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# A Framework for the Nationwide Multimode Transportation Demand Analysis

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16. Abstract

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Abstract

This study attempts to analyze the impact of traffic on the US highway system considering both passenger vehicles and trucks. For the analysis, a pseudo-dynamic traffic assignment model is proposed to estimate the time-dependent link flow from the intercity travelers on the network covering the continental U.S. A two-stage simulation scheme was designed to separate the intercity and non-intercity travelers involved in the link flow. The fuel consumption and emissions from the intercity travelers are estimated based on data in Mobile, the emission model developed by EPA. The suggested methodology could be adopted in further deployment of a nationwide transportation system analysis model that supports the evaluation of planned transportation improvement plans. Several suggestions are made for future study.

# Chapter 1 Introduction

The number of intercity travelers has been increasing during recent years and this poses a serious challenge for the current nationwide highway transportation system. In order for transportation planners and engineers to create efficient modes of transportation, an accurate prediction of the impact of the intercity travel demand is essential in evaluating or expanding the current transportation system network. When considering management strategies, the intercity transportation providers, such as Amtrak and airliners, are particularly interested in long distance traveler demand in association with the travel cost and travel time experienced by the travelers. For the environmentalist, the amount of pollution generated by automobiles is of great concern. Cars typically consume more fuel and thus create more emissions per capita when compared with other long distance public transportation modes, such as trains and planes. Moreover, the negative effects of those travelers on the transportation system and environment provide significant incentives for the government to invest funding sources in the infrastructure system or other alternatives. One of the most important estimates measuring those effects is the traffic pattern of intercity travelers, for example, how those travelers will be distributed throughout the network.

The primary tool for projecting these estimates of the traffic pattern of intercity travelers has long been the Static Traffic Assignment (STA). During recent decades, research efforts have focused on solving the STA problem. According to the assumptions on travelers' route choice behavior, the solution methods can be classified into the following four types. The first type is the All or Nothing (AON) traffic assignment, which assumes that every traveler has perfect information about link travel impedance. Therefore, the traveler chooses the route with the least travel impedance without considering the effect of other travelers' choices. As a result, all origin-destination (OD) demand will use the route with the least travel impedance connecting the OD pair and no travelers will use any the other connecting routes. The second type is the User Equilibrium (1) assignment, which assumes that travelers have perfect network information and consider other travelers when making choices. A User Equilibrium (UE) state is reached when no traveler can reduce his travel impedance by unilaterally changing his route. In addition, for all the routes connecting the same OD pair, those having non-zero traveler flow will have the same travel impedance and this impedance is the smallest for this OD pair. The third type is the System Optimal (SO) traffic assignment, which assumes that travelers choose their routes in such a way that the total travel time in the network is minimized. This situation cannot exist in reality because under the SO state, travelers can reduce their travel impedance by unilaterally changing their routes. Usually, it serves as a yardstick by which the performance of different flow patterns can be measured. The last type is the Stochastic User Equilibrium (SUE) traffic assignment, which considers the travelers' preference and perception errors with a certain probability density function. In SUE assignment, travelers choose the routes with minimum perceived travel impedance. A SUE is reached when no travelers can reduce his perceived travel impedance by unilaterally changing his route.

The four types of STA do provide important benefits in transportation planning, but there are significant drawbacks. In STA, the dynamic features of traffic demand and network conditions are ignored. As is easily observed, traffic flows are not necessarily uniformly distributed, but fluctuate over time, especially during the rush hour. It is logical that congestion and delays may occur at different locations at different time. For example, according to traffic flow data, drivers may experience more delays from 7:00 AM to 8:30 AM on suburban roads, and from 7:00 AM to 9:30 AM on highways than any other time period. This shortcoming of STA makes it an inadequate tool to model intercity traffic assignment. STA may significantly underestimate the congestion effects caused by temporary intercity demand exceeding the capacity as STA relies on the uniformly distributed average intercity demand, which may turn out to be far less than the capacity. Furthermore, STA cannot capture the speed variance of intercity drivers resulting from the dynamics of local traffic. Intercity travelers have to share roads with local drivers, thus the local dynamic traffic conditions will have a significant influence on the speed of intercity travelers. For instance, the intercity travelers may be slowed down by the local stop-and-go type of traffic during the peak hours. Speed variance is a very crucial factor that influences emissions and fuel consumption. Unfortunately, this effect cannot be appropriately captured by the STA methods. In fact, emissions and fuel consumption is potentially underestimated by STAP methods. The third issue is that some intercity travelers choose their departure time or even part of their routes to avoid expected congestions at certain time periods. In STA methods, the drivers' dynamic choice behaviors cannot be accounted for since no such information can be provided on time-variant traffic condition.

Due to the shortcomings of STA, it was necessary to develop other approaches for transportation planning and management. Dynamic Traffic Assignment (DTA) provides an effective way to estimate the time-dependent traffic flow and speed variance in the network. Besides the time-dependent OD demand, one of the major differences between STA and DTA concerns link travel impedance. In STA, it is assumed the instantaneous link travel impedance measured at the moment when the travelers choose their routes is the travel impedance they will experience in the network. It is also assumed that travelers will contribute to the flows of all the links that are on the selected routes. In DTA, as travelers move along their routes, new travelers will keep entering the network and share the same roadways. Travelers' experienced travel impedance may be different from the instantaneous travel impedance estimated when entering the network because those who enter afterwards may have more significant impact on link travel impedance. Moreover, at each moment, each traveler can contribute to the flow of only one link on his route. If all of the time-dependent OD information is available over the entire period of study, then the concepts for the STA can be generalized to the time-dependent case (2). The route travel impedance is computed based on the time-dependent link impedance instead of the instantaneous link impedance. This general overview served to provide some insight to the advantages of DTA models before examining DTA in more detail.

DTA models are typically classified into two categories: mathematical and simulation based. Peeta and Ziliaskopoulos (3) and Peeta (4) provide an excellent review of the two approaches. Mathematical approaches can be further divided into three sub-categories: mathematical programming models as proposed by Janson (6), Smith (7), and Ziliaskopoulos (8); optimal control theory based formulations designed in Friesz, et al (9); and variational inequality methods introduced in Boyce, et al

(10), Lee (11), Ran, et al (12), and Ran et al (13). Most mathematical formulations are a generalization of their equivalent static formulations and suffer from two main disadvantages. First, they may not be able to adequately capture the realities due to over simplifications of networks' topology and driver behaviors. Second, they are generally difficult to solve mathematically and tend to be intractable for large size networks.

Simulation based approaches overcome these disadvantages and have been incorporated in solution algorithms to be used directly for a solution. For example, DYNASMART is incorporated as a simulator in the solution algorithms proposed by Peeta and Mahmassani (2); Mahmassani, et al (14); Peeta and Mahmassani (15); and Ziliaskopoulos, et al (16). DYNAMIT is also utilized as part of the DTA system intended for generating real-time prediction-based guidance information by Ben-Akiva, et al (17). Although simulation models can't provide the analytical insight and guarantee the uniqueness and convergence of the solution, they have been considered an efficient way to reduce the mathematical complexity, as well as computational time. In this study, a simulation method is developed and adopted for the DTA. The goal of this study is to propose a pseudo-dynamic traffic assignment (PDTA), which can give a fair estimation of the time-dependent traffic flow pattern, emissions, and fuel consumption resulting from the intercity demand for the continental U.S. transportation network.

