by the test cases.

It was obvious that the CO and HC estimates are very sensitive to the change in the volume–speed curves. Even for the modified BPR–HCM85 and the original BPR cases, where the overall system performance were similar, the emission estimate variation was still considerable. A reasonable explanation for this was that the modified BPR–HCM85 curve changed the speed and VMT distribution among facilities, and then affected the emission rates. With the results from the two HCM85 curve based functions, the modified BPR and the Overgarrd's, the speed difference was obvious: the system VMT only had a 0.4% difference while the average speed had a 21.9% difference between the two cases. As a result, 14.9%, 13.9% and 7.2% variations were observed on the HC, CO and NOx emissions, respectively. However, the volume–speed functions displayed in Figures 5.1 to 5.3 show little differences on the shapes of the curve at v/c ratios less than 1.0 and large differences at the v/c ratios greater 1.0. This implied that the curve characteristics at v/c ratio > 1.0 can played an important role in determining the system performance measures.

5.5.2 V/C Ratio and NVSFIV

Investigating how system performance measures are distributed at different v/c ratios was another aspect of the analysis. After the tests, the v/c ratios on the links were classified into seven intervals: (0, 0.25], (0.25, 0.5], (0.5, 0.75], (0.75, 1.0], (1.0, 1.25], (1.25, 1.5], and (1.5, ∞). The VMT and the speed were also summarized by these seven intervals for analysis. To simplify the analysis, only the freeway performance is discussed in this section. However, a separate analysis proved that the conclusions derived from the freeway facility were applicable to other facility types and system performance.

For the freeway speed (Figure 5.14), the estimated capacity speed for each v/c region was defined for the test cases. The estimated speeds followed their corresponding volume–speed functions closely. In the original BPR function case, the assignment resultant speed changes at different v/c ratios had the same trend as the original BPR volume–speed function. It was also observed that the HCM85 curve case generated speeds declined much faster than the BPR function when the v/c ratio approached 1.0 and above. The Overgarrd's HCM85 case had the quickest reduction in speed between the v/c ratio of 1.0–1.5. The original BPR case had the highest estimated speed at each v/c ratio interval. At the v/c ratios from 1.0 to 1.25, the estimated speed from Overgarrd's HCM85 based assignment was about 20 mph, while the modified BPR and the original BPR functions were about 28 and 37 mph, respectively. When the v/c ratio was at the 1.25 to 1.5 interval, the Overgarrd's function assigned no traffic in the system. The modified BPR and original BPR function cases, at the same time, produced speeds of 10 mph and 25 mph, respectively. This speed difference played a very critical rule in determining the applicable emission rates and directly influenced the calculation of vehicle emissions.

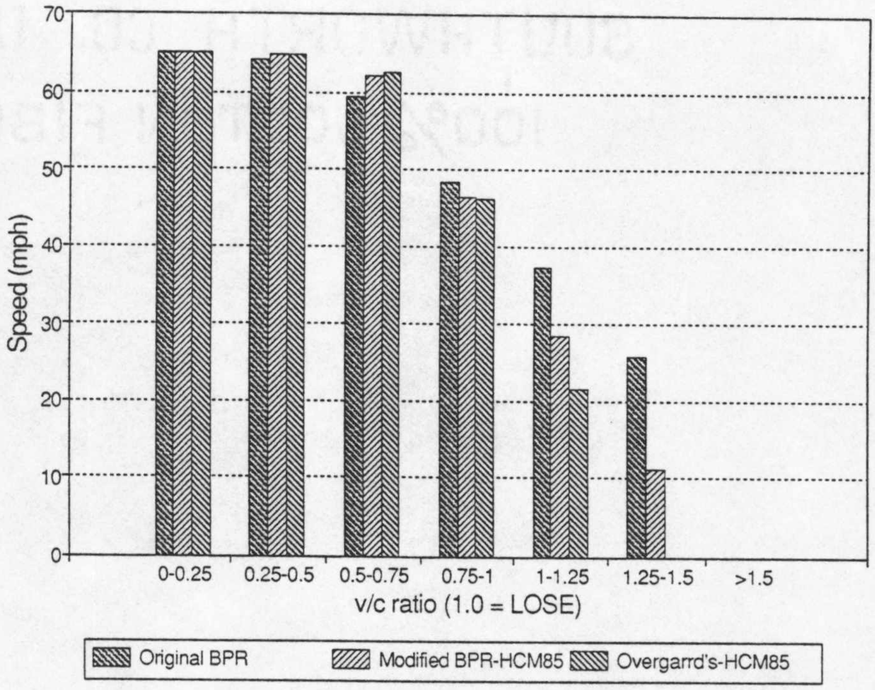

Figure 5.14 Average Freeway Speed Versus v/c Ratio

The shape of the curve affected not only the speed distribution in the assignment, but the VMT distribution as well. Figure 5.15 displays the freeway VMT distribution changes by v/c ratio interval for three test cases: the original BPR, modified BPR–HCM85 and the Overgarrd's HCM85 volume–speed functions. At the v/c ratios above 1.0, the Overgarrd's HCM85 case had the lowest percentage of VMT while the original BPR case had the highest. This reflected the general trend of the volume–speed functions. It was also noted, that both HCM85 curve based assignments had considerably lower VMT distributed within the v/c ratio > 1.0 area than the original BPR curve based assignment. Between the two HCM85 assignments, the Overgarrd's function showed even lower VMT than the modified BPR function when the v/c ratio was between 1.0 to 1.5.

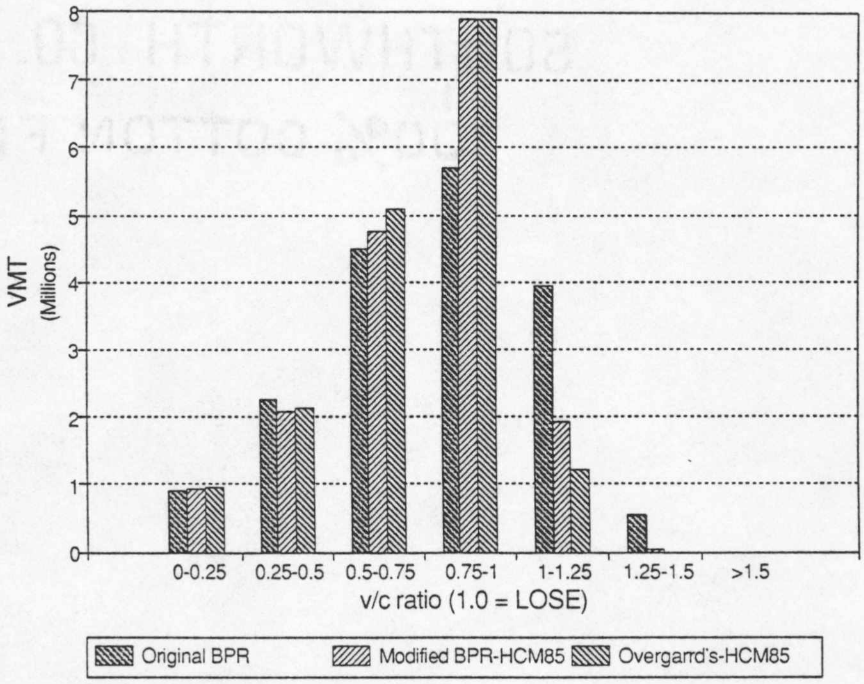

Figure 5.15 Freeway VMT Distribution by v/c Ratio Intervals

In three test cases, the NVSFIVs at the v/c ratio > 1.0 portion were then compared to the VMT with the link v/c ratio > 1. Table 5.6 shows this comparison by using the freeway class as an example. In the table, the NVSFIV at the v/c ratio > 1.0 portion is expressed as a percentage of the total NVSFIV, which is defined at v/c ratio from zero to infinity. The VMT with the volume at the v/c ratio > 1.0 is also expressed as a percentage of total freeway VMT. As noted the percent VMT clearly resembles the percent NVSFIVs.

In the volume-speed function development stage, a least squared objective function was used to find the volume-speed function that can best fit the volume-speed curve in the [0,1) v/c ratio interval. As indicated in Table 5.1, both the modified BPR-HCM85 and Overgarrd's HCM85 volume-speed functions had almost the same least squared function

Table 5.6 A Comparison on Percentages of Freeway VMT and NVSFIV at V/C > 1.0

Vol-Speed Functions	% VMT		% NVSFIV	
	v/c<1.0	v/c>1.0	v/c<1.0	v/c>1.0
Orginal BPR	74.8%	25.2%	68.9%	31.1%
Mod.BPR-HCM85	88.9%	11.1%	85.8%	14.2%
Overgarrd's-HCM85	93.0%	7.0%	93.3%	6.7%

values and correlation coefficients (R^2) derived from HCM85 defined volume–speed curves for each highway class. In addition, the NVSFIVs between modified BPR and Overgarrd's functions by roadway class at the v/c ratio less than 1.0 are about the same. However, the NVSFIVs at the v/c ratio > 1.0 showed considerable differences. This provided more evidence that the differences in system performance were mainly caused by the section of the curves where the v/c ratio was greater than 1.0.

5.5.3 Impact of Extended Assignable Volume

Capacity is defined as the maximum rate of flow at which vehicles can reasonably travel along a lane of roadway segment during a period of time[2]. In the assignment, the maximum volume that can be assigned on a link is determined by the maximum assignable volume, not the capacity. In practice, many planning agencies use a VMT weighted system v/c ratio to measure the system congestion levels between different planning alternatives. This measure is defined as:

$$\text{VMT Weighted System v/c} = \Sigma\, d_i{*}v_i \,/\, \Sigma\, d_i{*}nl_i{*}c_i \qquad (5.11)$$

where, d_i is the distance on link i,

v_i is the volume assigned on link i,

nl_i is number of lanes of link i,

c_i is the capacity of link i.

In fact, $\Sigma\, d_i{*}v_i$ is the system VMT while the $\Sigma\, d_i{*}nl_i{*}c_i$ represents the maximum VMT that can be loaded on a network. Under a normal situation the capacity c_i is a constant for link i, the system speed should not change as long as the VMT and other conditions are the same.

Unfortunately, this was not the case in the assignment procedures that used different volume-speed functions. It was more important to consider the maximum assignable volume along with the capacity in an analysis of volume-speed curve. Table 5.7 shows capacities and maximum assignable volumes for volume-speed functions of freeway, arterial and multi-lane facilities. It was found that the maximum assignable volume in the assignment could be as large as 2-3 times the HCM defined capacity. This was the factor that influenced the speed and the VMT in the assignment, not the capacity per say. As a reference, Table 5.8 displays the capacity based and maximum assignable volume based congestion levels and speeds for three test cases. For freeways, the capacity based congestion levels kept a constant of 0.63 with different volume-speed functions, while maximum assignable volume based congestion levels varied between 0.22 to 0.49. Same observation was found in the system congestion levels defined by these two different definitions.

5.5.4 Volume-Speed Function Development Criteria

Since the NVSFIV, the maximum assignable volume, and the volume-speed function performance in the assignment have a close relationship, it is possible to use these characteristics to help define a curve that reflects actual traffic flow condition more closely

Table 5.7 HCM85 Capacity and Maximum Assignable Volume

Volume-Speed Functions	Capacity (pcphpl)	Assignable Volume(pcphpl) Extended	Maximum
Freeways			
Orginal BPR	1,500	4,200	5,700
Mod. BPR-HCM85	2,000	2,000	4,000
Overgarrd's-HCM85	2,000	580	2,580
Arterials			
Orginal BPR	600	1,680	2,280
Mod. BPR-HCM85	800	1,024	1,824
Overgarrd's-HCM85	800	328	1,128
Multi-lane Highways			
Orginal BPR	1,350	3,780	5,130
Mod. BPR-HCM85	1,800	16,740	18,540
Overgarrd's-HCM85	1,800	3,150	4,950

Table 5.8 Capacity Based and Maximum Assignable Volume Based

Congestion Levels

	Freeways			
	VMT	Speed	Congestion Level	
Vol-Speed Functions	(millions)	(mph)	Capacity Based	Max. Assn Vol Based
Orginal BPR	17.8	48.4	0.63	0.22
Mod. BPR-HCM85	17.6	48.5	0.63	0.31
Overgarrd's-HCM85	17.9	34.2	0.63	0.49
	System			
	VMT	Speed	Congestion Level	
Vol-Speed Functions	(millions)	(mph)	Capacity Based	Max. Assn Vol Based
Orginal BPR	40.3	39.8	0.40	0.14
Mod. BPR-HCM85	40.8	39.6	0.40	0.16
Overgarrd's-HCM85	41.0	30.9	0.41	0.22

in the capacity–restraint assignment. The question becomes how to minimize the area under v/c > 1 or the extended assignable volume. In other words, how to make the difference between HCM defined capacity and volume–speed function defined maximum assignable volume as small as possible.

To perform capacity–restraint equilibrium assignment, several criteria must be also met in addition to the coefficient(s) of the volume–speed function. Horowitz[3] and others defined five standards for the volume–speed functions:

1. The function should be monotone;
2. The function should provide a realistic value of delay across the range of volumes from zero to capacity, especially at zero and at capacity;
3. The function should have a few well defined parameters;
4. The function should be finite for all volumes;
5. The function should have a positive derivative at zero volume.

Through the analysis in the previous sections, the following two criteria were recommended to be added in the selection of volume–speed functions.

1. min. $\Sigma\, [f_2(xi)-f_1(xi)]^2$ $x \in [0, 1]$ (5.12)
2. min. $\int_1^\infty f_2(x)dx$ $x \in (1, \infty)$ (5.13)

The expression(5.12) is natural, because volume–speed function developed from the HCM curve should follow this object function to best fit the field observation when the v/c ratio is less than 1.0. The expression(5.13) implies that the NVSFIV should be as small as possible in order to make the volume–speed function close to reality since the v/c > 1.0 area is an imaginary area used in the assignment. Related to the NVSFIV, the extended assignable volume should also be minimized. By using these two additional criteria to evaluate the volume–speed functions used in the test cases, it was found that Overgarrd's function has the smallest NVSFIV and extended assignable volume among all three sets of volume–speed functions (see Table 5.3 and Table 5.7). Therefore, the Overgarrd's base function should be given a higher priority in considering volume–speed function used in the capacity–restraint assignment.

5.5.5 Emission Sensitivity to the Volume–Speed Curves

The VMT and the speed were two measures that have great impact on estimating vehicle emissions. A sensitivity analysis was performed to see which measure had a larger impact on overall emission estimates under different volume–speed functions. Table 5.9 displays the results which compare the modified BPR–HCM85 case to the original BPR case, and the Overgarrd's HCM85 case to the original BPR case. From the tests, it was concluded that speed change still played a major role in influencing the vehicle emission estimates. The HC and CO were very sensitive to the speed change. The average speed in the Overgarrd's HCM85 function case dropped about 9% from the original BPR function case while both HC and CO increased 16%. The Overgarrd's HCM85 function case had 1.5% more VMT than the original BPR function case and a 1.5% change in emission estimates, because emission was proportional to the VMT. The VMT and the speed differences between the modified BPR and the original BPR function cases were not large, but the test result still showed that the speed is a major determinant factor. The 1.3% to 2.3% changes on the HC and CO were caused by 0.6% change of average speed. The NOx was less sensitive to the speed due to its flatter speed–emission rate relationship.

Table 5.9 Vehicle Emission Sensitivity to Assignment Performance Measures

Modified BPR-HCM85 vs Original BPR						
	VMT	Speed				
% Difference	1.1%	-0.6%				
	HC		CO		NOx	
Changes	% Diff	Emission (kgs)	% Diff	Emission (kgs)	% Diff	Emission (kgs)
Due to VMT	1.1%	802	1.1%	7,519	1.1%	1,282
Due to speed	1.2%	933	2.3%	16,323	0.5%	621
Total	2.3%	1,736	3.4%	23,842	1.6%	1,903

Overgarrd's HCM85 vs Original BPR						
	VMT	Speed				
% Difference	1.5%	-22.3%				
	HC		CO		NOx	
Changes	% Diff	Emission (kgs)	% Diff	Emission (kgs)	% Diff	Emission (kgs)
Due to VMT	1.5%	1,126	1.5%	10,548	1.5%	1,799
Due to speed	16.1%	11,842	16.2%	112,262	-7.2%	(8,479)
Total	17.6%	13,146	17.8%	124,498	-5.7%	(6,808)

5.6 Test Results: HCM94 Curve Evaluation

5.6.1 Performance Changes in v/c Ratio < 1.0 Area

The evaluation of the HCM94 based volume-speed functions were addressed in three aspects. The first was the changes made in the v/c ratio < 1.0 area. The 1994 HCM increased the 1985 HCM defined freeway and multi-lane highway capacity by about 10-15 percent. It also changed the shape of volume-speed curves for all three facilities: freeway, arterial and multi-lane highway. These changes influenced the coefficients of the base mathematical expressions in both the modified BPR and the Overgarrd's functions. The system performance differences between the HCM85 and HCM94 volume-speed functions reflect these changes. Table 5.10 exhibits a comparison of the performance measures and the emission estimates differences for two distinct HCM curve sets. In general, the HCM94 based assignments produced very similar VMT estimates as the

Table 5.10 Assignment Performance Measures and Vehicle Emission Estimates

A Comparison of HCM85 and HCM94 Functions

Volume-Speed Functions	VMT in 1000s	VHT in 1000s	Speed (mph)	EMISSIONS (1000kgs) HC	CO	NOx
Modified BPR						
HCM85	40,779	1,031	39.6	76.6	725.1	121.5
HCM94	40,768	953	42.8	76.0	783.2	131.0
Difference	(11)	(77)	3.2	-0.6	58.1	9.5
Percent Change	-0.0%	-7.5%	8.1%	-0.7%	8.0%	7.8%
Overgarrd's						
HCM85	40,953	1,324	30.9	88.0	825.8	112.8
HCM94	40,846	1,126	36.3	80.8	789.4	120.7
Difference	(107)	(198)	5.3	-7.2	-36.4	7.9
Percent Change	-0.3%	-15.0%	17.3%	-8.2%	-4.4%	7.0%

HCM85 based assignments. However, the HCM94 assignments generated much lower VHT than the HCM85 assignments, resulting in an 8%–17% increase in system average speed, because of higher capacities defined for freeways and multi-lane highways. The emission was closely related to the speed, so the emission estimates demonstrated a 0.7%–8.2% decrease in all three pollutants.