The report is organized as follows: the methodology is given in chapter 2, input data is presented in chapter 3, simulation results and analysis are shown in chapter 4, and the conclusions and recommended future work are discussed in chapter 5.

# Chapter 2 Methodology

## 2.1 Computation Issues and Simulation Assumptions

In order to further understand the concerns we wish to address, we present the computational difficulties involved in the PDTA simulation model. Firstly, inter-city traffic assignment at the national level involves a large-scale network with great variation in traffic conditions. In the simulation model, vehicle interactions at the microscopic level, such as first in, first out (FIFO) and delay holding, have to be considered. For a small or even medium network, it is possible to incorporate the microscopic vehicle interactions but it is impractical for the network scale of our study. Secondly, travelers may stay in the network for a relatively long period before reaching destinations which would require excessive computational efforts and memory to trace. Thirdly, travelers with different preferences and trip purposes may react differently given the same traffic situation. As a result, a large amount of computation time has to be spent on deciding their shortest routes. To simplify the computational complexity, the following assumptions are made: 1) Travelers are assumed to be homogeneous in terms of information availability, the type of information, and their reaction to the information; 2) Travelers are assumed to have no information about the time-dependent OD demand. Thus, they have no information about the routes travel impedance from the time-dependent link impedance. However, they do have some static link information, such as speed limit and local traffic conditions estimated when they depart. They will choose the shortest routes based on this instantaneous traffic condition; 3) The route travel impedance of travelers entering the network is assumed not to be affected by those who enter the network afterwards. This means that travelers choose their routes based on the travel impedance estimated at the moment they enter the network. Furthermore, the route travel impedance they will experience is assumed to be the same as the impedance at the moment when they made the decision; 4) The microscopic-level vehicle interactions are not considered. Instead, the macroscopic relationship between speed and flow is applied to estimate the delays on each link.

## 2.2 Simulation Model

Our simulation is macro-level and based on the supposition that at each time interval, an OD demand is generated and travelers choose their shortest routes based on the current local traffic flow. All of the travelers of an OD pair departing at time interval *k* are assumed to stay together in a queue on their route (note that based on the aforementioned assumptions 1 and 2, they will stay on the same route with the least instantaneous travel impedance estimated when entering the network). The queue will never break but it can be expanded or squeezed based on the traffic conditions. At each time interval, only the position of the first and last vehicle in the queue is updated and the length of queue is computed as the distance between the two vehicles. Such scheme has been successively applied to estimate the assignment matrix for Kalman Filter (18). The vehicle distribution among the links that form the queue depends on the links' travel time. The queue contributes to the flow of the links it covers at each time interval. Figure 2.1 illustrates the calculation of vehicle distribution; where *N* is the number of vehicles in the queue, *T* is the travel time from the tail to the head of the queue, *T1* represents the time needed for the tail to reach node *B*, *T2* is the travel time from node *B* to *C*, *T3* means the travel time needed to travel from node *C* to the head. Figure 2.2 presents the flow chart of the pseudo-dynamic traffic assignment scheme. The simulation procedure in its entirety can be found in chapter 4.

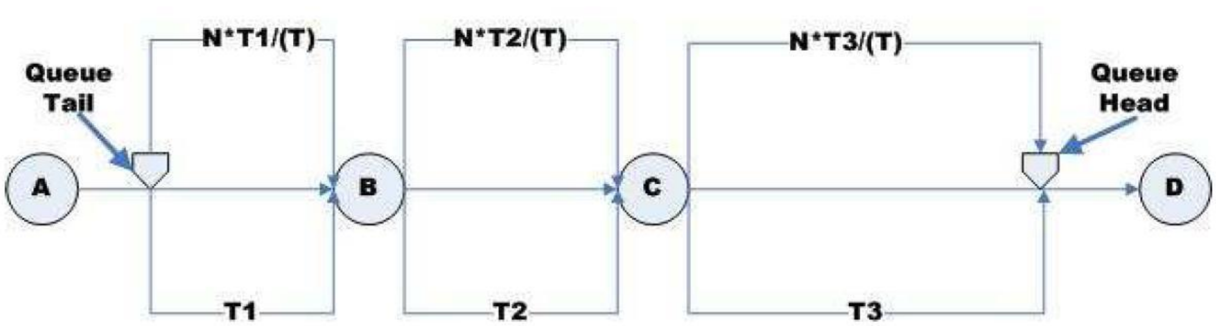


**Figure 2.1** Example on How to Calculate the Vehicle Distribution in the Queue

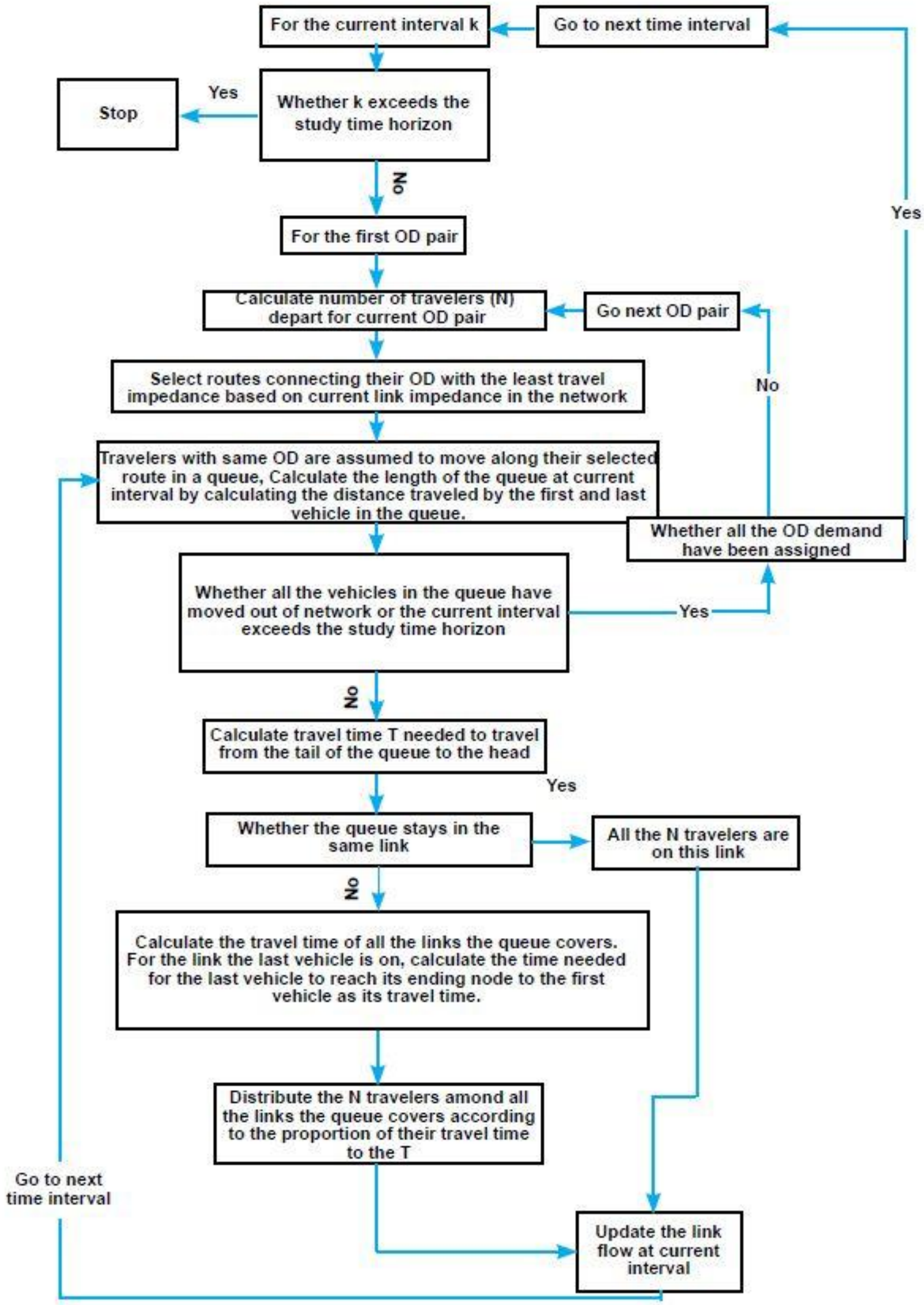


**Figure 2.2** Flow Chart of the Pseudo-Dynamic Traffic Assignment

## 2.3 Shortest Path Algorithm

The algorithm utilized in our study is known as the label−correcting method. It finds the shortest path from a given origin to all other nodes in the network. A detail description of the algorithm is presented in Sheffi's research (19). The shortest path algorithm is implemented using parallel computing toolbox available in Matlab.

# Chapter 3 Input Data

## 3.1 Network

The Freight Analysis Framework-2 (FAF2) network originally prepared for analyzing freight movement by truck encompasses the highway system in the continental US and Alaska (Alaska not included in this study). The network data contains information about the length, direction, capacity, Annual Average Daily Traffic (AADT), and AADTT (Annual Average Daily Truck Traffic) on each link of roadways. While FAF2 provides AADT and AADTT in both directions for bi-directional roadways, the capacity is given for one direction on multilane facilities and for both directions on 2-or 3-lane facilities. Note that FAF2 data only contains information about whether the road is bi-directional or not, no further details are given. Each roadway link is assigned to a RUCODE) and a Functional Class (FClass) denoting its location and the functional type, respectively. The corresponding descriptions are given in tables 3.1 and 3.2. Table 3.3 summarizes the distribution of directional roadways by FClass and state.

The number of lanes is inevitable information in characterizing the link performance function, namely speed-volume (or speed-delay) relationship. However, it should be pointed out that the number of lanes on each roadway is not provided in FAF2. In order to overcome this practical impediment, the directional capacity is estimated by assuming the capacity of roads with functional class 1, 2, 11, and 12 are given in one direction, and the others in both directions. Some pre-processing effort is also applied to the original network, for instance fixing the link connectivity and missing data. So as to represent an aggregate of trip origins and destinations, a total of 3,625 traffic nodes (3,076 county centroids plus 549 airports) were added to the original network, as well as 3,625 bi-direction connectors that connect the traffic nodes to the highway network. It is assumed that the connectors have an infinite capacity with zeros travel impedance. The highway network and traffic nodes are illustrated in figure 3.1.

**Table 3.1** Description of RUCODE

| RUCODE | Description |
|---|---|
| 1 | Rural |
| 2 | Small urban area (populations 5,000 to 49,999) |
| 3 | Small urbanized area (population 5,000 to 199,999) |
| 4 | Large urbanized area (population 200,000 or more) |

**Table 3.2** Description of Functional Class

| Functional Class | Description |
|---|---|
| 0 | No info |
| 1 | Rural principal arterial-Interstate |
| 2 | Rural principal arterial-Other |
| 6 | Rural minor arterial |
| 7 | Rural major collector |
| 8 | Rural minor collector |
| 9 | Rural local |
| 11 | Urban principal arterial-Interstate |
| 12 | Urban principal arterial-other freeways and expressways |
| 14 | Urban principal arterial-other |
| 16 | Urban minor arterial |
| 17 | Urban collector |
| 19 | Urban local |

**Table 3.3** Directional Roadways by Functional Class and State

| FClass/ State | AL | AK | AZ | AR | CA | CO | CT | DE | DC | FL | GA | HI | ID | IL | IN | IA | KS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 122 | 82 | 138 | 76 | 274 | 142 | 18 | 0 | 0 | 220 | 244 | 0 | 74 | 324 | 162 | 120 | 108 |
| 2 | 446 | 54 | 142 | 480 | 717 | 346 | 44 | 90 | 0 | 908 | 1022 | 70 | 218 | 710 | 398 | 826 | 662 |
| 6 | 792 | 52 | 160 | 604 | 1274 | 468 | 194 | 78 | 0 | 788 | 1998 | 90 | 158 | 1125 | 458 | 752 | 756 |
| 7 | 10 | 4 | 10 | 4 | 16 | 4 | 0 | 0 | 0 | 2 | 20 | 0 | 0 | 0 | 6 | 6 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | 0 |
| 11 | 206 | 54 | 158 | 188 | 1535 | 206 | 282 | 46 | 38 | 386 | 368 | 68 | 75 | 638 | 280 | 134 | 200 |
| 12 | 22 | 0 | 166 | 90 | 1876 | 224 | 326 | 20 | 50 | 355 | 124 | 30 | 0 | 74 | 122 | 0 | 142 |
| 14 | 801 | 80 | 1222 | 774 | 10571 | 1162 | 930 | 286 | 352 | 2688 | 2284 | 230 | 498 | 3016 | 1515 | 794 | 885 |
| 16 | 24 | 20 | 28 | 8 | 209 | 42 | 8 | 4 | 4 | 254 | 63 | 2 | 0 | 181 | 0 | 44 | 2 |
| 17 | 0 | 2 | 8 | 0 | 42 | 12 | 2 | 0 | 0 | 20 | 18 | 2 | 12 | 110 | 0 | 4 | 4 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 4 | 0 | 0 | 41 | 0 | 10 | 0 |
| Noninfo | 460 | 390 | 315 | 386 | 436 | 249 | 502 | 78 | 56 | 748 | 1361 | 278 | 218 | 352 | 290 | 314 | 302 |
| Missing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 2883 | 738 | 2347 | 2612 | 16950 | 2857 | 2306 | 602 | 500 | 6381 | 7508 | 770 | 1253 | 6571 | 3231 | 3006 | 3061 |