5.6.2 Performance Changes in v/c Ratio > 1.0 Area

The second consideration was the volume-speed function changes in the v/c ratio > 1.0 area. Since the HCM94 modified BPR and Overgarrd's functions used HCM94 curves as a base, and the volume-speed relationship in both functions for the v/c ratios less than 1.0 were identical, the performance differences should reflect the differences of the functions where the v/c ratio was greater than 1.0. A comparison on the outcomes of the two volume-speed function sets was meaningful as noted in Table 5.11. Similar to the

Table 5.11 Performance Summary on Assignments Using Different HCM94 Functions

Volume-Speed Functions	VMT in 1000s	VHT in 1000s	Speed (mph)
Modified BPR-HCM94	40,768	953	42.8
Overgarrd's-HCM94	40,846	1,126	36.3
Difference	78	173	-6.5
Percent Change	0.2%	18.2%	-15.2%
	Emission Estimates (1000 kgs)		
Volume-Speed Functions	HC	CO	NOx
Modified BPR-HCM94	76.0	783.2	131.0
Overgarrd's-HCM94	80.8	789.4	120.7
Difference	4.7	6.2	-10.3
Percent Change	6.2%	0.8%	-7.9%

analysis of the HCM85 functions, the HCM94 modified BPR functions and Overgarrd's functions showed large performance differences (more than 15%) for both VHT and speed, and small to moderate differences (0.1%–8%) for the emission estimates. It was also observed that the distributions of system performance measures and emissions varied between facility types. This is analyzed later in this chapter.

5.6.3 Maximum Assignable Volume Changes

The third aspect was to investigate the changes in the NVSFIVs and the maximum assignable volumes. As previously shown in Table 5.2, the mathematical expressions of the HCM94 volume–speed curve, the NVSFIV, and the extended assignable volume were determined when the coefficients in the volume–speed functions were established by minimizing the least squared objective function. In the HCM94, both the modified BPR and the Overgarrd's functions showed larger NVSFIVs when the v/c ratio > 1.0 and larger extended assignable volumes than the HCM85 curve based functions for freeways. For the arterials and multi-lane highways, the HCM94 volume-speed functions produced smaller extended assignable volumes than HCM85 functions. As a result, more trips were diverted from these facilities to the freeways in the assignment phase. From Table 5.10, it was also observed that the HCM94 volume-speed curve based assignment produces higher overall speed estimates in both the modified BPR and Overgarrd's cases than the HCM85 curve based assignments. Table 5.12 displays the extended and maximum assignable volumes for both HCM94 modified BPR and Overgarrd's volume-speed functions.

Table 5.12 Maximum and Extended Assignable Volumes For HCM94 Functions

Volume-Speed Functions	Capacity (pcphpl)	Assignable Volume(pcphpl)	
		Extended	Maximum
Freeways			
Orginal BPR	1,500	4,200	5,700
Mod. BPR-HCM94	2,300	2,576	4,876
Overgarrd's-HCM94	2,300	1,173	3,473
Arterials			
Orginal BPR	600	1,680	2,280
Mod. BPR-HCM94	800	600	1,400
Overgarrd's-HCM94	800	237	1,037
Multi-lane Highways			
Orginal BPR	1,500	4,200	5,700
Mod. BPR-HCM94	2,000	5,300	7,300
Overgarrd's-HCM94	2,000	2,001	4,001

In summary, the HCM94 curves had significant impact on both the assignment performance and the vehicle emission estimates. For the volume-speed functions at the v/c ratio < 1.0, the changes were controlled by the HCM94 defined volume-speed curves. The HCM94 curves produced higher speed estimates and thus influenced the amount of pollutants estimated. For the volume-speed functions at the v/c ratio > 1.0, the changes were controlled by the base mathematical functions which caused larger extended assignable volumes as well as higher NVSFIVs. As a result, both portions of the volume-speed functions had moderate to high impacts on the assignment performance as well as vehicle emissions.

5.6.4 Comparison on VMT Distribution Between Facilities

The air quality assessment on the vehicle emissions needs to look at both overall emission levels and the emission distributions between facility types. When comparing the distributions of system performance measures and vehicle emission estimates between two major highway groups: freeway/expressway versus major/minor arterials, differences were discovered. Figures 5.16 through 5.19 exhibit the VMT, speed, CO and NOx distributions for all five of the volume-speed function test cases. For the VMT, the HCM94 functions produced about a 10% higher freeway VMT and a 10% lower arterial VMT than the HCM85 functions and the original BPR functions. By contrast, the system VMT among all five test cases differed by less than 1.5%. The HCM85 volume-speed functions resulted in a relatively even distribution of VMT between the two highway groups, while the HCM94 functions tended to have a larger percentage share of freeway VMT. When considering the speed, the Overgarrd's-HCM85 functions resulted in the lowest speeds of all for both facility types, while the modified BPR-HCM94 functions achieved the

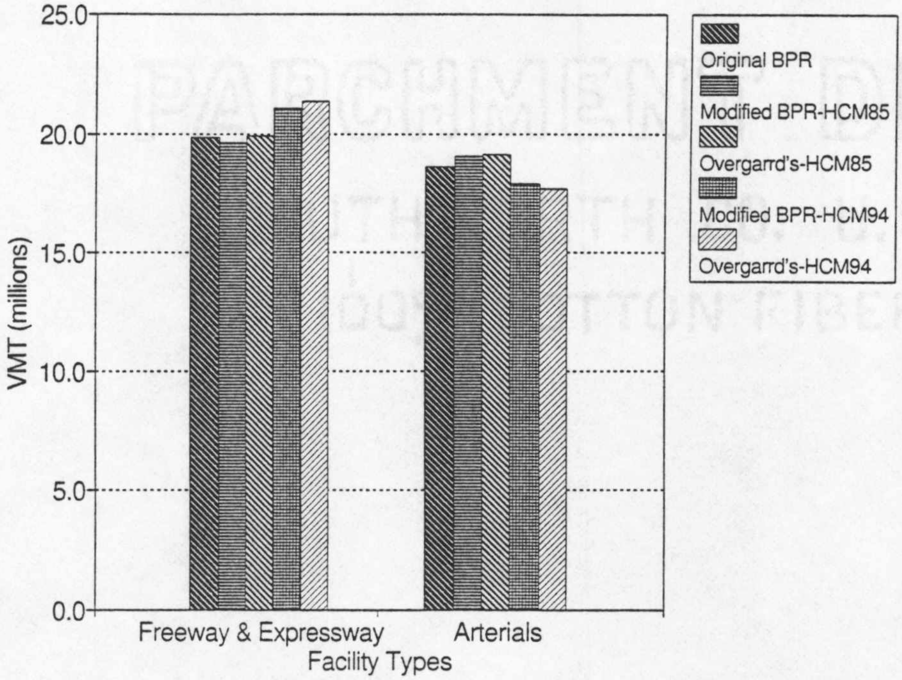

Figure 5.16 VMT Distribution Changes Between Highway Facilities

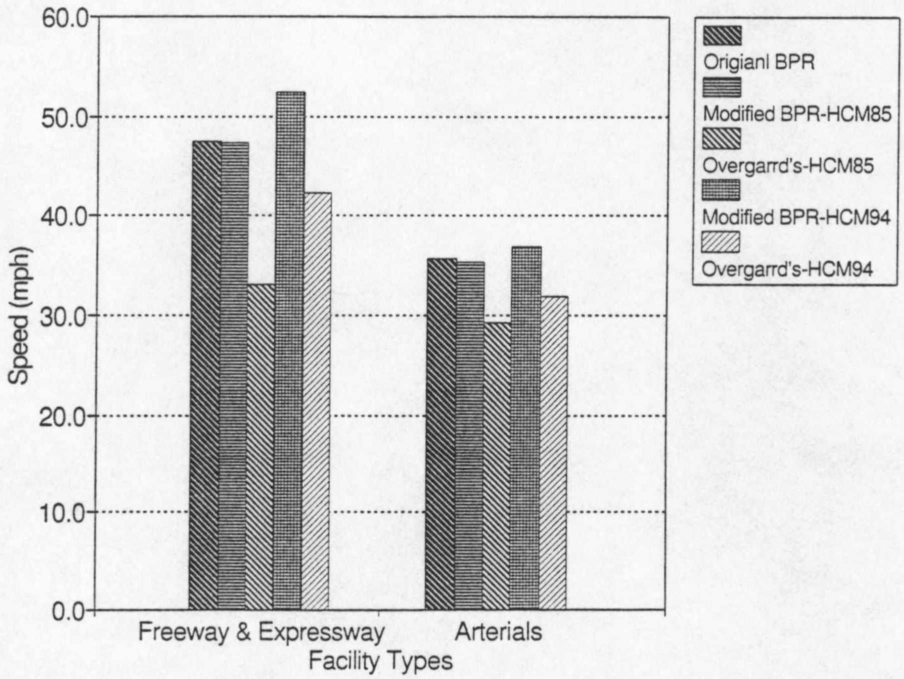

Figure 5.17 Speed Distribution Changes Between Highway Facilities

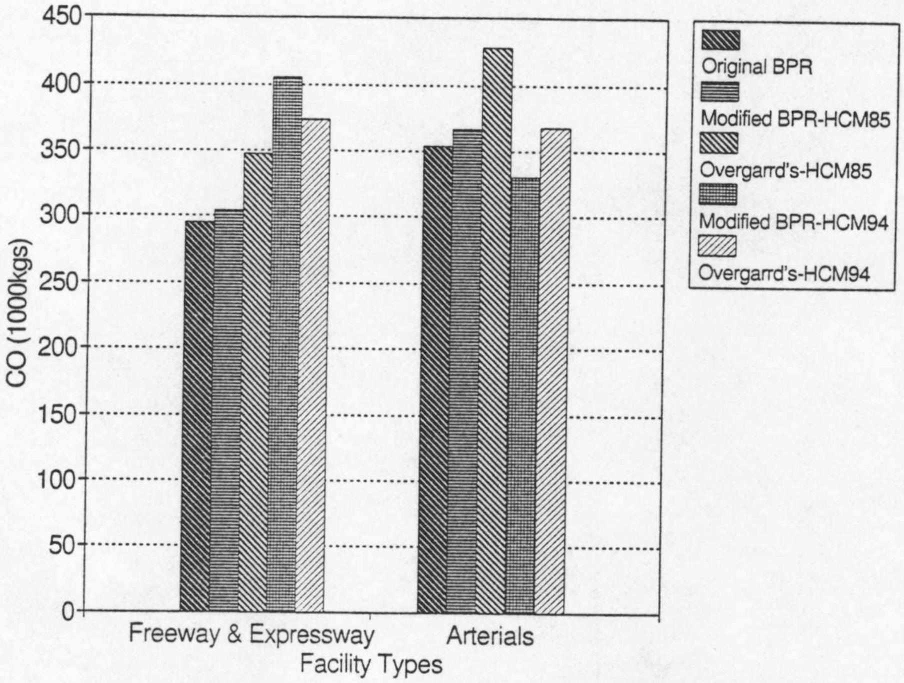

Figure 5.18 CO Distribution Changes Between Highway Facilities

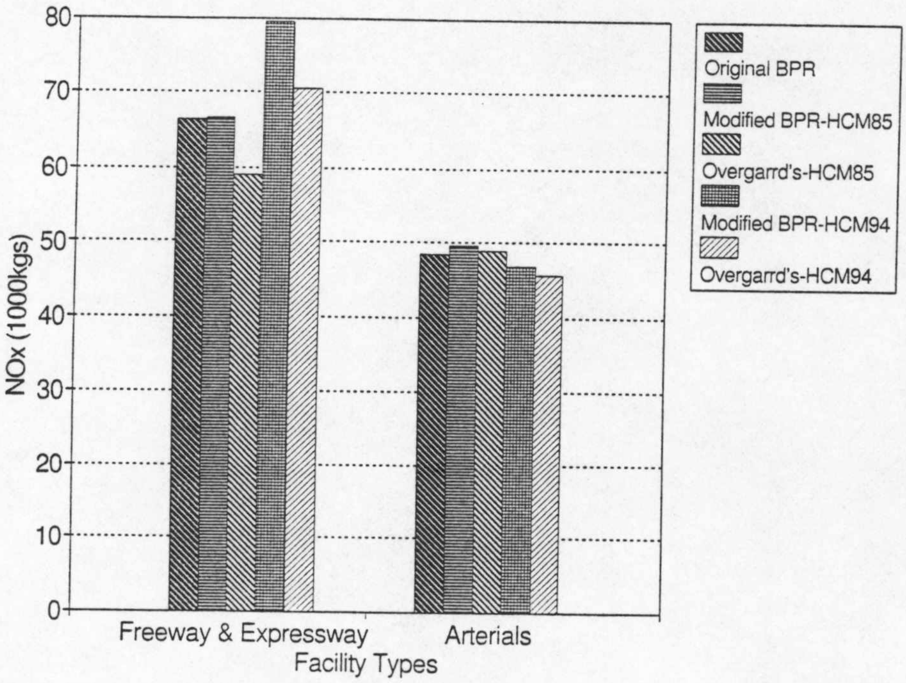

Figure 5.19 NOx Distribution Changes Between Highway Facilities

highest. The speed differences reached 20 mph or 59% for freeways and 8 mph or 28% for arterials. The distribution changes of VMT and speeds caused very large variations on vehicle emission estimates for both facility groups. For the CO, the variation was more than 30% for each facility type which accounted to about 100,000 kilograms daily. Among the distinct volume-speed functions, the original BPR function delivered the lowest overall CO estimates, while the Overgarrd's-HCM94 functions yielded even distributions between facilities. For the NOx, all five test cases presented slightly different estimates on arterials, but a very large discrepancy (30% or 20,000 kilograms) for freeways.

5.7 Chapter Summary

In this chapter, the research first reviewed the HCM85 and HCM94 volume-speed curves and created their mathematical expressions. A NVSFIV function and its numerical solution were developed to evaluate the volume-speed function performance. After the test design and tests, the results of experiments were analyzed for Denver case study. The analysis emphasized the volume-speed function performances and the impacts on emission estimates. The study defined the maximum assignable volume and the extended assignable volume to assist evaluating the volume-speed function performances. The volume-speed function development criteria, the emission sensitivity to the VMT and speed, the VMT distribution patterns between facility types, and vehicle emission differences were also discussed. Finally, the HCM94 curves' performances were assessed.

The findings of this chapter are summarized as the following:

1. According to traffic flow theory, traffic does not exist when the v/c ratio is greater

than 1.0. Due to the algorithm requirement, traffic has to be assigned under the v/c ratio > 1.0 condition in the existing UTP model capacity-restraint assignment procedure. The NVSFIV and the extended assignable volume were developed to evaluate the assignment performance of different volume-speed functions under the v/c ratio > 1.0 condition. The HCM85 and HCM94 function based assignments produced a more realistic volume-speed relationship that reflected traffic flow pattern than the original BPR volume-speed function based assignment. Among different mathematical base functions, the Overgarrd's base function is recommended for assignment since it achieved the smallest NVSFIV and extended assignable volume in the test.

2. Assignments with different volume-speed functions needed different numbers of iterations to allow the assignment to reach convergency status. The relative percentage error was used as a measure to monitor the convergency status and determine the termination of assignment. An error margin of 0.5 % was considered as a practical value to end the assignment process. When the network congestion level increases significantly, the number of iterations required should be changed accordingly. Under Denver test case condition, which reflected a moderate congestion, the number of iterations for the equilibrium assignment should be no fewer than 10.

3. For the two HCM85 volume-speed function based assignments, the system performance measure VHT and speed varied considerably (28.5% and 21.9%, respectively), and naturally, the vehicle emission estimates changed, too. The HC and CO estimates had 15% and 14% changes and NOx had a moderate 7% change. It was the speed that played an important role in determining final

emission estimates, while impact of VMT was secondary. In the test cases, about 15% of the CO change was due to the impact of the speed variation while only 1.5% of CO change was caused by the VMT variations.

4. The HCM94 curves generated higher speed estimates on freeways and multi-lane highways than the HCM85 based volume-speed functions. When changing the volume-speed curves, although the total VMT estimates varied less than speeds, it was observed that a considerable amount (up to 10%) of VMT shifted among facility types, therefore, the model volume and speeds should be re-validated against the road counts when implementing different volume-speed functions.

5. The NVSFIVs at the v/c ratio > 1.0 for the HCM94 freeway volume-speed functions developed in this research were larger than those for HCM85 functions. These values were controlled by the shape of the original HCM94 curve at the v/c ratio interval (0,1), the curve fitting technique, and the selection of base mathematical function. The selection of base mathematical function played a critical role. A better method to define the base mathematical function and to minimize the NVSFIV in the v/c ratio > 1.0 area for future volume-speed function development under the capacity-restraint assignment procedure is needed.

CHAPTER SIX

IMPACT OF TIME-OF-DAY STRATIFICATION

6.1 Study Approach

In the previous two chapters, the different assignment algorithms and volume-speed functions were discussed. The purpose of this chapter is to explore how stratification of assigned trips to a highway network affects the system performance measures, and indirectly influences the vehicle emission estimates. The temporal change of trips in the traffic assignment is done through time-of-day (TOD) stratification.

The time-of-day stratification does not belong to any particular step the traditional four steps of the UTP model. It can be done at different stage of the four step modeling process, pre-distribution or post-distribution. In the Denver regional model, the stratification serves as a mid-step between the modal split and the traffic assignment steps to transform the all-day trip table into several sub-tables by time periods. The assignment is then performed for each time period. Since this process has a direct influence to the way the assignment process executed, this research categorized the stratification as an important element of traffic assignment procedure.

There is no formal process involved in early modeling practice. Eight to 12 percent of the trips in an origin-destination table are assigned to the network with hourly link capacity. Then the program converts the assigned link volume back to an all-day volume by using the same percentage factor. This is still used by many planning agencies. The stratification process in the Denver regional travel model has three functions:

1. Transpose the home based trip P–A tables into all–day O–D trip tables;
2. Divide all–day O–D tables into several time period O–D tables, such as am peak, pm peak, etc.; and
3. Convert person trips into vehicle trips.

Within these three functions, the first and second functions play a critical role to affect the outcome of the assignment. Therefore, the study on the impact of different stratifications will focus on these two functions.

Recently, it was suggested that a higher time resolution assignment, such as 24 hourly assignments instead of a 24–hour combined single period assignment, would give improved assignment results[19]. During a 24–hour period, the temporal distribution of traffic in a highway system varies from time to time and from area to area. It is, therefore, expected that a multitude of time periods in the assignment would be helpful to better reflect the temporal distribution of traffic. Of course, the system performance of a multi–period assignment would differ from a one period assignment. The purpose of this stratification impact study was to identify the differences on system performance measures and the estimates of air quality model due to different time–of–day stratifications using Denver as a case study. Specifically, the research focused on issues such as system performance changes, the VMT and speed distribution changes among facility types, and the change of vehicle emission estimates.