**Table 3.3** Directional Roadways by Functional Class and State (cont.)

| FClass/ State | KY | LA | ME | MD | MA | MI | MN | MS | MO | MT | NE | NV | NH | NJ | NM | NY | NC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 122 | 130 | 90 | 66 | 54 | 202 | 172 | 92 | 168 | 156 | 62 | 52 | 46 | 40 | 122 | 342 | 178 |
| 2 | 568 | 256 | 214 | 220 | 113 | 564 | 862 | 506 | 602 | 212 | 512 | 132 | 96 | 232 | 212 | 884 | 640 |
| 6 | 420 | 378 | 334 | 274 | 264 | 860 | 1511 | 710 | 536 | 314 | 752 | 66 | 112 | 280 | 192 | 1873 | 658 |
| 7 | 10 | 12 | 2 | 0 | 0 | 12 | 2 | 14 | 2 | 0 | 0 | 2 | 0 | 2 | 0 | 36 | 22 |
| 8 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 182 | 306 | 72 | 340 | 432 | 576 | 194 | 146 | 402 | 48 | 64 | 60 | 48 | 302 | 134 | 1006 | 302 |
| 12 | 88 | 50 | 32 | 255 | 273 | 286 | 112 | 34 | 298 | 0 | 26 | 34 | 34 | 342 | 2 | 1142 | 317 |
| 14 | 1000 | 1154 | 376 | 1387 | 2986 | 3015 | 557 | 846 | 1400 | 328 | 586 | 244 | 160 | 1603 | 922 | 5784 | 1593 |
| 16 | 16 | 44 | 18 | 74 | 14 | 20 | 12 | 10 | 0 | 0 | 0 | 8 | 0 | 128 | 0 | 1092 | 24 |
| 17 | 6 | 0 | 8 | 16 | 0 | 20 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 26 | 0 | 6 | 0 |
| 19 | 2 | 4 | 0 | 13 | 2 | 4 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 34 | 0 | 12 | 2 |
| Noninfo | 635 | 696 | 390 | 232 | 302 | 443 | 435 | 494 | 264 | 112 | 168 | 172 | 130 | 242 | 426 | 2381 | 1041 |
| Missing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 3059 | 3030 | 1536 | 2879 | 4440 | 6002 | 3867 | 2860 | 3672 | 1170 | 2170 | 770 | 626 | 3233 | 2010 | 14558 | 4777 |

**Table 3.3** Directional Roadways by Functional Class and State (cont.)

| FClass/ State | ND | OH | OK | OR | PA | RI | SC | SD | TN | TX | UT | VT | VA | WA | WV | WI | WY | Missing |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 88 | 200 | 142 | 120 | 336 | 8 | 206 | 122 | 132 | 408 | 116 | 76 | 208 | 118 | 96 | 176 | 116 | 0 |
| 2 | 554 | 746 | 380 | 356 | 958 | 42 | 438 | 428 | 428 | 1132 | 122 | 94 | 446 | 415 | 284 | 1002 | 234 | 2 |
| 6 | 332 | 674 | 458 | 390 | 1694 | 42 | 956 | 514 | 660 | 1440 | 218 | 180 | 852 | 352 | 362 | 1136 | 146 | 2 |
| 7 | 0 | 20 | 4 | 4 | 4 | 0 | 0 | 0 | 2 | 30 | 0 | 0 | 2 | 4 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 48 | 801 | 234 | 196 | 490 | 86 | 136 | 54 | 328 | 1200 | 148 | 34 | 378 | 364 | 106 | 196 | 72 | 0 |
| 12 | 0 | 556 | 158 | 80 | 524 | 92 | 60 | 0 | 112 | 1195 | 10 | 34 | 258 | 521 | 36 | 253 | 2 | 0 |
| 14 | 192 | 2805 | 910 | 1198 | 3768 | 602 | 708 | 298 | 1266 | 6162 | 257 | 126 | 1212 | 2554 | 388 | 1849 | 190 | 0 |
| 16 | 0 | 57 | 94 | 60 | 38 | 2 | 0 | 0 | 34 | 165 | 2 | 0 | 42 | 63 | 0 | 12 | 0 | 0 |
| 17 | 0 | 26 | 0 | 30 | 43 | 2 | 0 | 0 | 10 | 82 | 0 | 0 | 2 | 10 | 0 | 4 | 0 | 0 |
| 19 | 0 | 48 | 0 | 24 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Non-info | 178 | 571 | 478 | 302 | 629 | 44 | 270 | 98 | 330 | 1742 | 190 | 168 | 616 | 855 | 234 | 520 | 238 | 2 |
| Missing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 |
| Total | 1392 | 6504 | 2858 | 2768 | 8484 | 920 | 2774 | 1514 | 3298 | 13560 | 1063 | 712 | 4016 | 5256 | 1506 | 5148 | 998 | 26 |

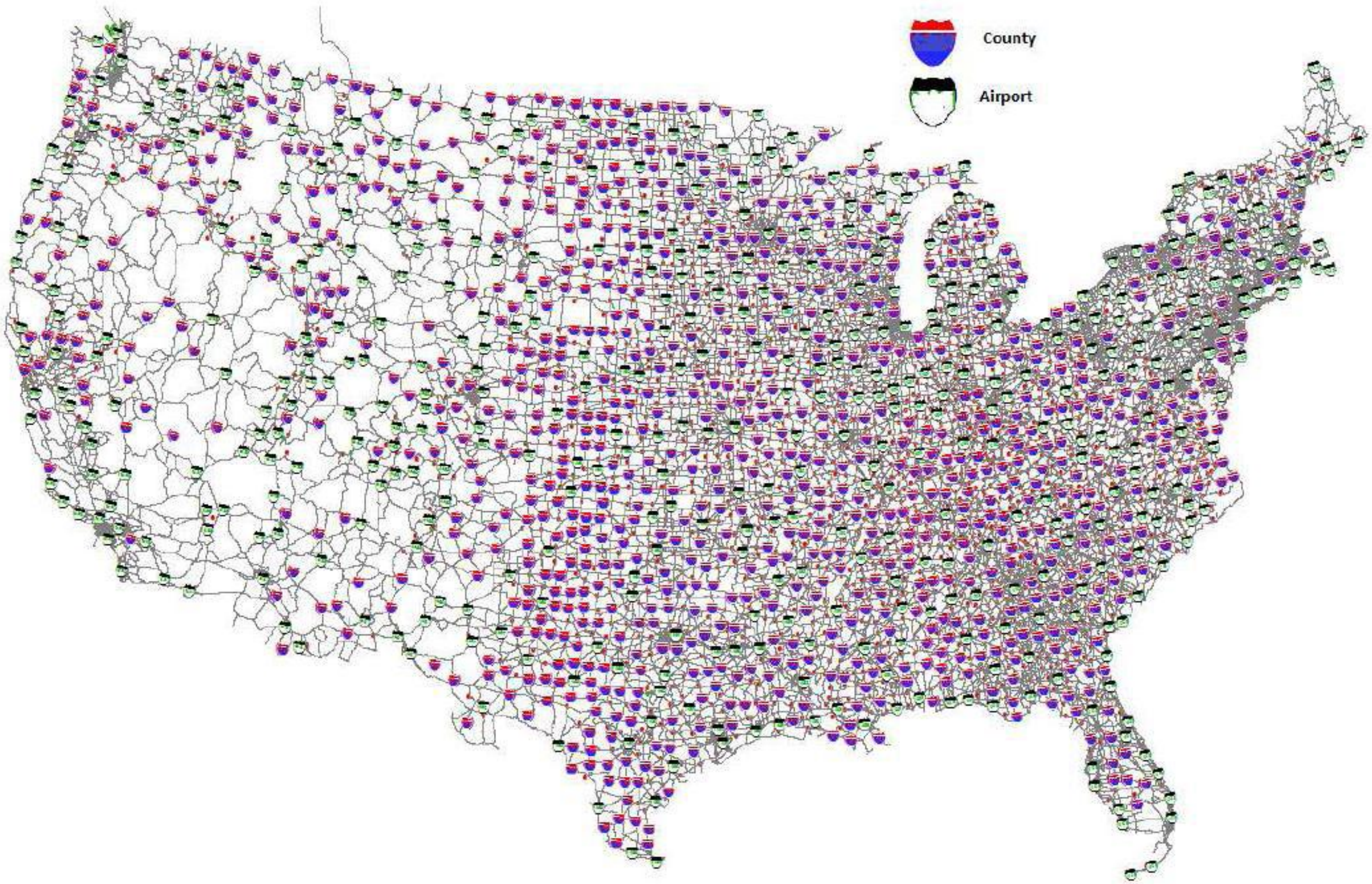


**Figure 3.1**: The US Highway Network and County Centroid

3.2 Link Performance Function

Link performance function plays a key role in the traffic assignment. It provides a measurement of the link travel impedance, for instance travel time or travel time reliability. Among various types of functions, the Bureau of Public Roads (BPR) function is widely adopted by the planners. The function is given as by:

$$TT = FFT \times (1 + \alpha\,(V/C)\beta) \qquad (3.1)$$

where, *TT* is the link travel time, *FFT* is the link free flow travel time, α > 0 and β > 0 are parameters to be calibrated (typically α = 0.15, β = 4.0), *V* is the link volume, and *C* is the link capacity.