The research approach consisted of three tasks. The first was to define the temporal distribution of trips. The second was to design and perform several tests on different processes, and the third was to analyze the test results on both system performance and vehicle emission estimates. Reflecting the current practice and research developments, three tests were selected to test the influence of time-of-day stratifications:

1. a single period assignment,
2. a three period assignment, and
3. 24 hourly assignments

6.2 Temporal Distribution of Trips

In general, the temporal distribution of trips can be characterized into three types. The Type I is an origin-destination and trip purpose temporal distribution. It is a set of distributions that exhibits the change of the O-D distribution pattern during a 24 hour period by trip purpose. The information to construct such distributions are often obtained from an O-D survey. For example, different trip purposes, such as work trips and shopping trips do not usually have the same trip making time. Also the people with the same work trip purpose have different trip lengths and work schedules resulting in different trip starting and ending times at different origins and destinations.

Type II is the traffic volume related distribution. For example, traffic observations on different types of highway facilities and different area types display differences over a 24 hour period. Type II distribution reflects the result of a mixed type I distribution on the streets.

The third type, Type III, is a distance weighted Type II distribution. In transportation modeling, Type III is used to estimate the VMT during a certain period of the day. Type III reflects a general trend of Type II and indirectly shows the Type I distribution characteristics. In other words, Type II distribution serves as a result of Type I distribution and a source of Type III distribution. Figure 6.1 graphically shows a typical Type III distribution over 24-hour period. The bar shows the percentage of VMT over all-day for a specific hour. The sum of 24 hourly VMT percentage factors is 100. As expected, the graph displays two humps for am and pm peak periods, and the morning peak is steeper than the one in the afternoon. Due to the nature of the UTP model, the description of temporal distributions of trips is not available on an individual trip-making basis. Instead,

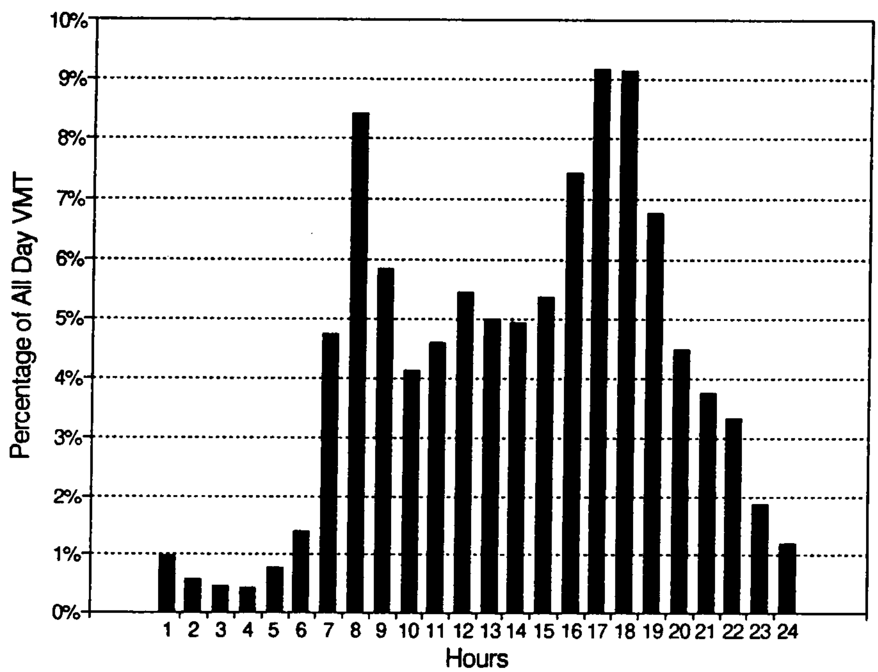

Figure 6.1 VMT Distribution Over 24 Hour Period

a time-of-day stratification is used as a tool to model the distributions in an aggregated manner. In addition, the time-of-day stratification is a very extensive term, as it could mean any of the three types of distribution used in the UTP model.

6.3 Test Plan

6.3.1 Test Environment

Three test cases were studied to investigate the impact of time-of-day stratification. Case 1 used a single period assignment technique, case 2 used a three period assignment, and case 3 used 24 hourly assignments. To maintain a uniform test environment, the capacity-restraint equilibrium assignment method was used for all three test cases. Based on the conclusion derived in Chapter Five, 15 iterations were applied for each assignment. The O-D tables maintain the same amount of trips as used in the previous two chapters. As recommended in Chapter Five, the Overgarrd's volume-speed functions generated from the HCM85 curves were applied for three test cases. The MINUTP's NETMRG, MATRIX, and ASSIGN modules were the major programs used in this study. Displayed in Figure 6.2 is the test plan for the time-of-day stratification.

6.3.2 Single Period and Three Period Assignments

The single period assignment utilized the equilibrium assignment with the Overgarrd's HCM85 volume-speed functions used in the Chapter Five. The all-day O-D table was converted to a single-hour table with a factor of 9%. This was done through defining a special variable, PCTADT, used in the MINUTP ASSIGN program, to 9. After this equilibrium assignment, the link volumes resulting from this one hour single period assignment were converted back into all-day link volumes.

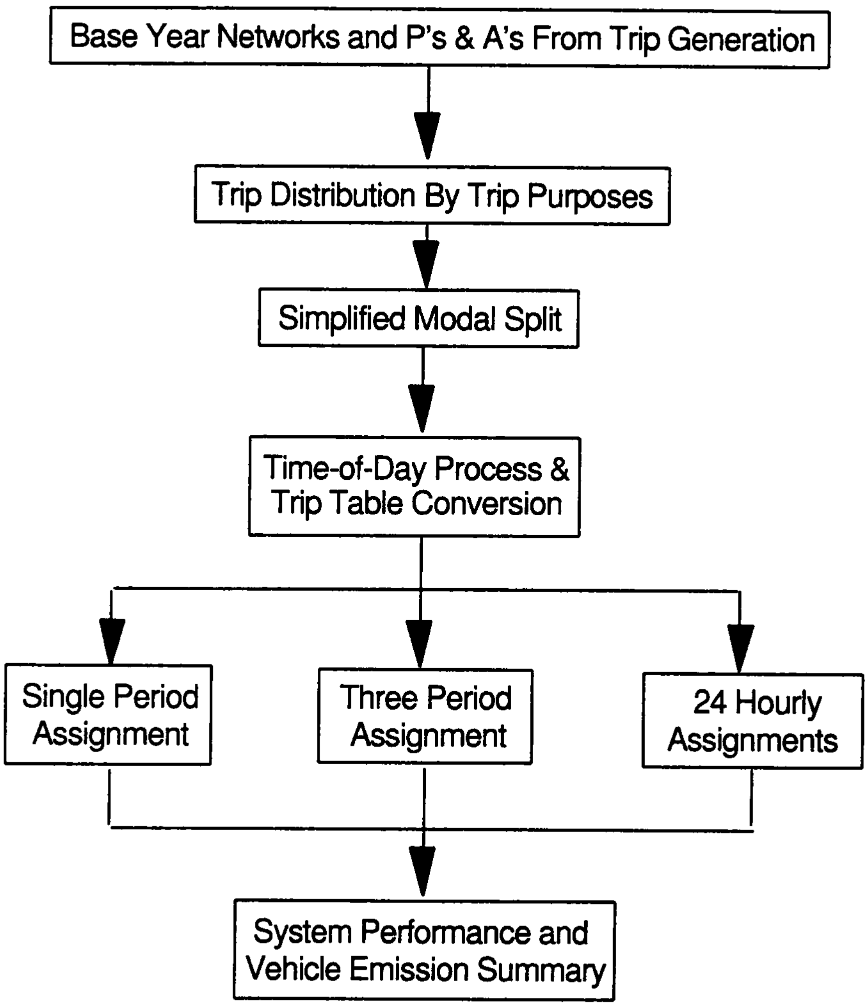

Figure 6.2 Test Plan on Time-of-Day Stratifications

The second case consisted of an am peak, pm peak and off peak three period assignments. The temporal distribution information was obtained from the Denver regional travel model. Before performing the assignment procedures, the all–day trip tables with different trip purposes were converted into three period trip tables. This conversion process used information generated by the 1985 Denver O–D survey, and considered two major travel characteristics. The first was unbalanced trip making which meant that the trips to and from a zone were not equal during a certain time period. The second was that different trip purposes had a different temporal distribution over 24 hours. For example, the traffic volume contained more home–to–work trips (production to attraction) than from work–to–home trips (attraction to production) during the morning peak, and there were fewer non–work trips during the peak periods.

Based on an O–D survey and field traffic observations, a method was developed for the Denver regional model to describe the Type I distribution by trip purpose and the Type III VMT distribution. Based on the Type I and Type III distribution facts, the all–day trip tables (P–A tables for home based trips and O–D tables for non–home based trips) were divided and converted into the tables for the three time periods. In MINUTP, the conversions were done through a series of MATBAL and MATRIX programs specially designed for trip table transposing and factoring. Seven trip purposes were involved in this process. Table 6.1 shows two trip purposes as an example of the conversion factors used in the three period assignment test case. This trip table manipulation process can be described as the following by using am peak period HBW and NHB trip purposes as an example.

Table 6.1 Examples of Trip Table Conversion Factors

Period Percent (%)	Home-Based Work		Non-Home Based
	From Home Production	To Home Attraction	All
AM Peak Period	30.7	0.3	3.9
PM Peak Period	3.5	30.0	26.5
Off Peak Period	21.8	13.8	69.6
Total	55.9	44.1	100.0

Note:
AM Peak: 6:30-8:30
PM Peak: 15:00-18:30
Off Peak: Rest of the Day

1. Multiply all-day HBW P-A trip table by 0.307 to create matrix one;
2. Multiply all-day HBW P-A trip table by 0.003 to create matrix two;
3. Transpose matrix two for reverse direction HBW trips during the am peak;
4. Add matrix one and transposed matrix two to create am peak HBW O-D trip table;
5. Multiply all-day NHB trip table by 0.039 to create am peak NHB O-D trip table.

Notice that the HBW trip purpose has different factors for the productions and the attractions, while the NHB trip purpose only has a single factor for both the origin and destination.

Similar to the single period assignment, each of the three periods had a PerCenT Average Daily Traffic (PCTADT) variable defined by the MINUTP program. This PCTADT variable indicated the highest one hour link volume factor for that respective period. The MINUTP program used this PCTADT variable to internally construct an O-D table to be used in each period of the assignments. Obviously, the variable PCTADT here did not mean "percentage of ADT" which was true in the single period assignment case. Instead, it referred to the percentage of trips of the period under discussion. Table 6.2 displays the MINUTP defined PCTADT variables used in the three period assignment case. The PCTADT=57 meant the highest one hour had 57% of the link volume for the two hour morning peak period. For pm peak period, the conversion factor 34.9 meant the peak one hour had about 35% of the volume that occurred during the three and half hour afternoon peak period. During the off peak period, the highest one hour appeared at 12:30 to 13:30 which represented 9.8% of the 18.5 hour off peak period link volume in the system. Finally, the program converted the one hour link volumes into period volumes and reports the VMT and VHT by facility type and area type. The all-day VMT and VHT were then summarized from the three periods.

Table 6.2 Percent ADT Factors in Three Period Assignment

Periods	a.m. Peak	p.m. Peak	Off Peak
Duration	6:30-8:30	15:00-18:30	Other
Highest One Hour	7:00-8:00	16:30-17:30	12:30-13:30
No. of Hours	2.0	3.5	18.5
PCTADT	57.0	34.9	9.8
Examples			
Hourly Link Volume	570	349	98
Period Link Volume	1000	1,000	1,000

6.3.3 Twenty-four Hourly Assignments

The third case demonstrated a 24 hourly assignments procedure. In this case, the all-day trip tables were converted into 27 sub-tables to reflect an hourly distribution of trips. In order to maintain the Type I distribution properly, the creation of hourly trip tables were based on the trip tables generated from the three period assignment case. Since more detailed Type I distribution information was not available, the Type III distribution data was used to segregate by time period. The Type I and Type III distributions were different but related. If there were a large difference in the directional movement by time of day, the Type I distribution could not be replaced by the Type III distribution. In the study case, the trip tables in the three period assignment case were already transformed into three periods with the Type I distribution information, therefore, the majority of the trip directional split problem was solved. In the 24 hourly assignments case, the trip table conversion was to further divide the existing trip tables used in the three period assignment case into a higher resolution (24 periods versus 3 periods). Three assumptions were made for the 24 hourly assignments time-of-day stratification:

1. The Type I trip directional distribution did not vary significantly within each period;
2. The number of trips generated within each hour was roughly proportional to the VMT generated in that hour;
3. Most of the trips started and ended within one hour, and the number of trips that crossed in and out of the time boundary were balanced.

With these assumptions, the hourly trip tables in the 24 hourly assignments case were generated by simply factoring the am, pm, and off peak tables. In most of the tables, an hourly unit was adopted, but at the beginning or at the end of the same time periods, an half hour trip table was created and expanded to an hourly basis, since assignment could only be performed by using an hourly unit. The resultant VMT and VHT were then converted back to half hour situations. Figure 6.3 is a flow chart of the trip table conversion process. The am period trip table was divided into three trip tables since it had a two-hour morning peak period ranging from 6:30 to 8:30 am with the highest one-hour appearing from 7:00 to 8:00 am. The pm peak O-D tables were divided into three one hour trip tables plus a half hour table, since the pm peak lasted three and half hours. The off peak trip table was treated similarly. Table 6.3 lists all the time-of-day factors used in the test cases.

6.3.4 Test Result Aggregation Scheme

Same as the summary method used in the two previous chapters, after assignments were performed for three test cases, the link volume, link travel time were summarized by area type and facility type for single period assignment to obtain VMT, VHT and speed. For the three period assignment, the link volume, travel time and speed were summarized by am, pm, and off peak periods in addition to the facility type and area type. For the 24 hourly assignments, this summary is done by each time period as well. The summarized disaggregated speeds were then imported into MOBILE5A model to produce emission rates for three pollutants: CO, HC, and NOx. Finally, the emission rates generated were multiplied by their corresponding VMT to generate emission estimates for each facility type, area type and time period. The emission estimates used in the analysis were aggregated from those discrete emission estimates.

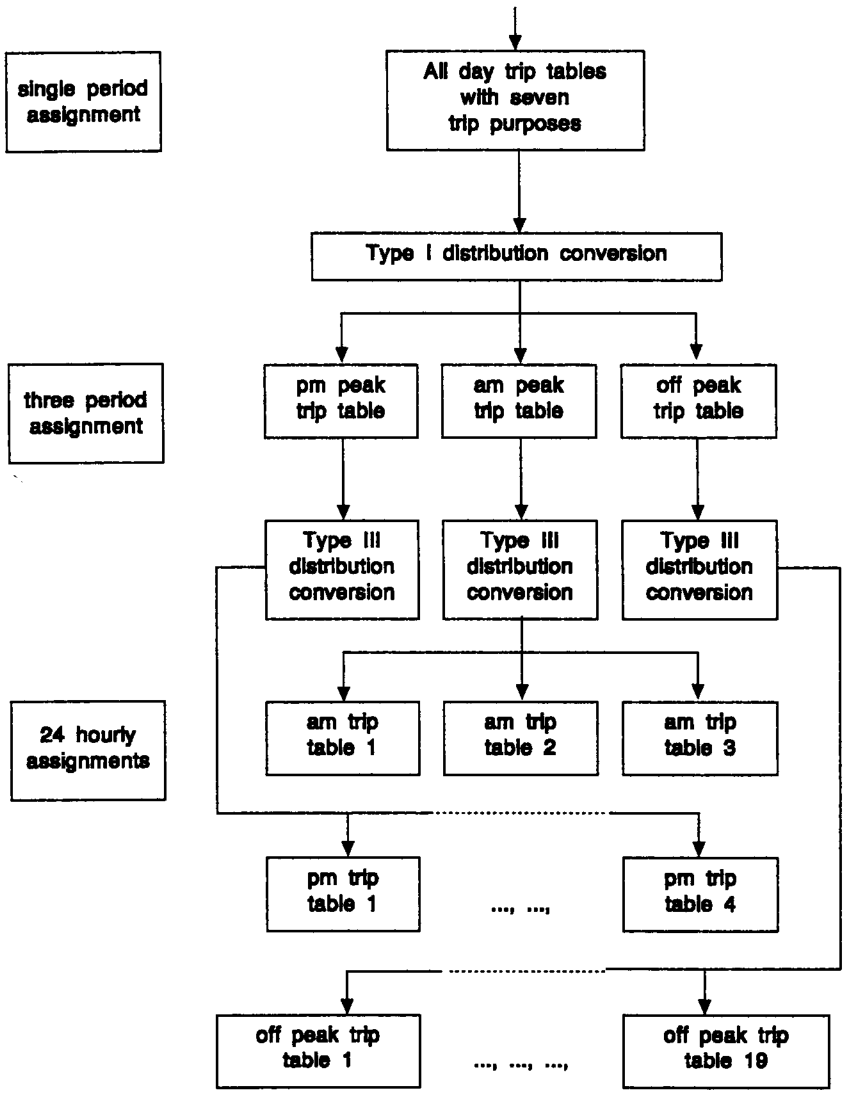

Figure 6.3 Trip Table Conversion Process

Table 6.3 Time-of-Day Factors in 24 Hourly Assignments

AM Peak		PM Peak			
Periods	TOD Factor	Periods	TOD Factor		
6:30-7:00	0.218	3:00-3:30	0.121		
7:00-8:00	0.570	3:30-4:30	0.279		
8:00-8:30	0.212	4:30-5:30	0.349		
		5:30-6:30	0.251		
Total	1.000	Total	1.000		
Off Peak					
Period I	TOD Factor	Period II	TOD Factor	Period III	TOD Factor
0:00-1:00	0.019	8:30-9:30	0.086	18:30-19:30	0.097
1:00-2:00	0.011	9:30-10:30	0.075	19:30-20:30	0.065
2:00-3:00	0.010	10:30-11:30	0.081	20:30-21:30	0.065
3:00-4:00	0.009	11:30-12:30	0.087	21:30-22:30	0.044
4:00-5:00	0.017	12:30-13:30	0.096	22:30-23:30	0.026
5:00-6:00	0.031	13:30-14:30	0.084	23:30-0:00	0.010
6:00-6:30	0.036	14:30-15:00	0.049		
Sub-Total	0.133		0.559		0.308
Total	1.000				

6.4 Analysis of Test Results

6.4.1 Assignment System Performance

Table 6.4 shows the three major system performance measures (VMT, VHT and speeds) for each of three test cases. In general, three assignment cases produced only slightly different VMT estimates, which was largely due to a fixed O-D table pattern for all three test cases. However, the estimation of VHT and speed showed notable distinctions. The three period assignment produced the highest VHT and the lowest speed estimates, while the 24 hourly assignments case generated the lowest VHT and the highest average speed. The differences between three period assignment and 24 hourly assignments for all-day VHT and the average speed estimates were about 20%. The single period assignment case produced very similar VHT and speeds to the three period assignment case.

Table 6.4 System Performance Measures for Three Test Cases

System Performance	Assignment Types		
	Single Period	Three Periods	24 Hourly
VMT (millions)	40.95	41.49	41.09
VHT (millions)	1.32	1.39	1.14
Speed (mph)	30.92	29.91	36.09

It must be noted that the VHT and speed estimates in the single period assignment case could vary considerably if the percentage ADT factor used in the ASSIGN module has moderate change. For example, a separate test proved that the final system speed decreased by as much 25% if the peak hour percent ADT factor was altered from 9% to 10%.

To compare the system performance by time period, the results from the 24 hourly assignments were combined into three periods. Table 6.5 lists the VMT, VHT and speeds produced by the three period and 24 hourly assignments cases and their relative percentage difference. It was clear that the speed and VHTs in the am and pm peak periods differed between the two cases, especially for the am peak. The two test cases also demonstrated that peak VHT reduced from 927 thousand hours to 692 thousand

Table 6.5 A Comparison of Three Period and 24 Hourly Assignments Performance

	3 Period	24 Hourly	Difference	% Diff
VMT (1000s)				
AM Peak	7,703	7,567	(136)	-1.8%
PM Peak	12,411	12,174	(237)	-1.9%
Off Peak	21,373	21,353	(20)	-0.1%
All Day	41,487	41,093	(394)	-0.9%
VHT (1000hrs)				
AM Peak	492	342	(149)	-30.4%
PM Peak	436	349	(86)	-19.8%
Off Peak	459	447	(13)	-2.8%
All Day	1,387	1,139	(248)	-17.9%
Speed(mph)				
AM Peak	15.7	22.1	6.4	41.1%
PM Peak	28.5	34.8	6.4	22.4%
Off Peak	46.5	47.8	1.3	2.7%
All Day	29.9	36.1	6.2	20.7%

hours by utilizing the higher resolution 24 hourly assignments. This gain was translated into a 20%–40% increase in speed for the peak periods. This presented a substantial change in the CO estimates which are analyzed later in this chapter. For the VMT, the difference between the three period assignment and the 24 hourly assignments was small (0.9%), but the peak VMT showed a larger change than the off peak period (0.9% versus 0.1%).

Two reasons were explored to explain the test differences. The first was that the three period assignment selected the worst one–hour congestion situation which represented the whole period performance, while the 24 hourly assignments case used separate time–of–day factors to simulate different congestion levels. As a result, the 24 hourly assignments produced much higher system speeds and lower VHT estimates. For the

VMT estimates, a lower congestion level made it easier for the algorithm to find shorter paths, so the 24 hourly assignments case delivered slightly lower VMT estimates during the peak periods. In fact, three assignments presented very different speed distributions during a 24 hour period. Figure 6.4 shows the impact of the three assignments on the speeds.

The second reason was the property of volume-speed curves. During the off peak period, most of the vehicles operated under an uncongested highway situation corresponding to the flat part of the volume-speed curve (v/c ratio < 0.8). In the three period and 24 hourly assignments cases, therefore, the VHT estimates demonstrated a less than 3% difference in speed and VHT during the off peak assignment.

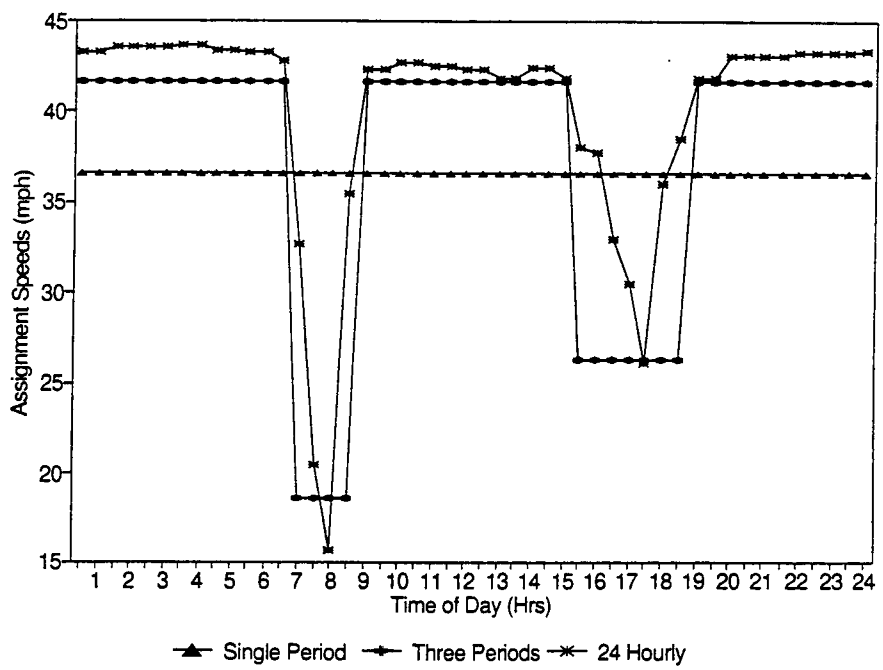

Figure 6.4 Assignment Impacts on Estimated Average Speeds

6.4.2 Vehicle Emission Estimates

In general, the single period assignment had a considerably lower emission for all three pollutants. For example, the CO estimates from the single period assignment case were about 200,000 kilograms less than the three period assignment case. This figure was about 1/5 of current Denver regional CO budget. Although the system average speeds between the single and three period assignment cases did not show large differences, the distribution of VMT and speed between the facility types played a critical role in determining the emissions. This impact is discussed in a later section. For the same reason, the HC and NOx estimates showed 10.5% and 14% differences between the single period and the three period cases.

When comparing system vehicle emission estimates of the three period and 24 hourly assignments cases, the 24 period case produced 14% lower HC and 11.1.% lower CO emission estimates. In practice, these changes were considered as a large decline on emission estimates, especially for cities like Denver which struggles to meet the air quality conformity tests. But for the NOx, the 24 period case generated a 2.9% higher emission, changing from 131.3 thousand kilograms to 135.1 thousand kilograms. Table 6.6 presents the system emission estimates for three test cases.

When the emissions are compared by time period, Table 6.7 reveals that large emission estimates changes occur during the peak periods, especially for the am peak period. By comparing the 24 period assignment case to the three period assignment case, a 26% reduction was observed for both HC and CO estimates during the peak period, while only 2% and 7% changes were found for the HC and CO during the off peak period. Because

Table 6.6 Vehicle Emission Estimates for TOD Stratification Tests

Vehicle Emission Estimates	Assignment Types		
	Single Period	Three Periods	24 Hourly
HC (1000 kgms)	88.0	98.3	84.0
CO (1000 kgms)	825.8	1,018.9	905.6
NOx (1000 kgms)	112.8	131.3	135.1

Table 6.7 Vehicle Emission Estimates: Three Period and 24 hourly Assignments

	3 Period	24 Hourly	Difference	% Diff
HC (1000kgms)				
AM Peak	28.6	18.0	(10.7)	-37.3%
PM Peak	29.6	25.3	(4.3)	-14.6%
Off Peak	40.0	40.8	0.8	1.9%
All Day	98.3	84.0	(14.2)	-14.5%
CO (1000kgms)				
AM Peak	282.7	172.7	(110.0)	-38.9%
PM Peak	280.9	243.7	(37.1)	-13.2%
Off Peak	455.4	489.2	33.9	7.4%
All Day	1,018.9	905.6	(113.2)	-11.1%
NOx (1000kgms)				
AM Peak	21.8	21.9	0.1	0.3%
PM Peak	34.8	35.9	1.1	3.2%
Off Peak	74.8	77.3	2.5	3.3%
All Day	131.4	135.1	3.6	2.8%

its emission rate was not as sensitive to speed as the other two pollutants, NOx had only about a 3% change between the three period and 24 hourly assignments cases for both peak and off peak periods.

6.4.3 Emission Sensitivity to the VMT and Speed

For vehicle emissions, the three cases presented quite different estimates. Wide variations of the three major pollutant estimates were noticed. Both the three period and 24 hourly assignments cases were compared to the single period assignment case to see which performance measure, VMT or speed, would have a larger impact on the emission estimates. The analysis showed that the system VMT deviations caused only a 0.3%–1.3% change in the vehicle emission estimates among the three test cases. The speeds, however, caused a 4%–10% change in HC, a 9%–22% change in CO, and a 15%–20% change in NOx estimates. This again proved that speed played a major role in the assignment process with different time-of-day factors. For the peak periods, the analysis indicated that the VMT differences caused less than a 2% change in all three pollutant estimates, while the speed impact accounted for a 10%–35% difference in HC and CO estimates.

6.4.4 Impact of VMT Distribution

The VMT, VHT, speed, and the vehicle emission estimates for each test case were summarized by two facility groups for a better understanding of the test results. Freeways and expressways formed one group, and major and minor arterials became another group. Figures 6.5 to 6.8 display the VMT and the speed distributions among the two facility groups as well as the CO and NOx emission distributions.

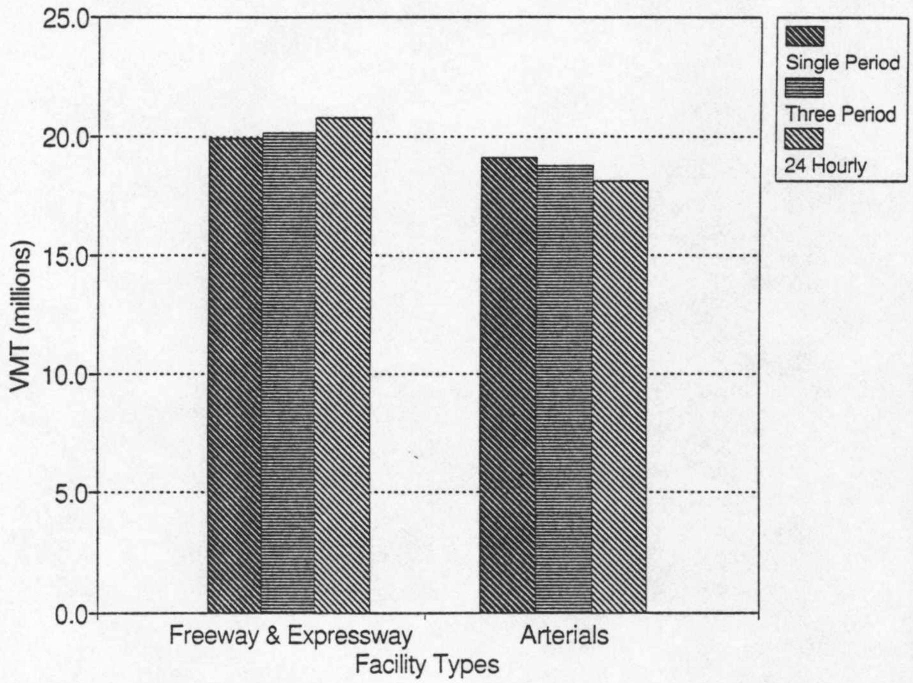

Figure 6.5 VMT Distribution Changes: Different TOD Stratifications

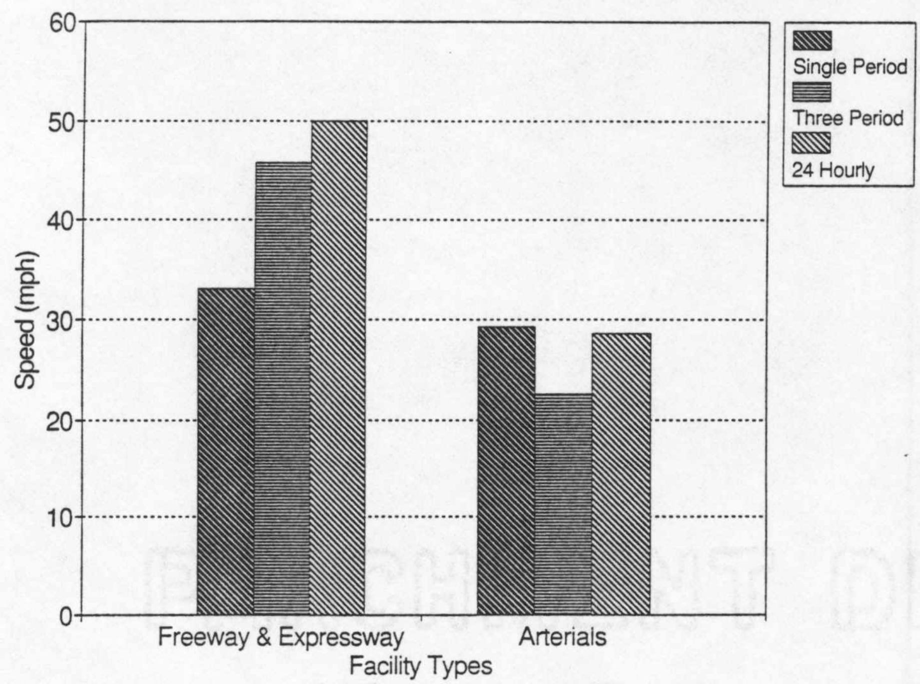

Figure 6.6 Speed Distribution Changes: Different TOD Stratifications

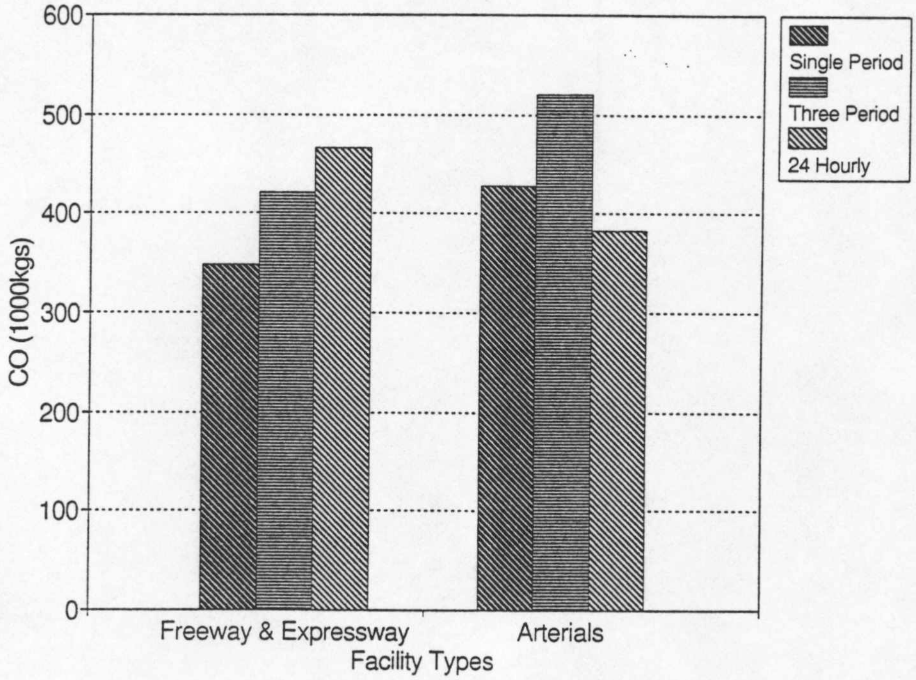

Figure 6.7 CO Distribution Changes: Different TOD Stratifications

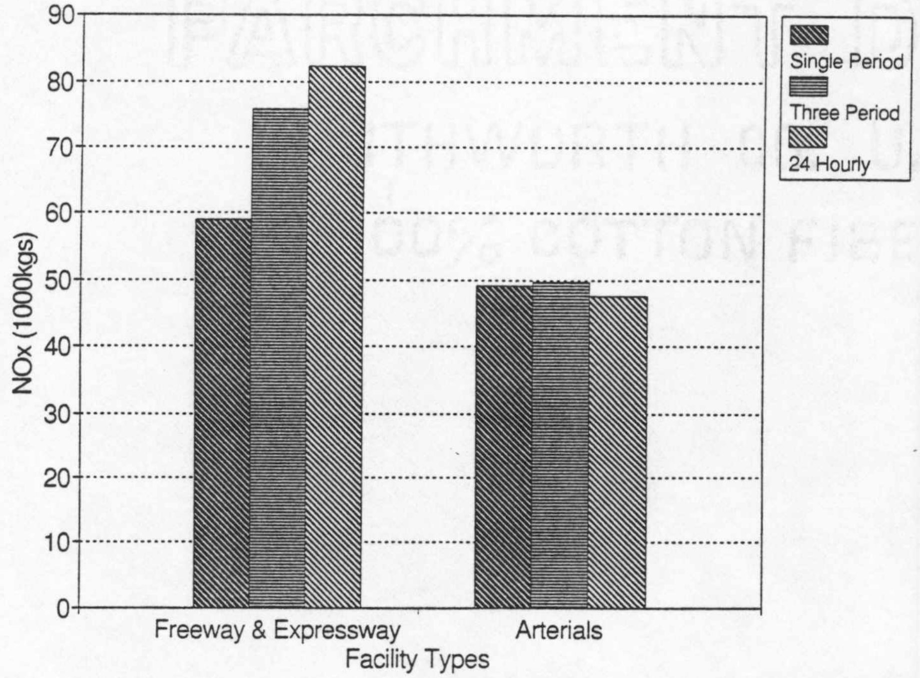

Figure 6.8 NOx Distribution Changes: Different TOD Stratifications

For the VMT, it was observed that the variations among the test cases of both groups were in a 5% range. The 24 hourly assignments case produced the highest VMT on the freeway group and the lowest on arterials, although the overall VMT did not vary much. The single period assignment case had more evenly distributed VMT between two groups. For the speed, large variations were also observed. Compared to the single period case, the three period and 24 hourly cases both displayed large increases of 13 to 17 mph on freeways. This exhibited that the freeway in the single period case experienced higher congestion and the traffic had to divert to other facility classes. The different O–D table split explained this discrepancy. The single period assignment used a factored combined all–day trip table while the three period and 24 hourly assignments used separated trip tables although the total number of trips was the same.

As a composite impact of both VMT and speeds, the HC emission from the arterials was reduced from the single period case's 55,000 kilograms to 40,000 kilograms (a reduction rate of 37%) for the 24 hourly case. The freeway group HC emission remained the same. For the CO estimates, the 24 hourly assignments case reversed the HC distribution trend between the two roadway groups and showed that the freeways generated a higher CO emission than the arterials. But the single period and three period assignment cases had the opposite reactions. They produced lower CO estimates on freeways and higher CO estimates on arterials. For the NOx, large differences (up to 40%) were noticed on the freeway facility and little difference on the arterials.