Note that BPR function is convex and derivable in terms of *V*, which ensures certain desirable properties, such as uniqueness of any optimization problem using the function, resulting in computational simplicity. However, FAF2 data set contains no information about the parameters α and β for each link.

Another way for estimating the link travel time is to use a heuristic equation derived from the observational data. The following equation is the one that the Highway Capacity Manual (HCM) (21) offers based on the traffic data collected for years:

$$TT=FFT+D_0+ 0.25\times T\times[\ VC-1 + VC-1\ 2+16\times J\times V/C\times L2T2 \qquad (3.2)$$

where, *TT* = the travel time in hours, *FFT* = the free flow travel time in hours, $D_0$ = zero flow control delay at signalized intersections in hours, *T* = the expected duration of demand in hours (typically 1 hr is used), *V/C* = link volume to link capacity ratio, *J* = calibration parameter, and *L* = link length in miles.

The *FFT* is also empirically computed for each roadway by the following equation (21):

$$FFS = 0.88 \times \text{Speed Limit} + 14, \text{ for speed limit} > 50\text{mph, and} \quad (3.3)$$

$$FFS = 0.79 \times \text{Speed Limit} + 12, \text{ for speed limit} \leq 50\text{mph.} \quad (3.4)$$

The link speed limit needed in equations (3.3) and (3.4) is not provided in the original FAF2 data. This lack of practical information is compensated by using the speed limit provided by HCM (21) as a function of the functional class (i.e., FClass) of each roadway. The speed limit for each FClass and its corresponding FFS are given in table 3.5. The value of *J* in equation (3.2) is chosen based on the RUCODE, FClass, and speed limit. The scheme is demonstrated in table 3.4. The $D_0$ in equation (3.2) is computed by the following equation (21):

$$D_0 = (N/3600) \times AF \times (CL/2) \times (1 - EG/CL)2 \quad (3.5)$$

where, *N* = the number of signals on the link, 3600 = the conversion factor converting seconds to hours, *EG* = the effective green time per cycle for signals on link, *CL* = average cycle length (*s*) for all signals on link and *AF* = the adjustment factor to compute zero-flow control delay.

In this study, it is assumed that following the default values suggested in HCM, *AF* = 1,0, *EG*/*CL* = 0.45 and *CL* = 100s. Table 3.5 shows a signal density factor (=signals/mi) is given in

HCM as a function of FClass. Then, the $N$ of each road in equation (3.5) is calculated by multiplying its signal density by road length.

**Table 3.4** Selection of $J$ Value

| RUCODE Type | Functional Classification | Free Flow Speed (mph) | J |
|---|---|---|---|
| 1 | -- | 70.1-85.0 | 2.69E-05 |
| | | 65.1-70.0 | 2.10-O5 |
| | | 60.1-65.0 | 1.48E-05 |
| | | 55.1-60.0 | 8.65E-06 |
| | | >55.0 | 3.31E-06 |
| 2 | -- | 55.1-80.0 | 2.30E-06 |
| | | 50.1-55.0 | 2.03E-06 |
| | | 45.1-50.0 | 1.63E-06 |
| | | >45.0 | 2.52E-06 |
| 3 | -- | 63.1-80.0 | 6.91E-05 |
| | | 56.1-63.0 | 0.000114 |
| | | 50.1-56.0 | 0.000202 |
| | | 44.1-50.0 | 0.000400 |
| | | >44.0 | 0.000929 |
| 4 | 14 | -- | 0.000468 |
| | 16 | | 0.000502 |
| | 17 | | 0.004550 |
| | 19 | | 0.013700 |

**Table 3.5** Assignment of Speed Limit and Signals per mile

| Functional Class | Assigned Speed Limit (mph) | Free Flow Speed (mphr) | Signals per Mile |
|---|---|---|---|
| 0 | 55 | 62.4 | 0.6 |
| 1 | 70 | 75.6 | 0.0 |
| 2 | 65 | 71.2 | 0.2 |
| 6 | 55 | 62.4 | 0.6 |
| 7 | 55 | 62.4 | 0.6 |
| 8 | 45 | 47.6 | 0.6 |
| 9 | 35 | 39.7 | 1.9 |
| 11 | 65 | 71.2 | 0.0 |
| 12 | 65 | 71.2 | 0.2 |
| 14 | 55 | 62.4 | 0.6 |
| 16 | 45 | 47.5 | 0.6 |
| 17 | 35 | 39.7 | 1.9 |
| 19 | 30 | 35.7 | 3.1 |

## 3.3 Time-Dependent Intercity Traveler Origin-Destination Demand

Defining intercity trips as those that travel longer than 100 miles of one-way distance, an existing travel demand model named Transportation Systems Analysis Mode (TSAM) estimates the static intercity travel demand by trip purpose (i.e., business and non-business trips) at the county level. Its development was based on the concept of the traditional four-step transportation demand modeling process and TSAM essentially involves a series of sub-models that are calibrated using travel survey data combined with socio-economic and demographic data [22]. By using average party sizes for each trip purpose collected from the survey data, the traveler OD tables are converted to the passenger-car OD tables. The resulting static passenger-car OD tables are then converted to the time-dependent passenger-car demand using the percentage of departures for every 30-minute interval estimated from Jin and Horowitx (20). Figure 3.2 shows the distribution of the departures in every 30 minute interval.