Besides the entire day VMT distribution variation, the VMT distribution variations for each individual period were also observed. Tables 6.8 and 6.9 produce two comparison reports

Table 6.8 Performance Measures and Vehicle Emission Distribution by Facilities

Peak Period: Three Period and 24 Hourly Assignments

Facilities	Peak VMT (1000 miles)			Peak VHT (1000 hrs)			Peak Speed (mph)		
	3 Period	24 Hourly	% Change	3 Period	24 Hourly	% Change	3 Period	24 Hourly	% Change
Freeways	7,558	7,999	5.8%	187	178	-4.7%	40.4	44.9	11.0%
Expressways	926	937	1.1%	49	37	-25.2%	18.8	25.4	35.2%
Maj. Arterials	6,626	6,480	-2.2%	291	225	-22.7%	22.8	28.8	26.5%
Min. Arterials	3,272	2,973	-9.1%	318	194	-38.9%	10.3	15.3	48.7%
Local Roads	1,732	1,353	-21.9%	83	58	-30.2%	20.9	23.4	11.8%
TOTAL	20,114	19,741	-1.9%	928	692	-25.4%	21.7	28.5	31.6%
	Peak HC (1000 kgs)			Peak CO (1000 kgs)			Peak NOx (1000 kgs)		
Facilities	3 Period	24 Hourly	% Change	3 Period	24 Hourly	% Change	3 Period	24 Hourly	% Change
Freeways	12.5	12.8	2.6%	117.0	129.1	10.4%	23.6	27.2	15.0%
Expressways	2.5	1.9	-24.5%	25.1	18.2	-27.6%	2.7	2.7	0.4%
Maj. Arterials	17.1	13.5	-21.4%	165.8	126.8	-23.6%	16.7	16.5	-1.1%
Min. Arterials	20.1	11.0	-45.4%	198.7	103.9	-47.7%	9.4	8.1	-13.9%
Local Roads	6.0	4.1	-31.5%	57.0	38.5	-32.4%	4.3	3.4	-21.0%
TOTAL	58.2	43.2	-25.7%	563.5	416.4	-26.1%	56.7	57.8	2.0%

Table 6.9 Performance Measures and Vehicle Emission Distribution by Facilities

Off Peak Period: Three Period and 24 Hourly Assignments

	Off Peak VMT (1000 miles)			Off Peak VHT (1000 hrs)			Off Peak Speed (mph)		
Facilities	3 Period	24 Hourly	% Change	3 Period	24 Hourly	% Change	3 Period	24 Hourly	% Change
Freeways	10,522	10,747	2.1%	178	175	-1.3%	59.2	61.2	3.5%
Expressways	1,121	1,127	0.6%	26	26	-2.2%	42.5	43.7	2.9%
Maj. Arterials	6,365	6,190	-2.7%	159	152	-4.2%	40.1	40.7	1.6%
Min. Arterials	2,527	2,475	-2.1%	67	65	-2.9%	37.5	37.8	0.8%
Local Roads	838	814	-2.8%	29	28	-3.6%	28.9	29.2	0.8%
TOTAL	21,373	21,353	-0.1%	459	447	-2.8%	46.5	47.8	2.7%
	Off Peak HC (1000 kgs)			Off Peak CO (1000 kgs)			Off Peak NOx (1000 kgs)		
Facilities	3 Period	24 Hourly	% Change	3 Period	24 Hourly	% Change	3 Period	24 Hourly	% Change
Freeways	18.8	20.3	7.5%	261.5	301.6	15.3%	45.9	49.0	6.7%
Expressways	1.8	1.8	-0.7%	16.4	16.2	-0.9%	3.3	3.3	0.9%
Maj. Arterials	11.2	10.8	-3.7%	102.7	98.8	-3.7%	16.5	16.1	-2.6%
Min. Arterials	6.0	5.8	-2.7%	53.4	51.9	-2.7%	6.9	6.8	-2.0%
Local Roads	2.3	2.2	-3.4%	21.4	20.7	-3.4%	2.1	2.1	-2.8%
TOTAL	40.0	40.8	1.9%	455.4	489.2	7.4%	74.8	77.3	3.3%

for the three period and the 24 hourly assignments on both the system assignment performance measures and the vehicle emission estimates by peak and off peak periods. The reports demonstrate an even clearer picture on how traffic would divert when the system congestion level changes. It was also found that the peak period always had larger changes in the performance measures and emission estimates than the off peak period. The test results revealed that VMT generated from the 24 hourly assignments case had a tendency to shift from lower level facility classified roads to higher level roads, particularly during the peak period. For example, the 24 hourly assignments had only about 1.7% less overall VMT than the three period assignment case, but its freeway VMT was 5.8% (0.44 million) higher than the three period assignment case. Meanwhile, the lower grade roads suffered from a large decline of VMT in the 24 hourly assignments case. For instance, the minor arterials shifted 8%–10% of their VMT to other types of facilities, and the local roads changed even more. For the off peak period, the VMT shifting was not as obvious as it was during the peak. The VMT on the freeways in the 24 hourly assignments case increased only a moderate 2.1%, while the local roads VMT decreased only 2.8%.

Two possible reasons were used to explain this phenomenon. The first was the 24 hourly assignments use various time-of-day factors for different hours. For example, the am peak period trips loaded onto the network before and after the highest peak one hour, which is sometimes called the shoulder period, were only about 75% of the highest one-hour trip loadings. So the congestion in the network for this one-hour shoulder period was much less serious than using uniformed loading over the entire period. Therefore, the algorithm routed more trips on the freeways than on other lower class roads.

The second explanation was the shape of the volume–speed curve, or the absolute value of the first derivative of the volume–speed function. The Highway Capacity Manual provided a description of the volume–speed relationship on the v/c ratios less than 1.0. The characteristics of volume–speed function at the v/c ratio over 1.0 area depended solely on the type of mathematical base function selected. For the v/c ratio > 1.0 area, it was observed that the Overgarrd's HCM85 and the modified BPR–HCM85 speed curves were steeper on the freeways than on the arterials. And, the arterials were steeper than the multi–lane highways. This can be mathematically expressed as:

$$|f'_1(x)| > |f'_2(x)| > |f'_3(x)| \qquad x > 1.0 \qquad (6.1)$$

where, $f_1(x)$, $f_2(x)$, $f_3(x)$ are the volume–speed functions for freeway, arterial and multi–lane highway.

x is the v/c ratio.

Because of the different shapes of the curves, the speeds on arterials and multi–lane highways had lower decline rates, along with the increase of v/c ratio. This achieved a relatively shorter travel time under a congested network (v/c ratio around 1.0), so more trips were attracted to arterials and multi–lane highways. This caused VMT shifting among the facilities. During the off peak period, this VMT shifting was not as serious as during the peak period, because assignments operated under a much less congested situation.

In summary, the variations of system performance measures and vehicle emissions during the peak period were much larger than those during the off peak period. The change of the VMT and speed distributions among facility types was another critical factor in determining the overall vehicle emission levels.

6.4.5 Improved Off Peak Assignment

The 24 hourly assignments showed obvious differences on air quality results than the other two test cases. It was believed that this case had more reasonable estimates than the other two methods. However, it took considerably longer to prepare the program control files and to execute the program. In a planning agency, time is always critical to finish a certain task. In the research, a time-of-day factor average method was developed to reduce the number of off peak assignment periods and, at the same time, to maintain the same level of precision.

Figure 6.9 presents a curve describing the relationship between the off peak time-of-day factors and assignment speeds. In the test, it was also observed that the speed reduced gradually as the time-of-day factor value increased. A larger time-of-day factor produced

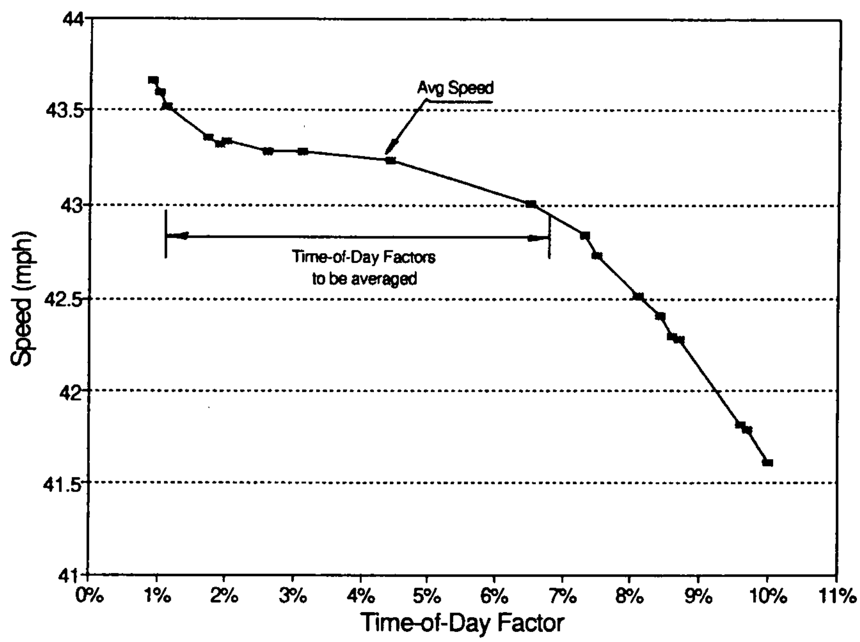

Figure 6.9 TOD Factors and Speeds in Off Peak Hourly Assignment

a higher speed reduction rate. As discussed in Chapter Four, the emission rate was a function of speed. The speed was a function of time–of–day factor. This can be expressed as:

$$\text{HC rate} = F_1(s); \qquad (6.2)$$

$$\text{CO rate} = F_2(s), \qquad (6.3)$$

$$\text{NOx rate} = F_3(s), \qquad (6.4)$$

$$s = S(p) \qquad (6.5)$$

where, s is the speed,

p is the time–of–day factor,

F, S are functions.

It was also observed that if the speed changed in a very short range, then the vehicle emission rate would not vary significantly. Therefore, an average time–of–day factor p_{avg} was selected in such a way that made $F(S(p_{avg}))$ represent the emission rate for the area of $(p_{avg}-\Delta p,\ p_{avg}+\Delta p)$. That is:

$$F(s_{avg}) \approx \Sigma F(s_{avg}+\Delta i)/n \approx \Sigma F(S(p_{avg}+\Delta j))/n \qquad (6.6)$$

where, $i \in (s_{avg}-\Delta s,\ s_{avg}+\Delta s)$,

$j \in (p_{avg}-\Delta p,\ p_{avg}+\Delta p)$,

n is number of observations in the area discussed.

Therefore, $F(s_{avg})$ can be used to approximate the speeds and to reduce the operation from 20 runs to 4–5 runs. The key is to make Δs and Δp small enough so that the emission rate changes are unnoticeable. In the test, it was proved that 0.25 mph for Δs and 0.005 to 0.03 for Δp would be accurate enough to approximate the assignment results. Four assignments with time–of–day factors of 2.1%, 7.1%, 9.0% and 10.2% were adopted to replace the previous 20 period off-peak assignments. Table 6.10 is a comparison of the two assignments on the system performance measures as well as the vehicle emissions. The computing time was also reduced to only 25% of the 20 period off-peak assignment.

6.5 Chapter Summary

This chapter compared the assignment procedures with different time-of-day stratification: the single period, the three period and the 24 hourly assignments. Compared to the single period assignment, the three period assignment had the advantage of being able to differentiate the traffic situation between peak and off peak periods. However, the speeds in the three period assignment were produced under the worst traffic congestion conditions. The 24 hourly assignments procedure significantly improved the travel speed estimates, especially for the peak periods by further differentiating the O-D table into shorter periods. As a result, more reasonable vehicle emission estimates of the three

Table 6.10 Performance Measures and Vehicle Emissions:

Test Result Comparison on Two Off Peak Assignments

Off Peak	VMT	VHT	Speed	HC	CO	NOx
Assignment	(1000)	(1000hrs)	(mph)	(1000 kgs)		
20 Periods	21,352.7	446.7	47.8	40.8	489.2	77.3
4 Periods	21,323.3	446.6	47.7	40.7	487.0	77.0
Difference	(29.4)	(0.2)	(0.0)	(0.1)	(2.3)	(0.3)
% Diff	-0.1%	-0.0%	-0.1%	-0.2%	-0.5%	-0.4%

major pollutants were produced. The HC and CO estimates reduced as much as 25% from the different speeds. The research also verified that the emission estimates are very sensitive to the speed changes among the three different assignment procedures while VMT presents a secondary role.

For the VMT distribution, moderate changes were observed on the VMT distribution among facility types. The peak VMT shift played a critical role in determining the speed and emissions for the peak period. In the 24 hourly assignments, it was found that more VMT were assigned on the freeway facilities while arterial and local road were allocated fewer VMT. Although the system VMT were almost the same, the uneven distribution of performance measures contributed a larger emission deviation among three tested assignment processes.

To reduce computing time and operation complexity, an average time-of-day factor method was suggested to reduce number of periods required for the off peak assignment without hurting the precision of the results.

Three recommendations can be drawn from the analysis of the test results as follows:

1. More information on the Type I distribution needs to be collected to support a higher resolution assignment method. The UTP model should be re-calibrated against base year traffic counts when a high resolution assignment such as a 24 period assignment is implemented due to the variation on VMT distribution among facility types.
2. Post-processing of link volume and speed using time-of-day factors and effect

on emission estimates should be reviewed and compared to the 24 hourly assignments result.

3. As a mid-term solution, the advanced process and its associated assignment procedures, such as dynamic assignment method, should be considered. Due to the test condition limitation, this research was unable to test dynamic assignment and its impacts for the Denver region. The effects of such new procedures on mobile source emission estimates should be studied in the future.

CHAPTER SEVEN

SUMMARY AND CONCLUSIONS

7.1 General Review

This research reviewed different commonly used assignment procedures and proposed advanced procedures, and examined the outputs through a series of carefully designed experiments as applied to Denver as a test case. Three aspects of the assignment procedures were studied: the algorithms, the volume–speed functions, and the time–of–day stratifications. The research also compared and evaluated the impacts of these distinctive assignment procedures on vehicular emission estimates. Several related issues, such as the definition of volume–speed functions at v/c ratio greater than 1.0, the assignment termination condition, the possibility of improvement of multi–period off peak period assignment, were also studied. Recommendations were made for the application of different assignment procedures and future assignment procedural improvements.

7.2 Major Research Conclusions

7.2.1 Algorithms

For the Denver case study, it was found that the equilibrium algorithm produced the lowest overall VHT and the highest estimated speeds among all the tested algorithms. It also produces the lowest system HC and CO estimates and the highest NOx estimates. In the 1990 Denver regional model calibration process, it was found that the equilibrium algorithm assignment result matched both overall ground traffic counts and screen line counts better than other algorithms. The Percent Root Mean Squared Errors(PRMSE) for the estimated link volumes versus overall counts and screen line counts were both under 30%[9]. There were small (<5%) system VMT changes but very large VHT and speed variations (>15%) among the test algorithms. The variations of assignment performance caused the large variation in the order of 20% on the HC and CO estimates. The deviation on NOx estimates was relatively small in the magnitude of 10% due to its flatter speed-emission rate curve.

Although system VMT had small changes among the test algorithms, the allocation of VMT changes between the two major facility groups, freeways and arterials, was very large (>15%). For example, the freeway VMT produced by the all-or-nothing incremental assignment was about 14% more than the VMT from the equilibrium assignment. Together with the speed changes, the VMT shifting caused vehicle emission distribution among facilities to fluctuate greatly. For the freeway, the single iteration unconstrained all-or-nothing assignment and all-or-nothing incremental assignments estimated the highest levels of HC and CO, and the equilibrium and all-or-nothing volume averaging algorithms estimated lower levels of HC and CO. Under the test conditions, stochastic assignment algorithm failed to produce compatible system performance to equilibrium assignment.

7.2.2 Volume-Speed Functions

The volume-speed function is used to control the link volume and link travel time in the capacity-restraint assignment. This research found the v/c ratio greater 1.0 portion of the volume-speed function played a very important role in determining the system performance as well as the vehicle emission through defining two measures: the NVSFIV and the extended assignable volume. The impact of the volume-speed function on HC and

CO emissions were in the order of 17% between original BPR and HCM85 based volume-speed functions, especially in a congested highway system. The HCM85 and HCM94 curves provide a more realistic way than BPR function to define the volume-speed relationships. However, the VMT shifting among facility types was considerable in both between HCM85 and HCM94 volume-speed functions, and this caused large emission variations among facility types.

The research also found that the number of iterations required in the equilibrium assignment changed slightly if the extended assignable volume or NVSFIV of a volume-speed function changes. In the current planning practice, the number of iterations in the equilibrium assignment is obviously lower than that concluded in the research when a relative percentage error conception is introduced.

7.2.3 Time-of-Day Stratifications

The nature of the different time-of-day stratifications is to alter the trip loadings to the network through the disaggregation of the temporal distribution of trips. The major impacts were found on the speed changes (in the order of 20%) and, thus, influenced vehicle emission estimates on all three pollutants. For example, the 24 hourly assignments produced 15% and 11% lower HC and CO estimates and a 3% higher NOx estimate than the three period assignment. The emission variations were at 17%-23% levels among three test cases. It was also found that the 24 hourly assignments replicated the speed distribution better during a 24-hour period. A three period assignment generated the worst traffic situation for the peak periods. It was observed that peak VMT shifting between the facility types was significant as well as the emission estimates. An average time-of-day factor method with fewer number of assignments is possible to replace an off peak assignment with 20 or more periods.

As a summary, Table 7.1 presents the performance of three assignment procedures and their impacts on the vehicle emission estimates concluded in this research.

7.2.4 Estimated Vehicle Emission Variations and the Conformity

The major responsibility of MPO is to develop short and long range plans for transportation project implementation. The UTP model is used to demonstrate that plans and programs pass federally mandated requirements regarding acceptable vehicle pollutant levels to the future years. This conformity finding must be approved by the US Department of Transportation in order to obtain federal funding for the region. Since all the regional transportation plans have to be verified through travel models and vehicle emission factor model, the precision and stability of estimated vehicle emissions through transportation modeling processes become critical. However, based on the finding of this research, the estimated vehicle emissions could vary greatly when traffic assignment procedures are altered. The traffic assignment procedure is just one of several steps in the urban transportation modeling process. This added an uncertainty in conformity findings due to the variation of transportation modeling process. For example, the estimated CO emission in 1995 was 1,057 tons (1 ton = 1,000 kilograms) based on standard Denver regional travel model estimate, and the emission budget for 2001 is 666.7 tons for the Denver region. About 390 tons or 1/3 of 1995 CO emission need to be reduced in six years. On the other hand, as found by this research, the variations for CO estimation were 150 tons for different algorithms, 125 tons for different volume–speed

Table 7.1 Summary of Traffic Assignments and the Imapcts on Emission Estimates in

Denver Case Study

Assignment Procedures	Algorithms	Vol-Speed Functions	Time-of-Day
Nature of Changes	Alter travel paths & Path optimal level	Alter extended assignable volume	Trip loading change
Impact on VMT	Small*	Small	Small
Range	40.7-41.5 million	40.3-41.0 million	40.1-41.5 million
Difference	0.8 million	0.6 million	0.5 million
% Difference	1.9%	1.5%	1.3%
Impact on Speed	Large	Large	Large
Range	28.7-39.3 mph	30.9-39.8 mph	29.9-36.1 mph
Difference	10.6 mph	8.9 mph	6.2 mph
% Difference	36.9%	22.3%	20.7%
Impact on HC	Large	Large	Large
Range	76.8-92.4 tons	74.9-88.0 tons	84.0-98.3 tons
Difference	15.6 tons	13.1 tons	14.3 tons
% Difference	20.3%	17.6%	17.0%
Impact on CO	Large	Large	Large
Range	722.5-871.7 tons	701.3-825.8 tons	825.7-1018.9 tons
Difference	149.2 tons	124.5 tons	193.3 tons
% Difference	20.7%	17.8%	23.4%
Impact on NOx	Large	Medium	Large
Range	109.8-121.3 tons	112.8-121.5 tons	112.8-135.1 tons
Difference	11.5 tons	8.7 tons	22.3 tons
% Difference	10.4%	7.7%	19.7%

* AON unconstrained assignment is not included

** HCM94 curves are excluded

*** Assignment performance and emission estimates difference:
Small: < 5%
Medium: 5 - 10 %
Large: > 15 %

functions, and 190 tons for different time-of-day stratifications. Each of these difference by themselves can be accounted for more than 1/3 of the CO emission to be reduced.