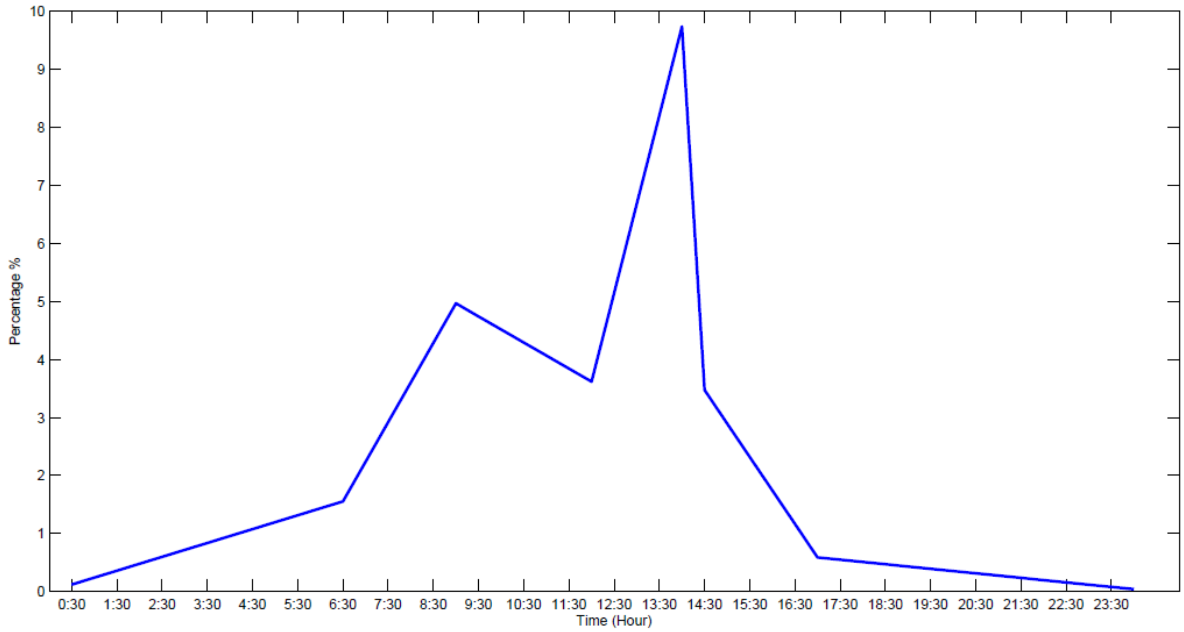


**Figure 3.2** Percentage of Departure During a Typical Day

3.4 Time-Dependent Link Flow

The time-dependent link flow is estimated from the AADT and AADTT in FAF2 data. The hourly distribution of passenger cars and trucks during one typical day is estimated using the traffic sensor data collected by Missouri Department of Transportation (MoDOT) using the Remote Traffic Microwave Sensor (RTMS) system installed on roadways around the St. Louis area. The sensor data contains complete one-year traffic counts of vehicles summarized in hourly traffic volume. In the data, vehicles are classified into four classes: class 1 is passenger-car, and classes 2-4 are different types of trucks. The distribution of traffic counts by vehicle class during a typical day is presented in figure 3.3. The AADTT on each link is split into different types of trucks for vehicle classes 2, 3, and 4.The number of trucks is then converted to equivalent passenger-cars using Passenger-Car Equivalence (PCE) since *V*/*C* in eq. (3.2) is given in passenger-car. The PCE conversion factors for each vehicle class are given in table 3.6.

**Table 3.6** Passenger Car Equivalence (PCE) Factors by Vehicle Type

| | Class 1 | Class 2 | Class 3 | Class 4 |
|---|---|---|---|---|
| PCE | 1.0 | 1.2 | 1.5 | 2.5 |

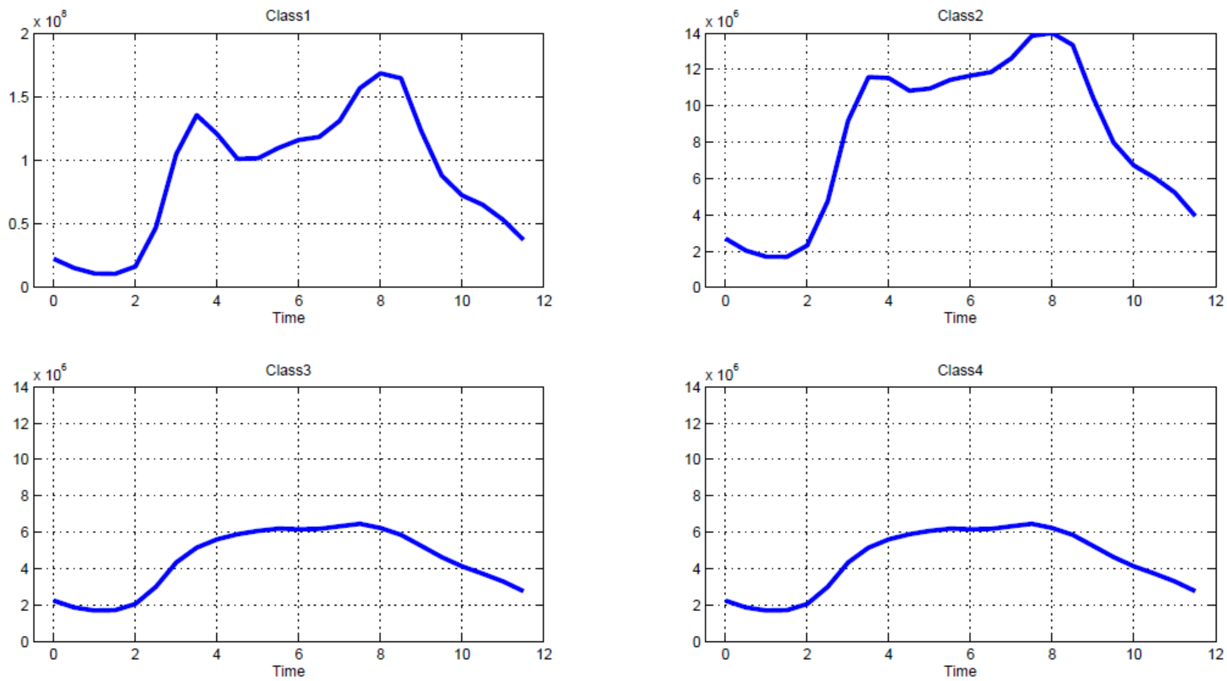


**Figure 3.3** Daily Distribution of Vehicles by Vehicle Type

It should be noted that the time-dependent traveler passenger-car (vehicle class 1) flow on roadways is composed of two different types of travelers: time-dependent inter-city and local or intra-city travelers. Note that the number of passenger cars by local travelers will serve as input preloaded on the network before assigning the intercity demand. However, no information of the local travelers is available in FAF2. To separate the time-dependent local traveler flow from the total passenger car flows on each link, a two-stage simulation scheme is utilized in our study. The detailed procedure will be discussed in the following section.

### 3.5 Fuel Consumption and Emission Rates

The inputs for the fuel consumption and emission are inferred from Mobile-6 developed by the Environmental Protection Agency (EPA). Mobile-6 is a computer program that estimates the emission rates (grams/mi) by considering various local factors, such as vehicle mix, speed, temperature, and so on. For computational simplicity, it is assumed that most passenger cars are light duty gasoline vehicles (LDGV) whose fuel consumption is, on average, about 23.9 mpg obtained from Mobile-6. Four kinds of emission are investigated in our study: $CO_2$, THC (Total hydrocarbon), CO, and $NO_x$. The emission rate of $CO_2$ is a given constant (371.2 gram/mi) in Mobile-6, whereas the emission rates of the other three components are functions of road type and average speed. In Mobile-6, three major road types are considered: freeway, arterial, and local roadway. Each roadway link in FAF2 is classified into one of the three road types defined in Mobile-6 according to its FClass in FAF2. The matching table used in the classification procedure is shown in table 3.7. Figure 3.4 shows the relationship between the emission rates and speed interpolated from Mobile-6 outputs for the freeway and arterial roadways. For the roads with local type, the following fixed emission rates are applied: 2.196 (gram/mi) for THC, 1.124 (gram/mi) for Nox, and 12.84(gram/mi) for CO.