7.3 Recommendations

The equilibrium assignment achieved the lowest VHT and the highest speed and it was easy to control the number of iterations and obtain a stable solution. It should be given a higher priority among all algorithms. The number of iterations in the equilibrium assignment should be no fewer than 10 to obtain a stable solution.

The development of mathematical expression of volume-speed curves should consider two criteria:

1. $\min. \sum [f_2(xi)-f_1(xi)]^2 \qquad x \in [0, 1] \qquad (7.1)$
2. $\min \text{NVSFIV} = \int_1^{\infty} f_2(x)dx \qquad x \in (1, \infty) \qquad (7.2)$

The Overgarrd's base function is recommended for the assignment since it achieves the smallest NVSFIV and extended assignable volume among all tested base functions.

For the time-of-day procedures, the 24 period assignment is recommended with carefully applied time-of-day factors. The peak assignment with higher resolution is highly recommended since the peak period demonstrated large variations on both speed and emission estimates. Model re-calibration is needed when different volume-speed functions and multi-period high resolution assignments are applied.

Due to great emission estimation variations found among different assignment procedures in Denver case study, and the requirement of air quality conformity, It is recommended that a standard modeling procedure be developed to reduce the discrepancy on vehicle emission estimates. Since there are so many factors in both travel model and vehicle emission factor model that could affect the conformity findings significantly, and it is difficulty to verify and calibrate the real emission levels for a region under the current technology, it was also recommended that the necessity of the conformity process be completely reviewed and other alternative solution for the conformity be studied.

7.4 Future Study Needs

Several study areas are defined for further study based on these research findings. These areas can be summarized as:

1. Using the criteria defined in this research, search for a better base mathematical expression that can reach a near ideal volume-speed relationship at the v/c ratio greater than 1.0 area, and meanwhile, maintain the stability of existing equilibrium assignment;
2. Search for better capacity constraint assignment algorithms that will produce a more stable result when NVSFIV -> 0 in the v/c ratio > 1.0 area;
3. Study temporal distribution in a more detailed manner and with better field data to support a more reasonable assignment. As a mid-term solution, the advanced time-of-day process and its associated assignment procedures, such as dynamic assignment method, should be considered. The impacts of such new procedures on mobile source emission estimates should also be studied.

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APPENDIX

Appendix A

MINUTP Control File For Simplified Denver UTP Model

```
$\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
$
$  PROGRAM BATCH FILE ***GF95S.SET*** 1995 SIMPLIFIED REGIONAL MODEL
$  FOR RESEARCH PURPOSE ONLY
$  DRCOG 1530 ZONE SYSTEM
$  MODIFIED BY LYFENG   NOV 22 1994
$///////////////////////////////////////////////////////////////////////////
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$     THIS STEP BUILDS PEAK HOUR SKIM MATRICES BASED ON ASSUMED PEAK
$     HOUR NETWORK SPEEDS
$
$     INPUT FILE  = GF9520.DAT          Network File
$
$     OUTPUT FILE = GF9511.DAT          Peak Hour Skim Matrices
$                                        Table 101 = Impedances (DUMMY)
$                                        Table 102 = Distances  (DUMMY)
$                                        Table 103 = Times
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
*PGM PTHBLD GF9520.DAT,03,0   Input Network File (20); Impedence (01),
$                             Distance (02) and Time (03) Output
Matrices;
$                             No Centroid Connector Paths
*ID  BUILD 1995 REGIONAL PEAK SKIM PATHS
*PAR MSGLEV=3
TCOST=8,DCOST=15,FCOST=10    IMP=((Time*TCOST)+(Dist*DCOST))/FCOST
INTFAC=0                     No Intra-Calcs
IMPFAC=1                     Do Not Scale
OPMAT=3                      Output #3 Matrix
TIMEFAC=100                  Time Matrix (03) divided by 100 (time=x.xx)
DISTFAC=10                   Distance Matrix (02) divided by 10
(dist=xx.x)
REPO 1,2                     Reports 1,2
$
$     SPEEDS BELOW ARE DRCOG 1995 PEAK HOUR SPEEDS FOR ANY
$     NUMBER OF LANES (1-7)
$
SPED  1-7,0,200                             Set Default Speeds to 20
mph
SPED  1-7,11,440,300,180,135,110,245     NL=1-7, AT=1, FT=1-6
SPED  1-7,21,440,300,210,165,135,245         "     = 2     "
SPED  1-7,31,480,335,220,190,135,245         "     = 3     "
SPED  1-7,41,520,335,270,220,165,270         "     = 4     "
SPED  1-7,51,520,375,285,240,190,270         "     = 5     "
*
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
```

```
$
$      THIS STEP BUILDS FINAL PEAK HOUR IMPEDENCE SKIM MATRIX FOR TRIP
$      DISTRIBUTION BY ADDING INTRAZONAL TIME AND TERMINAL TIME VALUES
$      TO THE PEAK HOUR SKIMS PREVIOUSLY BUILT. THIS SKIM MATRIX IS USED
$      FOR DISTRIBUTION OF ALL HBW TRIPS.
$
$      INPUT FILES = GF9511.DAT          Impedence Skim Matrices
$                    REG95G.ZBA        DRCOG Zonal Data
$
$      OUTPUT FILE = UNIT 13 = GF95PK.WTT
$                    Final Peak Hour Time Skim Matrix (Table 301)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$
*PGM MATRIX
*UNIT 13=GF95PK.WTT
*ID  BUILD FINAL 1995 REGIONAL PEAK SKIM MATRIX
*PAR MSGLEV=5
ZDAT REG95G.ZBA,,Z=1-4,1=5-6,2=25-30       Z=Zone, 1=Area Type, 2=Acres
$
$       PEAK HOUR INTRAZONAL TIME RANGE LOOKUP TABLE BY # ACRES IN ZONE
$       FOR EACH AREA TYPE (1-5)
$
L.1  R,0,0=1,066=2,0481=3,1216=4,02371=5,04101=6,06336=7,08961=8
L.2  R,0,0=1,131=2,0801=3,2111=4,04481=5,07841=6,12161=7,18561=8
L.3  R,0,0=1,231=2,1441=3,4481=4,09601=5,17921=6,32001=7
L.4  R,0,0=1,576=2,2241=3,6081=4,13121=5,24321=6,43521=7
L.5  R,0,0=1,960=2,4481=3,15361=4,37761=5
$
$      DIRECT LOOKUP TABLE FOR PEAK HOUR TERMINAL TIMES BY AREA TYPE
$
$      AREA TYPE      ORIGIN TERMINAL TIME      DESTINATION TERMINAL TIME
$          1                   7                             7
$          2                   4                             6
$          3                   3                             3
$          4                   2                             1
$          5                   1                             1
$
L.6  D,0,0,1,7,4,3,2,1      Peak Hour Origin Terminal Time
$                             Based On Area Type
L.7  D,0,0,1,7,6,3,1,1      Peak Hour Destination Terminal Time
$                             Based on Area Type
$
GET 1,103                    1 = UNIT 11, Output Matrix From Previous Job
$                          103 = Input Time Skim Matrix
$
IF J=I                     Process Intrazonal Trips Only
   COMP AREA=ZI1                Determine Area Type
   COMP ACRES=ZI2               Determine # Acres
$
$                               Determine Intrazonal Travel Times
$                                 for each Area Type (1-5)
$
   IF AREA=1.0                  Area Type 1
   COMP 1=L.1(ACRES)
   ENDIF
$
   IF AREA=2.0                  Area Type 2
   COMP 1=L.2(ACRES)
   ENDIF
$
```

```
   IF AREA=3.0                  Area Type 3
   COMP 1=L.3(ACRES)
   ENDIF
$
   IF AREA=4.0                  Area Type 4
   COMP 1=L.4(ACRES)
   ENDIF
$
   IF AREA=5.0                  Area Type 5
   COMP 1=L.5(ACRES)
   ENDIF
ENDIF
COMP 1=1+L.6(ZI1)+L.7(ZJ1)     Add Interzonal Impedence from Skims or
$                                 Intrazonal Impedence calculated above
$                                 (for I=J cells only) to Origin

$                                 Terminal Time and Destination
$                                 Terminal Time into Matrix 1
OUT  1,301                      Output File GF9513.DAT (Table 301)
*
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$     THIS STEP BUILDS OFF PEAK SKIM MATRICES BASED ON ASSUMED OFF PEAK
$     NETWORK SPEEDS. THIS STEP WILL OVERWRITE THE PREVIOUS SKIMS WHICH
$     ARE LARGE AND NO LONGER NEEDED.
$
$      INPUT FILE = GF9520.DAT        NETWORK FILE
$
$     OUTPUT FILE = GF9511.DAT        Off-Peak Skim Matrices
$                                        Table 101 = Impedances
$                                        Table 102 = Distances
$                                        Table 103 = Times
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
*PGM PTHBLD GF9520.DAT,03,0     Input Network File (20); Impedence (01),
$                                Distance (02), & Time (03) Output
$                                Matrices; No CC's in Paths
*ID  BUILD 1995 REGIONAL OFF-PEAK SKIM PATHS
*PAR MSGLEV=3
TCOST=6,DCOST=15,FCOST=10      IMP=((Time*TCOST)+(Dist*DCOST))/FCOST
INTFAC=0                       No Intra-Calcs
IMPFAC=1                       Do Not Scale
OPMAT=3                        Set Output To One Matrix
TIMEFAC=100                    Time Matrix (03) divided by 100 (time=x.xx)
DISTFAC=10                     Distance Matrix (02) divided by 10
(dist=xx.x)
REPO 1,2                       Reports 1,2
$
$     SPEEDS BELOW ARE DRCOG 1995 OFF-PEAK SPEEDS FOR ANY
$     NUMBER OF LANES (1-7)
$
SPED  1-7,0,300                              Set Default Speeds to 30
mph
SPED  1-7,11,440,300,180,135,110,245     NL=1-7, AT=1, FT=1-6
SPED  1-7,21,440,300,210,165,135,245         "     = 2     "
SPED  1-7,31,480,335,220,190,135,245         "     = 3     "
SPED  1-7,41,520,335,270,220,165,270         "     = 4     "
SPED  1-7,51,520,375,285,240,190,270         "     = 5     "
```

```
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$
$
$     THIS STEP BUILDS FINAL OFF-PEAK IMPEDENCE SKIM MATRIX FOR TRIP
$     DISTRIBUTION BY ADDING INTRAZONAL TIME AND TERMINAL TIME VALUES
$     TO THE OFF-PEAK HOUR SKIMS PREVIOUSLY BUILT. THIS SKIM MATRIX
$     (TABLE 301) IS USED FOR DISTRIBUTION OF TRUCK TRIPS. ALSO A SECOND
$     OFF-PEAK SKIM MATRIX IS CREATED WITH ALL AIRPORT (ZONES 280-284,
$     296,297) IMPEDENCES SET TO 21. THIS SKIM MATRIX (TABLE 302) IS
$     USED FOR THE DISTRIBUTION OF HBNW, NHB AND IE TRIPS. THIS STEP
$     WILL OVERWRITE THE NO LONGER NEEDED PEAK HOUR SKIMS.
$
$     INPUT FILES = GF9511.DAT          Impedence Skim Matrix
$                   REG95G.ZBA         Zonal Data
$
$   Final Off-Peak Time Skim Matrix
$   OUTPUT FILES = GF95OP.WTT          Table 301 = Off-Peak
$                  GF95OP.AIR          Table 401 = Off-Peak w/Airport
$                                      Cells Set at 21
$
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$$
$
*PGM MATRIX
*UNIT 13=GF95OP.WTT,14=GF95OP.AIR
*ID  BUILD FINAL 1995 REGIONAL OFF-PEAK SKIM MATRICES
*PAR MSGLEV=5
ZDAT REG95G.ZBA,,Z=1-4,1=5-6,2=25-30     Z=Zone, 1=Area Type, 2=Acres
$
$     OFF-PEAK INTRAZONAL TIME RANGE LOOKUP TABLE BY # ACRES IN ZONE
$     FOR EACH AREA TYPE (1-5)
$
L.1  R,0,0=1,131=2,0521=3,1341=4,02881=5,05761=6,10241=7,18111=8
L.2  R,0,0=1,191=2,0831=3,2431=4,05311=5,10881=6,20801=7,44801=8
L.3  R,0,0=1,231=2,1921=3,5121=4,12161=5,29441=6
L.4  R,0,0=1,576=2,2561=3,7041=4,16961=5,40000=6
L.5  R,0,0=1,960=2,4481=3,15361=4,42241=5
$
$     DIRECT LOOKUP TABLE FOR OFF-PEAK TERMINAL TIMES BY AREA TYPE
$
$     AREA TYPE      ORIGIN TERMINAL TIME      DESTINATION TERMINAL TIME
$         1                  9                            9
$         2                  3                            6
$         3                  3                            2
$         4                  2                            1
$         5                  1                            1
$
L.6  D,0,0,1,9,3,2,2,1      Off-Peak Origin Terminal Time
$                             Based on Area Type
L.7  D,0,0,1,9,6,2,1,1      Off-Peak Destination Terminal Time
$                             Based on Area Type
$
GET 1,103                   1 = Final Output Time Skim Matrix
$                           103 = Input Time Skim Matrix
$
IF J=I                      Process Intrazonal Trips Only
   COMP AREA=ZI1                  Determine Area Type
   COMP ACRES=ZI2                 Determine # Acres
$
$                                 Determine Intrazonal Travel Times
```

```
$                                 for Each Area Type (1-5)
$
   IF AREA=1.0                    Area Type 1
   COMP 1=L.1(ACRES)
   ENDIF
   IF AREA=2.0                    Area Type 2
   COMP 1=L.2(ACRES)
   ENDIF
   IF AREA=3.0                    Area Type 3
   COMP 1=L.3(ACRES)
   ENDIF
   IF AREA=4.0                    Area Type 4
   COMP 1=L.4(ACRES)
   ENDIF
   IF AREA=5.0                    Area Type 5
   COMP 1=L.5(ACRES)
   ENDIF
ENDIF
$
COMP 1=1+L.6(ZI1)+L.7(ZJ1)    Add Interzonal Impedence from Skims or
$                               Intrazonal Impedence calculated above
$                               (for I=J cells only) to Origin

$                               Terminal Time and Destination
$                               Terminal Time into Matrix 1
$
OUT  1,301                    Output to File GF95OP.WTT (Table 301)
$
ADD  2,M=1                        Copy Matrix 1 to Matrix 2
REP  2,21,I=356,357,359       Replace Airport Row Cells with 21
REP  2,21,J=356,357,359       Replace Airport Column Cells with 21
$
REP  2,99,I=356,357,359,J=356,357,359
REP  2,99,J=356,357,359,I=356,357,359
$                                 Replace Intra-Airport Cells with 99
OUT  2,401                        Output to File GF95OP.AIR (Table 401)
*
$=========================================================================
$ TRIP DISTRIBUTION: MODIFIED ON OCT 04, 1993, LYF                       =
$                                                                        =
$=========================================================================
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$     THIS STEP PERFORMS TRIP DISTRIBUTION FOR ALL HBW TRIPS
$
$           Purpose 1 = HBW LOW INCOME
$           Purpose 2 = HBW MEDIUM INCOME
$           Purpose 3 = HBW HIGH INCOME
$
$     INPUT FILES = GF9511.DAT           Final Peak Hour Skim Matrix
$                   GF9517.DAT           K-Factors Matrix (w/o Airport
$                                                       Kfactors)
$                   GF9509.DAT           Friction Factors Matrix
$                   GF9510.DAT           P/A Trip Ends by Purpose
$
$     OUTPUT FILE = GF9512.DAT           P/A Matrices by Purpose for
$                                          3 Trip Purposes:
$                                            201 = HBW Low Income
$                                            202 = HBW Medium Income
$                                            203 = HBW High Income
$
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$
$>COPY FFACTHBW.DAT GF9509.DAT
$>COPY GF95HBW.DAT GF9510.DAT
$>COPY GF95PK.WTT GF9511.DAT
$
*PGM TRPDST IT=5,OP=1,ST=10,PU=3,KS=100
*ID 1995 HBW TRIP DISTRIBUTION
*PAR MSGLEV=3
$  DIST WORK TRIPS (PK-SKIMS) ======
REPO 1,2,31,32,33,41,42,43
*
$
$>DEL GF9509.DAT
$>DEL GF9510.DAT
$>DEL GF9511.DAT
$>REN GF9512.DAT GF95HBW.PJ5
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$      THIS STEP PERFORMS TRIP DISTRIBUTION (USING SKIM MATRIX WITH
$      AIRPORT ZONE IMPEDENCES SET TO 21) FOR HBNW, NHB, AND IE TRIPS
$      USING OFF PEAK SKIM MATRIX.
$
$                        Purpose 1 = HBNW
$                        Purpose 2 = NHB
$                        Purpose 3 = IE
$
$      INPUT FILES = GF9511.DAT          Final Off-Peak Skim Matrix
$                                          (w/ Airport cells = 21)
$                                          - Table 302 -
$                    GF9517.DAT          K-Factors Matrix (w/ Airport
$                                                           Kfactors)
$                    GF9509.DAT          Friction Factors Matrix
$                    GF9510.DAT          P/A Trip Ends by Purpose
$
$      OUTPUT FILE = GF9512.DAT          P/A Matrices by Purpose for
$                                          4 Trip Purposes:
$                                           201 = HBNW
$                                           202 = NHB
$                                           203 = IE
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$
$>COPY FFACTNW.DAT GF9509.DAT
$>COPY GF95NW.DAT GF9510.DAT
$>COPY GF95OP.AIR GF9511.DAT
$
*PGM TRPDST IT=5,ST=10,PU=3,OP=1,KS=100
*ID GF95 Non-Work trip distribution
*PAR MSGLEV=3
*ID 1995 DIST HNW,NHB,IE TRIPS
$REPO 1,2,34,35,37,44,45,47
*
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$  OUTPUT HBNW, NHB,IE TRIP TABLES
$  THIS STEP IS TO SEPERATE NW AND IE TRIP TABELS INTO TWO FILES
```

```
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
*PGM MATRIX
*UNIT 13=GF95HNW.PJ5,14=GF95NHB.PJ5,15=GF95IE.VJ5
*ID GF95 NW PERSONS, IE VEHICLES
GET 1,201            HNW
GET 2,202            NHB
GET 3,203            IE
OUT 1,301            HNW
OUT 2,401            NHB
OUT 3,501            IE
*
$
$>DEL GF9509.DAT
$>DEL GF9510.DAT
$>DEL GF9511.DAT
$>DEL GF9512.DAT
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$     THIS STEP PERFORMS TRIP DISTRIBUTION FOR TRUCK TRIPS USING
$     OFF PEAK SKIM MATRIX WITHOUT ALL AIRPORT ZONE IMPEDANCES
$     SET TO 21.
$
$                      Purpose 1 = TRUCK
$
$     INPUT FILES = GF9511.DAT          Final Off-Peak Skim Matrix
$                                         (w/o Airport cells = 21)
$                                         - Table 301 -
$                   GF9517.DAT          K-Factors Matrix (w/o Airport
$                                                          Kfactors)
$                   GF9509.DAT          Friction Factors Matrix
$                   GF9510.DAT          P/A Trip Ends by Purpose
$
$     OUTPUT FILE = GF9512.DAT          P/A Matrix for Truck Trips
$                                         (Table 201)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$>COPY FFACTCOM.DAT GF9509.DAT
$>COPY GF95COM.DAT GF9510.DAT
$>COPY GF95OP.WTT GF9511.DAT
$
*PGM TRPDST IT=5,ST=10,OP=1,PU=1,KS=100
*ID GF95 DISTRIBUTE COMMERCIAL (TRUCK) TRIPS
*PAR MSGLEV=3
*ID 1995 COMMERCIAL TRIPS
$REPO 1,2,36,46
*
$-------------------------------------------------------------------
$>COPY GF9512.DAT GF95COMS.VJ5
$>DEL GF9509.DAT
$>DEL GF9510.DAT
$>DEL GF9511.DAT
$>DEL GF9512.DAT
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$   TRIP DISTRIBUTIO SUMMARY
```

```
$       HBW   - Person Trips: GF95HBW.PJ5 (01-03)   P-A
$       HBNW  - Person Trips: GF95NW.PJ5 (01)       P-A
$       NHB   - Person Trips: GF95NW.PJ5 (02)       O-D
$       TRUCK - Vehicle Trips GF95COM.VJ5           O-D
$       IE    - Vehicle Trips GF95IE.VJ5            P-A
$       EE    - Vehicle Trips GF95EE.VJ5            O-D
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$=======================================================================
$ END OF TRIP DISTRIBUTION
$======================================================================
$
$>COPY GF95HBW.PJ5 GF9511.DAT
$
*PGM MATRIX
*PAR MSGLEV=5
*ID   COMBINE HBW TRIPS,
*UNIT 12=GF95HBWS.PJ5
$   Define output files
$
ADD 1,M=101,102,103                     HBW trips for all income levels
OUT 1,201                               Output table HBW ALL TRIPS
REPO 1,2
*
$
$>DEL GF9511.DAT
$
$\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
$
$  PROGRAM BATCH FILE ***GF95S.SET*** 1995 SIMPLIFIED REGIONAL MODEL
$  FOR RESEARCH PURPOSE ONLY
$                      <<<<<< PART 2 OF 3 >>>>>>
$////////////////////////////////////////////////////////////////////////
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$     THIS STEP FACTORS THE HBW, HBNW, AND NHB TRIP MATRICES TO
$     ACCOUNT FOR MODE SPLIT AND AUTO OCCUPANCY.  THE FACTORS USED
$     ARE BASED ON DRCOG ESTIMATES.  AUTO OCCUPANCY IS ASSUMED TO BE
$     THE SAME AS THE DRCOG PROJECTED REGIONAL AVERAGE IN 1995.
$
$     INPUT FILES = GF95HBWS.PJ5          P/A Trip Matrix for HBW
$                   GF95HNW.PJ5                               HBNW
$                   GF95NHB.PJ5          O-D for NHB Purposes
$                                         Tables 101, 201, 301
$
$     OUTPUT FILES = GF95HBWS.PJ5          P/A Trip Matrix for HBW
$                    GF95HNWS.PJ5                              HBNW
$                    GF95NHBS.PJ5         O-D for NHB Purposes
$                                         Vehicle Trips, 401,501,601
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  APPLY MODE SPLIT/AUTO OCCUPANCY FACTORS
*PAR MSGLEV=3
*UNIT 11=GF95HBWS.PJ5,12=GF95HNW.PJ5,13=GF95NHB.PJ5
```

```
*UNIT 14=GF95HBWS.MSJ,15=GF95HNWS.MSJ,16=GF95NHBS.MSJ

$                                           Define Input Files
GET 1,101                                   HBW P/A Trip Matrix (all
incomes)
GET 2,201                                   HBNW P/A Trip Matrix
GET 3,301                                   NHB O-D Trip Matrix
FAC 1,0.887,B                               VEH OCC RATE 1.09
FAC 2,0.662,B                               VEH OCC RATE 1.49
FAC 3,0.712,B                               VEH OCC RATE 1.39
OUT 1,401                                   Output Table #
OUT 2,501                                        "
OUT 3,601                                        "
*
$
$\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
$
$  PROGRAM BATCH FILE ***GF95R.SET*** 1995 SIMPLIFIED REGIONAL MODEL
$  FOR RESEARCH PURPOSE ONLY
$  DRCOG 1530 ZONE SYSTEM
$                    <<<<<< PART 3 OF 3 >>>>>>
$
$///////////////////////////////////////////////////////////////////////
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$     THIS STEP CALCULATES THE AM PEAK PERIOD O/D HBW TRIP MATRIX
$     (INCLUDES TRIPS FOR ALL THREE INCOME LEVELS) BY FACTORING THE
$     DAILY HBW P/A TRIP MATRIX WITH AM PEAK PERIOD FACTORS
$
$     INPUT FILES = GF9511.DAT          P/A HBW Daily Trip Matrix
$
$     OUTPUT FILE = GF9512.DAT          O/D HBW AM Peak Period Trip
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$>COPY GF95HBWS.MSJ GF9511.DAT
$
*PGM MATBAL 101,201,307,003,1000        Input & Output file #s, row,
$                                         column & scaling factors
*ID  CALCULATE AM PEAK HBW O/D TRIP MATRIX
*PAR MSGLEV=3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$     THIS STEP CALCULATES THE AM PEAK PERIOD HBNW O/D TRIP MATRIX BY
$     FACTORING THE DAILY HBNW P/A TRIP MATRIX WITH AM PEAK PERIOD
$     FACTORS
$
$     INPUT FILE = GF9511.DAT          P/A HBNW Daily Trip Matrix
$
$     OUTPUT FILE = GF9513.DAT         O/D HBNW AM Peak Period Trip
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$>COPY GF95HNWS.MSJ GF9511.DAT
$
*PGM MATBAL 101,301,083,009,1000        Input & Output file #s, row,
```

```
$                                          column & scaling factors
*ID  CALCULATE AM PEAK HBNW O/D TRIP MATRIX
*PAR MSGLEV=3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE AM PEAK PERIOD TRIP MATRIX FOR
$      NHB PURPOSE BY FACTORING THE DAILY O-D TRIP MATRICES WITH
$      AM PEAK PERIOD FACTORS
$
$      INPUT FILES = GF9511.DAT          O-D Trip Matrix NHB (101)
$
$      OUTPUT FILE = GF9514.DAT          AM Peak Period Trip Matrix for
$                                          NHB (Table 401)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  CALCULATE AM PEAK NHB O/D TRIP MATRIX
*UNIT 11=GF95NHBS.MSJ
*PAR MSGLEV=3
GET 1=101                                 Input Tables
FAC 1,0.039,B                             NHB Factor
OUT 1,401                                 Output AM NHB
*
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE AM PEAK PERIOD TRIP MATRIX FOR
$      COM PURPOSE BY FACTORING THE DAILY O-D TRIP MATRIX WITH
$      AM PEAK PERIOD FACTORS
$
$      INPUT FILES = GF9511.DAT          O-D Vehicle Trip Matrix COM
(101)
$
$      OUTPUT FILE = GF9515.DAT          AM Peak Period Trip Matrix for
$                                          COM (Table 501)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  CALCULATE AM PEAK COM O/D TRIP MATRIX
*UNIT 11=GF95COMS.VJ5
*PAR MSGLEV=3
GET 1=101                                 Input Tables
FAC 1,0.160,B                             COM Factor
OUT 1,501                                 Output AM COM
*
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE AM PEAK PERIOD IE O/D TRIP MATRIX BY
$      FACTORING THE DAILY IE P/A TRIP MATRIX WITH AM PEAK PERIOD
$      FACTORS
$
$       INPUT FILE = GF9511.DAT          P/A IE Daily Trip Matrix
$                                          (Table 101)
```

```
$
$      OUTPUT FILE = GF9516.DAT          O/D IE AM Peak Period Trip
$                                          Matrix (Table 601)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$>COPY GF95IE.VJ5 GF9511.DAT
$
*PGM MATBAL 101,601,070,055,1000         Input & Output file #s, row,
$                                          column & scaling factors
*ID  CALCULATE AM PEAK IE O/D TRIP MATRIX
*PAR MSGLEV=3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$      THIS STEP CALCULATES THE AM PEAK PERIOD TRIP MATRIX FOR
$      E-E PURPOSE BY FACTORING THE DAILY O-D TRIP MATRIX WITH
$      AM PEAK PERIOD FACTORS
$
$      INPUT FILES = GF9511.DAT          O-D Vehicle Trip Matrix E-E
(101)
$
$      OUTPUT FILE = GF9517.DAT          AM Peak Period Trip Matrix for
$                                          COM (Table 701)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  CALCULATE AM PEAK EE O/D TRIP MATRIX
*UNIT 11=GF95EE.VJ5
*PAR MSGLEV=3
GET 1=101                                 Input Tables
FAC 1,0.125,B                             EE Factor
OUT 1,701                                 Output AM EE TRIPS
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CREATES THE AM PEAK PERIOD O/D TRIP MATRIX BY COMBINING
$      THE TRIP MATRICES CALCULATED IN THE SIX PREVIOUS STEPS.  THE
$      OUTPUT MATRIX FROM THIS STEP IS READY TO BE ASSIGNED.
$
$       INPUT FILE = GF9512.DAT          O/D AM PEAK HBW (201)
$                    GF9513.DAT               "      HBNW (301)
$                    GF9514.DAT               "      NHB (401)
$                    GF9515.DAT               "      COM (501)
$                    GF9516.DAT               "      I/E (601)
$                    GF9517.DAT               "      E-E (701)
$
$      OUTPUT FILE = GF95ODAM.VEH        AM Peak Period Trip Matrix for
$                                        COM (801), OTHERS (802)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  COMBINE AM PEAK O/D TRIP MATRICES
*UNIT 18=GF95ODAM.VEH                    Define output file
GET 1,201                       HBW
GET 2,301                       HBNW
```

```
GET 3,401                         NHB
GET 4,501                         COM
GET 5,601                         IE
GET 6,701                         EE
ADD 1,M=2,3,4,5,6                   Combine Trip Matrices for HBW, NW,
$                                       I/E, and EE Purposes
OUT 1,801                         Output Table # 801 ALL AM TRIPS
*
$
$>DEL GF9511.DAT
$>DEL GF9512.DAT
$>DEL GF9513.DAT
$>DEL GF9514.DAT
$>DEL GF9515.DAT
$>DEL GF9516.DAT
$>DEL GF9517.DAT
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$     THIS STEP CALCULATES THE PM PEAK PERIOD O/D HBW TRIP MATRIX
$     (INCLUDES TRIPS FOR ALL THREE INCOME LEVELS) BY FACTORING THE
$     DAILY HBW P/A TRIP MATRIX WITH PM PEAK PERIOD FACTORS
$
$     INPUT FILES = GF9511.DAT          P/A HBW Daily Trip Matrix
$
$     OUTPUT FILE = GF9512.DAT          O/D HBW PM Peak Period Trip
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$>COPY GF95HBWS.MSJ GF9511.DAT
$
*PGM MATBAL 101,201,035,300,1000        Input & Output file #s, row,
$                                         column & scaling factors
*ID  CALCULATE PM PEAK HBW O/D TRIP MATRIX
*PAR MSGLEV=3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$     THIS STEP CALCULATES THE PM PEAK PERIOD HBNW O/D TRIP MATRIX BY
$     FACTORING THE DAILY HBNW P/A TRIP MATRIX WITH PM PEAK PERIOD
$     FACTORS
$
$     INPUT FILE = GF9511.DAT          P/A HBNW Daily Trip Matrix
$
$     OUTPUT FILE = GF9513.DAT         O/D HBNW PM Peak Period Trip
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$>COPY GF95HNWS.MSJ GF9511.DAT
$
*PGM MATBAL 101,301,132,147,1000        Input & Output file #s, row,
$                                         column & scaling factors
*ID  CALCULATE PM PEAK HBNW O/D TRIP MATRIX
*PAR MSGLEV=3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
```

```
$      THIS STEP CALCULATES THE PM PEAK PERIOD TRIP MATRIX FOR
$      NHB PURPOSE BY FACTORING THE DAILY O-D TRIP MATRICES WITH
$      PM PEAK PERIOD FACTORS
$
$      INPUT FILES = GF9511.DAT          O-D Trip Matrix NHB (101)
$
$      OUTPUT FILE = GF9514.DAT          PM Peak Period Trip Matrix for
$                                          NHB (Table 401)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  CALCULATE PM PEAK NHB O/D TRIP MATRIX
*UNIT 11=GF95NHBS.MSJ
*PAR MSGLEV=3
GET 1=101                                Input Tables
FAC 1,0.265,B                            NHB Factor
OUT 1,401                                Output PM NHB
*
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE PM PEAK PERIOD TRIP MATRIX FOR
$      COM PURPOSE BY FACTORING THE DAILY O-D TRIP MATRIX WITH
$      PM PEAK PERIOD FACTORS
$
$      INPUT FILES = GF9511.DAT          O-D Vehicle Trip Matrix COM
(101)
$
$      OUTPUT FILE = GF9515.DAT          PM Peak Period Trip Matrix for
$                                          COM (Table 501)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  CALCULATE PM PEAK COM O/D TRIP MATRIX
*UNIT 11=GF95COMS.VJ5
*PAR MSGLEV=3
GET 1=101                                Input Tables
FAC 1,0.307,B                            COM Factor
OUT 1,501                                Output PM COM
*
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE PM PEAK PERIOD IE O/D TRIP MATRIX BY
$      FACTORING THE DAILY IE P/A TRIP MATRIX WITH PM PEAK PERIOD
$      FACTORS
$
$       INPUT FILE = GF9511.DAT          P/A IE Daily Trip Matrix
$                                          (Table 101)
$
$      OUTPUT FILE = GF9516.DAT          O/D IE PM Peak Period Trip
$                                          Matrix (Table 601)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$>COPY GF95IE.VJ5 GF9511.DAT
```

```
$
*PGM MATBAL 101,601,109,132,1000         Input & Output file #s, row,
$                                          column & scaling factors
*ID  CALCULATE PM PEAK IE O/D TRIP MATRIX
*PAR MSGLEV=3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$     THIS STEP CALCULATES THE PM PEAK PERIOD TRIP MATRIX FOR
$     E-E PURPOSE BY FACTORING THE DAILY O-D TRIP MATRIX WITH
$     PM PEAK PERIOD FACTORS
$
$     INPUT FILES = GF9511.DAT          O-D Vehicle Trip Matrix E-E
(101)
$
$     OUTPUT FILE = GF9517.DAT          PM Peak Period Trip Matrix for
$                                         COM (Table 701)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  CALCULATE PM PEAK EE O/D TRIP MATRIX
*UNIT 11=GF95EE.VJ5
*PAR MSGLEV=3
GET 1=101                                Input Tables
FAC 1,0.241,B                            EE Factor
OUT 1,701                                Output PM EE TRIPS
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$     THIS STEP CREATES THE PM PEAK PERIOD O/D TRIP MATRIX BY COMBINING
$     THE TRIP MATRICES CALCULATED IN THE SIX PREVIOUS STEPS.  THE
$     OUTPUT MATRIX FROM THIS STEP IS READY TO BE ASSIGNED.
$
$      INPUT FILE = GF9512.DAT          O/D PM PEAK HBW (201)
$                   GF9513.DAT               "      HBNW (301)
$                   GF9514.DAT               "      NHB (401)
$                   GF9515.DAT               "      COM (501)
$                   GF9516.DAT               "      I/E (601)
$                   GF9517.DAT               "      E-E (701)
$
$     OUTPUT FILE = GF95ODPM.VEH        PM Peak Period Trip Matrix for
$                                       COM (801), OTHERS (802)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  COMBINE PM PEAK O/D TRIP MATRICES
*UNIT 18=GF95ODPM.VEH                   Define output file
GET 1,201                       HBW
GET 2,301                       HBNW
GET 3,401                       NHB
GET 4,501                       COM
GET 5,601                       IE
GET 6,701                       EE
ADD 1,M=2,3,4,5,6                 Combine Trip Matrices for HBW, NW,
$                                    I/E, and EE Purposes
OUT 1,801                       Output Table # 801 FOR ALL PM TRIPS
```

```
*
$
$>DEL GF9511.DAT
$>DEL GF9512.DAT
$>DEL GF9513.DAT
$>DEL GF9514.DAT
$>DEL GF9515.DAT
$>DEL GF9516.DAT
$>DEL GF9517.DAT
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE OFF PEAK PERIOD O/D HBW TRIP MATRIX
$      (INCLUDES TRIPS FOR ALL THREE INCOME LEVELS) BY FACTORING THE
$      DAILY HBW P/A TRIP MATRIX WITH OFF PEAK PERIOD FACTORS
$
$      INPUT FILES = GF9511.DAT          P/A HBW Daily Trip Matrix
$
$      OUTPUT FILE = GF9512.DAT          O/D HBW OFF Peak Period Trip
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$>COPY GF95HBWS.MSJ GF9511.DAT
$
*PGM MATBAL 101,201,218,138,1000        Input & Output file #s, row,
$                                         column & scaling factors
*ID  CALCULATE OFF PEAK HBW O/D TRIP MATRIX
*PAR MSGLEV=3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE OFF PEAK PERIOD HBNW O/D TRIP MATRIX BY
$      FACTORING THE DAILY HBNW P/A TRIP MATRIX WITH OFF PEAK PERIOD
$      FACTORS
$
$      INPUT FILE = GF9511.DAT          P/A HBNW Daily Trip Matrix
$
$      OUTPUT FILE = GF9513.DAT         O/D HBNW OFF Peak Period Trip
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$>COPY GF95HNWS.MSJ GF9511.DAT
$
*PGM MATBAL 101,301,314,316,1000        Input & Output file #s, row,
$                                         column & scaling factors
*ID  CALCULATE OFF PEAK HBNW O/D TRIP MATRIX
*PAR MSGLEV=3
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE OFF PEAK PERIOD TRIP MATRIX FOR
$      NHB PURPOSE BY FACTORING THE DAILY O-D TRIP MATRICES WITH
$      OFF PEAK PERIOD FACTORS
$
$      INPUT FILES = GF9511.DAT          O-D Trip Matrix NHB (101)
$
```

```
$      OUTPUT FILE = GF9514.DAT          OFF Peak Period Trip Matrix for
$                                          NHB (Table 401)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  CALCULATE OFF PEAK NHB O/D TRIP MATRIX
*UNIT 11=GF95NHBS.MSJ
*PAR MSGLEV=3
GET 1=101                                 Input Tables
FAC 1,0.696,B                             NHB Factor
OUT 1,401                                 Output OFF NHB
*
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE OFF PEAK PERIOD TRIP MATRIX FOR
$      COM PURPOSE BY FACTORING THE DAILY O-D TRIP MATRIX WITH
$      OFF PEAK PERIOD FACTORS
$
$      INPUT FILES = GF9511.DAT          O-D Vehicle Trip Matrix COM
(101)
$
$      OUTPUT FILE = GF9515.DAT          OFF Peak Period Trip Matrix for
$                                          COM (Table 501)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  CALCULATE OFF PEAK COM O/D TRIP MATRIX
*UNIT 11=GF95COMS.VJ5
*PAR MSGLEV=3
GET 1=101                                 Input Tables
FAC 1,0.533,B                             COM Factor
OUT 1,501                                 Output OFF COM
*
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CALCULATES THE OFF PEAK PERIOD IE O/D TRIP MATRIX BY
$      FACTORING THE DAILY IE P/A TRIP MATRIX WITH OFF PEAK PERIOD
$      FACTORS
$
$       INPUT FILE = GF9511.DAT          P/A IE Daily Trip Matrix
$                                          (Table 101)
$
$      OUTPUT FILE = GF9516.DAT          O/D IE OFF Peak Period Trip
$                                          Matrix (Table 601)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$>COPY GF95IE.VJ5 GF9511.DAT
$
*PGM MATBAL 101,601,321,313,1000         Input & Output file #s, row,
$                                          column & scaling factors
*ID  CALCULATE OFF PEAK IE O/D TRIP MATRIX
*PAR MSGLEV=3
$
```