**Table 3.7** Roadway Types in Mobile-6 and FAF2

| | Freeway | Arterial | Local |
|---|---|---|---|
| FClass in FAF2 | 1, 2, 11, 12 | 6, 7, 14, 16 | 8, 9, 17, 19, and others |

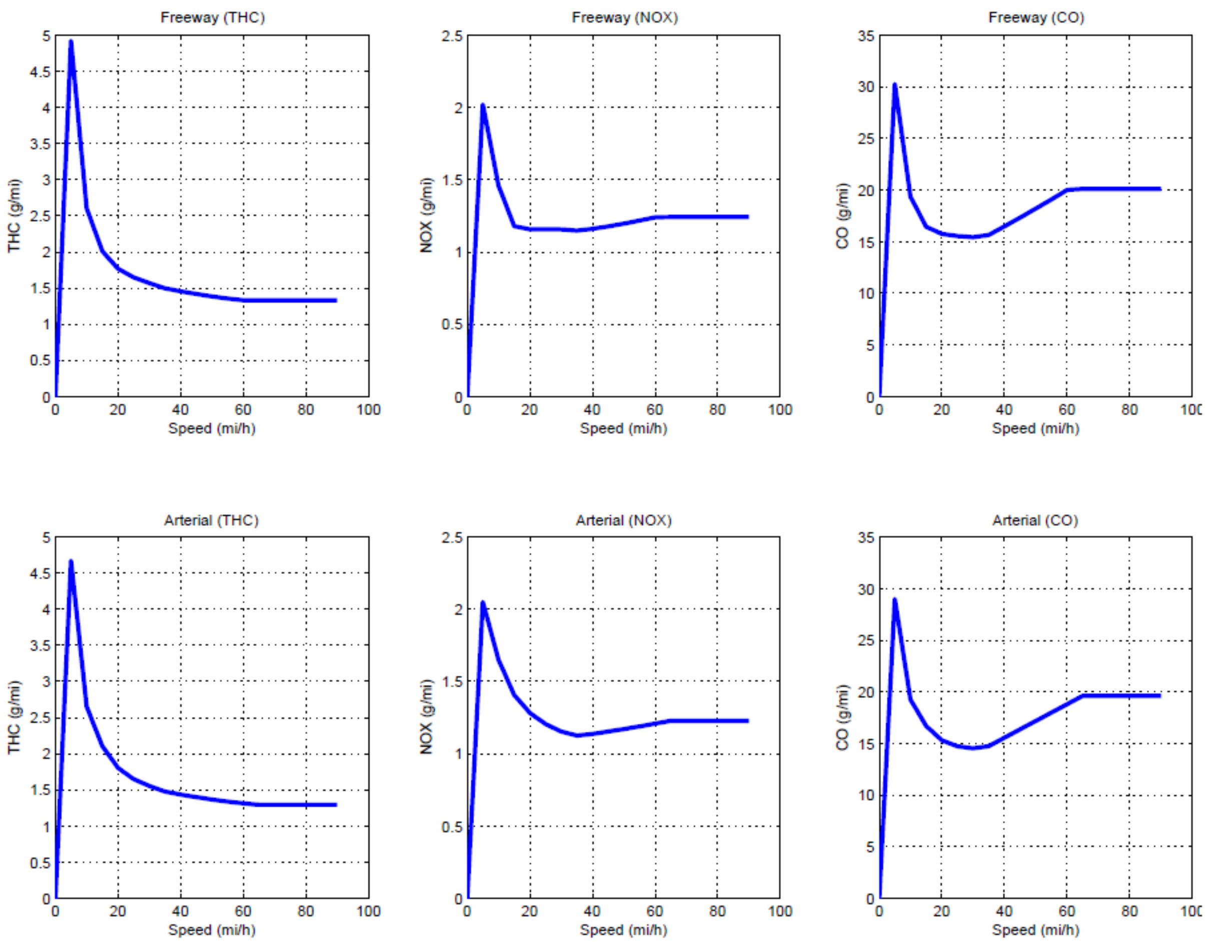


**Figure 3.4** Relationship between Emission Rate and Speed for Freeway and Arterial

# Chapter 4 Simulation and Results

In the simulation, the travel time is assumed to be the travel impedance. As mentioned in chapter 3, a two-stage simulation scheme is used to estimate the time-dependent local traveler flow, which is described below.

Stage 1: Load the time-dependent link flow estimated from AADT and AADTT as the time-dependent local traveler flow. Do the pseudo-DTA to get the time-dependent intercity flow. Compute the time-dependent local traveler flow by subtracting this flow from the time-dependent flow.

Stage 2:

Step 1. Load the new time-dependent non-intercity flow and do the pseudo-DTA to get the time-dependent intercity flow.

Step 2. Calculate the new time-dependent non-intercity flow and check the termination condition, if it is met, then stop; otherwise go back to step 1.

The whole simulation procedure is illustrated in figure 4.1. Six bi-direction roads were picked for analysis. Table 4.1 presents the detailed information about those roads, and their locations are given in figure 4.2. Based on Tables 3.2 and 3.7, the first and second roads are a rural and urban freeway respectively, the third and fourth are a rural and urban arterial respectively, and the fifth and sixth are local roadways. Since no detail is given about the directions of bi-direction roads, the two directions of those roads are called directions A and B arbitrarily.