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$
$
$      THIS STEP CALCULATES THE OFF PEAK PERIOD TRIP MATRIX FOR
$      E-E PURPOSE BY FACTORING THE DAILY O-D TRIP MATRIX WITH
$      OFF PEAK PERIOD FACTORS
$
$      INPUT FILES = GF9511.DAT          O-D Vehicle Trip Matrix E-E
(101)
$
$      OUTPUT FILE = GF9517.DAT          OFF Peak Period Trip Matrix for
$                                          COM (Table 701)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  CALCULATE OFF PEAK EE O/D TRIP MATRIX
*UNIT 11=GF95EE.VJ5
*PAR MSGLEV=3
GET 1=101                                 Input Tables
FAC 1,0.634,B                             EE Factor
OUT 1,701                                 Output OFF EE TRIPS
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
$      THIS STEP CREATES THE OFF PEAK PERIOD O/D TRIP MATRIX BY COMBINING
$      THE TRIP MATRICES CALCULATED IN THE SIX PREVIOUS STEPS.  THE
$      OUTPUT MATRIX FROM THIS STEP IS READY TO BE ASSIGNED.
$
$       INPUT FILE = GF9512.DAT          O/D OFF PEAK HBW (201)
$                    GF9513.DAT               "      HBNW (301)
$                    GF9514.DAT               "      NHB (401)
$                    GF9515.DAT               "      COM (501)
$                    GF9516.DAT               "      I/E (601)
$                    GF9517.DAT               "      E-E (701)
$
$      OUTPUT FILE = GF95ODOP.VEH        OFF Peak Period Trip Matrix for
$                                        COM (801), OTHERS (802)
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$$$
$
*PGM MATRIX
*ID  COMBINE OFF PEAK O/D TRIP MATRICES
*UNIT 18=GF95ODOP.VEH                            Define output file
GET 1,201                       HBW
GET 2,301                       HBNW
GET 3,401                       NHB
GET 4,501                       COM
GET 5,601                       IE
GET 6,701                       EE
ADD 1,M=2,3,4,5,6                 Combine Trip Matrices for HBW, NW,
$                                    I/E, and EE Purposes
OUT 1,801                       Output Table # 801 FOR ALL PM TRIPS

*
$
$>DEL GF9511.DAT
$>DEL GF9512.DAT
$>DEL GF9513.DAT
```

```
$>DEL GF9514.DAT
$>DEL GF9515.DAT
$>DEL GF9516.DAT
$>DEL GF9517.DAT
$
*PGM MATRIX
*ID  COMBINE AM, PM, OP TRIP TABLES TO ONE ALL DAY TABLE
*UNIT 11=GF95ODAM.VEH,12=GF95ODPM.VEH,13=GF95ODOP.VEH
*UNIT 14=GF95ODAD.VEH                    Define output file
GET 1,101                       HBW
GET 2,201                       HBNW
GET 3,301                       NHB
ADD 1,M=2,3                 Combine Three Trip Matrices
OUT 1,401                       Output Table # 401 FOR ALL DAY TRIPS
*
```

Appendix B

MOBILE5A Control File For Emission Rate Estimates

```
1          PROMPT
1995 Base I/M Program, EQUILIBRIUM 5 ITERATIONS
1          TAMFLG
1          SPDFLG
2          VMFLAG
3          MYMRFG
1          NEWFLG
3          IMFLAG
1          ALHFLG
2          ATPFLG
1          RLFLAG
2          LOCFLG
2          TEMFLG
4          OUTFMT
4          PRTFLG
1          IDLFLG
3          NMHFLG
1          HCFLAG
 .049 .065 .067 .074 .080 .083 .082 .068 .065 .043
 .058 .052 .045 .034 .028 .024 .021 .019 .017 .009
 .007 .005 .003 .001 .001
 .058 .055 .044 .047 .047 .078 .071 .065 .062 .045
 .056 .060 .051 .035 .032 .031 .033 .033 .033 .021
 .017 .013 .009 .004 .000
 .058 .055 .044 .047 .047 .078 .071 .065 .062 .045
 .056 .060 .051 .035 .032 .031 .033 .033 .033 .021
 .017 .013 .009 .004 .000
 .066 .062 .049 .050 .052 .084 .096 .069 .064 .042
 .052 .054 .044 .030 .026 .025 .027 .027 .027 .018
 .014 .011 .007 .004 .000
 .049 .065 .067 .074 .080 .083 .082 .068 .065 .043
 .058 .052 .045 .034 .028 .024 .021 .019 .017 .009
 .007 .005 .003 .001 .001
 .058 .055 .044 .047 .047 .078 .071 .065 .062 .045
 .056 .060 .051 .035 .032 .031 .033 .033 .033 .021
 .017 .013 .009 .004 .000
 .110 .095 .116 .113 .080 .102 .079 .062 .037 .050
 .048 .055 .044 .001 .001 .001 .001 .001 .001 .001
 .001 .001 .000 .000 .000
 .001 .001 .001 .001 .001 .001 .001 .001 .001 .001
 .001 .989 .000 .000 .000 .000 .000 .000 .000 .000
 .000 .000 .000 .000 .000
82 20 41 90 03 01 095 2 1 2222 2111
82 20 91 20 03 01 095 2 2 2222 2111
82 75 20 2222 21 095. 22211111
DRCOG 1995       C  20.  55. 12.4 12.4 92 2
.001 .999 .027 .033 1
2 95 44.7 47.9  8.0  6.0 11.3
.569.220.110.032.004.003.062.000    CBD      FREEWAY
2 95 24.7 47.9 41.1 11.3 51.9
.641.185.093.026.004.002.049.000    CBD      PRINCIPAL ARTERIAL
```

```
2 95 21.1 47.9 41.1 11.3 51.9
.641.185.093.026.004.002.049.000    CBD      MINOR ARTERIAL
2 95 18.8 47.9 38.7  8.5 47.9
.641.185.093.026.004.002.049.000    CBD      COLLECTOR
2 95 34.1 47.9 41.1 11.3 51.9
.641.185.093.026.004.002.049.000    CBD      RAMP
2 95 11.2 47.9 38.7  8.5 47.9
.641.185.093.026.004.002.049.000    CBD      LOCAL
2 95 35.6 47.9  8.0  6.0 11.3
.569.220.110.032.004.003.062.000    FRINGE   FREEWAY
2 95 32.5 47.9  8.0  6.0 11.3
.569.220.110.032.004.003.062.000    FRINGE   MAJOR REGIONAL
2 95 29.0 47.9 31.8 16.7 42.8
.679.167.084.022.004.002.042.000    FRINGE   PRINCIPAL ARTERIAL
2 95 26.5 47.9 31.8 16.7 42.8
.679.167.084.022.004.002.042.000    FRINGE   MINOR ARTERIAL
2 95 23.3 47.9 32.0 12.0 42.0
.679.167.084.022.004.002.042.000    FRINGE   COLLECTOR
2 95 32.0 47.9 31.8 16.7 42.8
.679.167.084.022.004.002.042.000    FRINGE   RAMP
2 95 14.7 47.9 32.0 11.9 42.2
.679.167.084.022.004.002.042.000    FRINGE   LOCAL
2 95 40.5 47.9 10.3  6.2 13.7
.656.184.092.021.004.002.041.000    URBAN    FREEWAY
2 95 34.3 47.9 16.5 12.0 23.2
.600.225.112.019.004.003.037.000    URBAN    MAJOR REGIONAL
2 95 31.6 47.9 22.3 14.9 31.7
.663.190.095.016.004.002.030.000    URBAN    PRINCIPAL ARTERIAL
2 95 30.7 47.9 45.9 32.1 63.8
.693.171.085.015.004.002.030.000    URBAN    MINOR ARTERIAL
2 95 24.5 47.9 31.4 21.2 43.4
.702.179.089.008.004.002.016.000    URBAN    COLLECTOR
2 95 32.8 47.9 22.3 14.9 31.7
.663.190.095.016.004.002.030.000    URBAN    RAMP
2 95 16.8 47.9 23.1 16.5 33.5
.702.179.089.008.004.002.016.000    URBAN    LOCAL
2 95 51.3 47.9 15.5  8.7 20.5
.595.216.108.025.004.003.049.000    SUBURBAN FREEWAY
2 95 35.7 47.9 14.8 19.5 21.5
.519.253.127.032.003.003.063.000    SUBURBAN MAJOR REGIONAL
2 95 38.8 47.9 16.5  9.7 21.5
.624.207.103.021.004.002.039.000    SUBURBAN PRINCIPAL ARTERIAL
2 95 36.0 47.9 33.6 21.4 43.6
.644.198.099.018.004.002.035.000    SUBURBAN MINOR ARTERIAL
2 95 28.3 47.9 35.4 22.9 48.0
.635.226.113.006.004.003.013.000    SUBURBAN COLLECTOR
2 95 36.8 47.9 16.5  9.7 21.5
.624.207.103.021.004.002.039.000    SUBURBAN RAMP
2 95 20.3 47.9 24.4 15.9 32.8
.635.226.113.006.004.003.013.000    SUBURBAN LOCAL
2 95 57.4 47.9 19.3  7.7 25.0
.459.210.105.076.003.002.145.000    RURAL    FREEWAY
2 95 49.4 47.9  3.8  1.7  5.5
.526.227.114.044.003.003.083.000    RURAL    MAJOR REGIONAL
2 95 46.3 47.9 15.5 11.0 22.2
.558.242.121.025.003.003.048.000    RURAL    PRINCIPAL ARTERIAL
2 95 43.5 47.9 15.5 11.0 22.2
.558.242.121.025.003.003.048.000    RURAL    MINOR ARTERIAL
2 95 34.4 47.9 28.6 11.2 37.8
.558.242.121.025.003.003.048.000    RURAL    COLLECTOR
2 95 38.3 47.9 15.5 11.0 22.2
.558.242.121.025.003.003.048.000    RURAL    RAMP
```

```
2 95 27.5 47.9 28.6 11.2 37.8
.558.242.121.025.003.003.048.000     RURAL     LOCAL
```

Appendix C

PASCAL Program for Calculating NVSFIV

```
program trapezoidal (input,output);
   {This program uses method}
   {to calculate integral value of different volume-speed functions}

   var
      e : real;             { error limit}
      h : real;             { step length}
      T1, T2 : real;        {T1 for temporary storage, T2 for final
integral value}
      s : real;
      x, x1, x2 : real;     { lower and upper limits of integrand}
      y, spd : real;        { speed variable}
      mm, nn : integer;     { switch variables used for function
selection}
      F: integer;           {}

   function vs(y, spd : real; mm, nn : integer): real;
       begin
          case mm*10+nn of
             11, 12, 13 : vs :=  spd / (1 + 0.15 * exp(4 * ln(y)));
             21 : vs := spd / (1 + 0.66 * exp(7.2 * ln(y)));
             22 : vs := spd / (1 + 0.76 * exp(5.9 * ln(y)));
             23 : vs := spd / (1 + 0.73 * exp(2.1 * ln(y)));
             31 : vs := spd / exp(exp(7.9 * ln(y)) * ln (1.84));
             32 : vs := spd / exp(exp(5.7 * ln(y)) * ln (1.875));
             33 : vs := spd / exp(sqr(y) * ln (1.84));
             41 : vs := spd / (1 + 0.23 * exp(8.1 * ln(y)));
             42 : vs := spd / (1 + 0.57 * exp(9.2 * ln(y)));
             43 : vs := spd / (1 + 0.08 * exp(5.5 * ln(y)));
             51 : vs := spd / exp(exp(7.6 * ln(y)) * ln (1.225));
             52 : vs := spd / exp(exp(8.7 * ln(y)) * ln (1.62));
             53 : vs := spd / exp(exp(5.3 * ln(y)) * ln (1.078))
          end; {of CASE mm*10+nn}
       end; {end of FUNCTION vs}

   procedure input1(var m : integer);
      begin
         writeln ('This program is to calculate the integral value of');
         writeln ('Volume-speed function used in traffic assignment');
         writeln;
         repeat
            writeln ('There are three choices on selecting the types of
base functions:');
            writeln ('Enter 1 to select Original BPR functions');
            writeln ('Enter 2 to select Modified BPR - HCM85
functions');
            writeln ('Enter 3 to select Overgarrd - HCM85 functions');
            writeln ('Enter 4 to select Modified BPR - HCM94
functions');
            writeln ('Enter 5 to select Overgarrd - HCM94 functions');
            writeln ('Enter 6 to exit the system');
            writeln;
```

```
            writeln ('Please enter your choice and followed by the
<Enter> key.');
            readln (m)
          until (m > 0) and (m < 7);

        case m of
           1 : writeln ('You have selected Original BPR function');
           2 : writeln ('You have selected Modified BPR - HCM85
functions');
           3 : writeln ('You have selected Overgarrd - HCM85 functions');
           4 : writeln ('You have selected Modified BPR - HCM94
functions');
           5 : writeln ('You have selected Overgarrd - HCM94 functions');
           6 : writeln ('You have selected to EXIT');
        end;  {end of CASE m }
        writeln
     end;

     procedure input2(var n : integer);
        begin
        repeat
           writeln ('There are three choices on selecting the highway
facilitiy types:');
           writeln ('Enter 1 to select the freeways');
           writeln ('Enter 2 to select the arterials');
           writeln ('Enter 3 to select the multi-lane highways');
           writeln ('Enter 4 to exit the system');
           writeln;
           writeln ('Please enter your choice and followed by the <Enter>
key.');
           readln (n);
        until (n > 0) and (n < 5);

        case n of
           1 : writeln ('You have selected freeway facility');
           2 : writeln ('You have selected arterial facility');
           3 : writeln ('You have selected multi-lane highway facility');
           4 : writeln ('You have selected to EXIT');
        end; { end of CASE n}
        writeln;

        end; {end of procedure input2}


     procedure input3(var speed, llimt, ulimt : real);
        begin
        repeat
           writeln ('Please select the free flow speed followed by
<Enter> key');
           readln (speed)
        until (speed > 0) and (speed <= 65);
        repeat
           repeat
              writeln ('Please select the integrand lower limit followed
by <Enter> key');
              readln (llimt)
           until (llimt >= 0) and (llimt < 200);
           repeat
              writeln ('Please select the integrand upper limit followed
by <Enter> key');
              readln (ulimt)
           until (ulimt >= 0) and (ulimt < 200);
```

```
        until llimt < ulimt;
        writeln
        end; { end of procedure input3}


begin  { of MAIN program}
   input1 (mm);
   if mm <> 6 then
      begin
         input2 (nn);
         if nn <> 4 then
            begin
               input3 (spd, x1, x2);

               e := 0.0001;
               h := x2 - x1;
               T1 := h/2 * (1 + vs(x2, spd, mm, nn));
               F := 0;

               repeat
                  if F=1 then
                  begin
                     h := h/2;
                     T1 := T2;
                  end;
                  s := 0;
                  x := x1 + h/2;

                  repeat
                     s := s + vs(x, spd, mm, nn);
                     x := x + h
                  until x >= x2;

                  T2 := T1/2 + h/2 * s;
                  writeln('T2:', T2);
                  F := 1
               until abs(T2 - T1) < e;
               writeln('T2:', T2);
            end
         end
end. { of main program}
```

VITA

Li-Yang Feng is a transportation planner III of the Denver Regional Council of Governments. He had a M. S. degree in civil engineering from the University of Tennessee, and a B. E. degree in transportation from the Shanghai Institute of Railway Technology, China. He has 14 years of experience in transportation engineering, especially in transportation modeling and quantitative analysis. He previously served as a transportation engineer for the Shanghai Bureau of Public Utilities, China, and for the Wilbur Smith Associates. He is a Member of the Institute of Transportation Engineers.