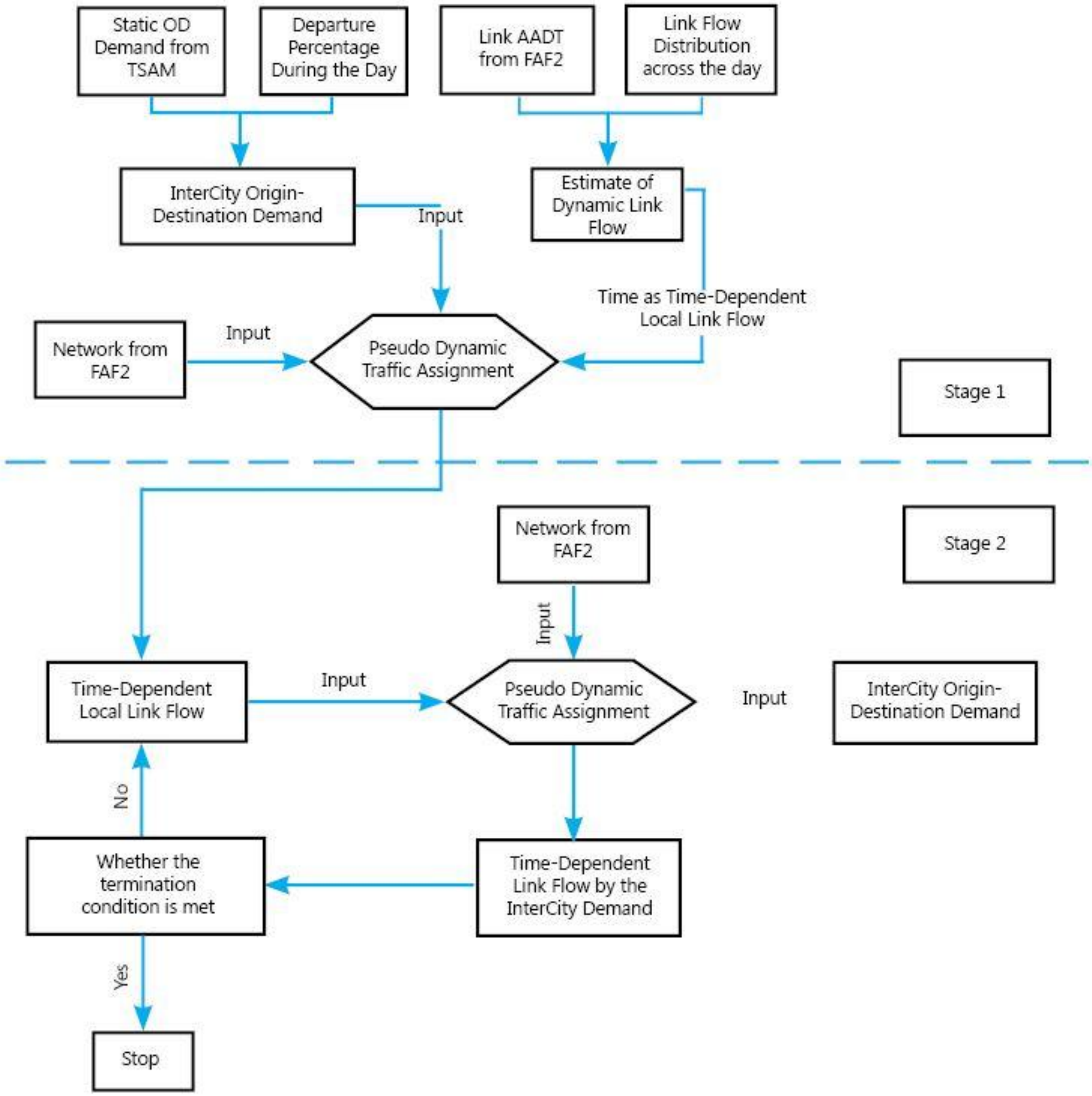


**Figure 4.1** Flow Chart of the Simulation Procedure

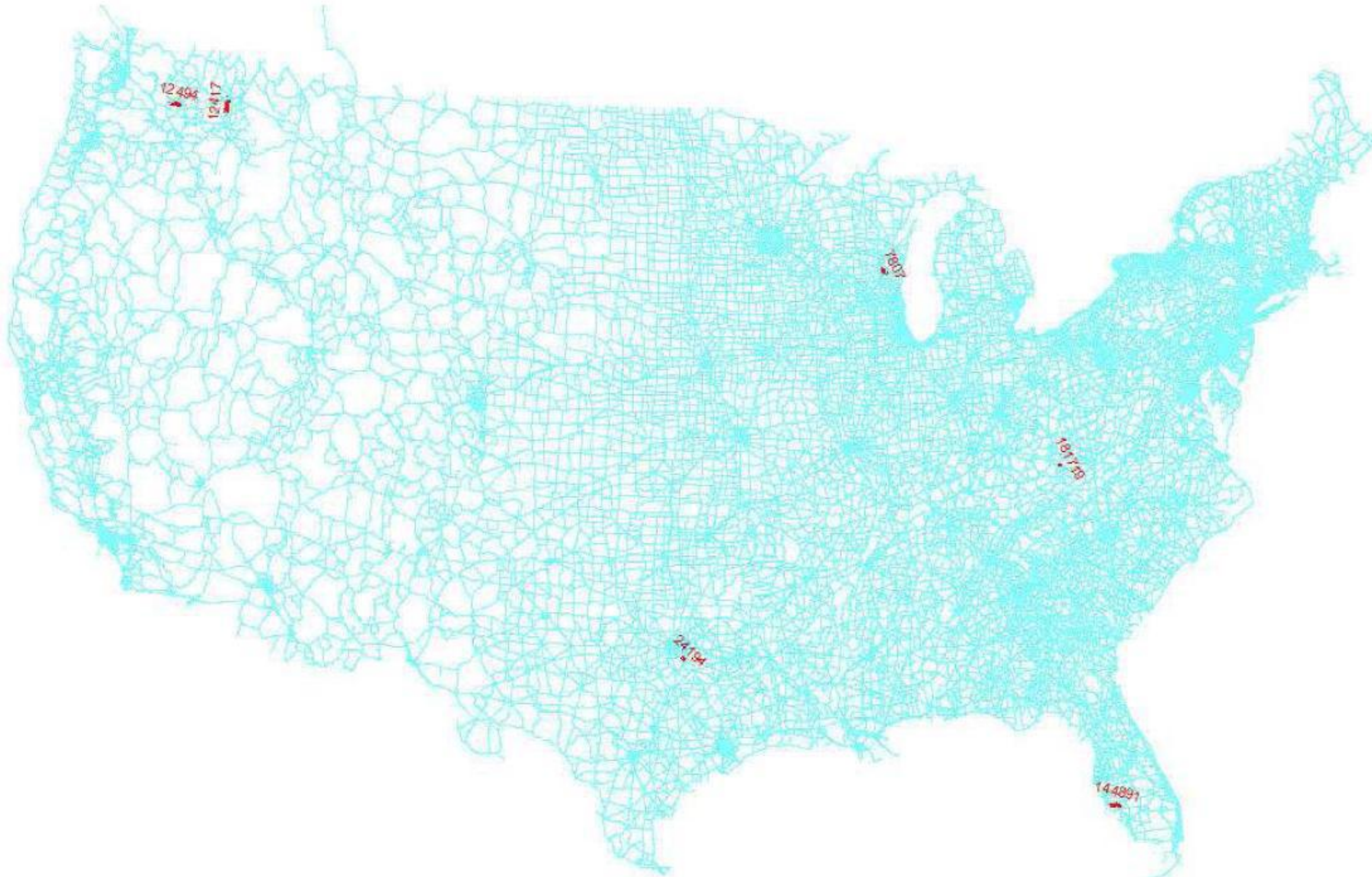


**Figure 4.2** Locations of the Selected Roads

**Table 4.1** Information on the Selected Roads

| ID | Length | RUCODE | State | FCLASS | AADT | AADTT | Speed Limit | FFS | Hourly Capacity | J | $D_O$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 144891 | 26.52 | 4 | FL | 1 | 50,000 | 8,360 | 70 | 75.6 | 3,718 | 5.67E-05 | 0 |
| 12494 | 24.07 | 2 | WA | 11 | 18,964 | 1,337 | 65 | 71.2 | 3,903 | 2.30E-06 | 0 |
| 7807 | 13.80 | 1 | WI | 2 | 33,437 | 33,437 | 65 | 71.2 | 3,543 | 2.69E-05 | 0.011596 |
| 12417 | 32.56 | 4 | WA | 12 | 14,136 | 14,136 | 65 | 71.2 | 3,750 | 5.67E-05 | 0.027359 |
| 181719 | 6.23 | 1 | KY | 8 | 10,234 | 10,234 | 45 | 47.55 | 1,102 | 3.31E-06 | 0.015705 |
| 24194 | 2.66 | 4 | TX | 17 | 12,860 | 12,860 | 35 | 39.65 | 1,255 | 0.00455 | 0.021234 |

Figures 4.3 and 4.4 illustrate the time-dependent intercity flow and related emissions and fuel consumption for road 144891. The same information is given in figures 4.5 and 4.6 for the road 12494. Based on their FClass, they are Rural and Urban principal arterial-interstate freeways respectively. The following conclusions can be drawn when analyzing these figures. For the same road, its directional time-dependent intercity flow patterns are different from each other, but a similar pattern to the time-dependent intercity demand can be observed. In most of the figures, the peaks of the time-dependent intercity flow appear about one and half hours later than the peaks of time-demand intercity demand. For example, two major peaks can be seen for the intercity demand, one is at around 9:00 AM, and the other 2:00 PM as illustrated in figure 3.2. Consequently, in figures 4.5 and 4.6 two major peaks in the intercity flow can be determined around 10:30 AM and 3:30 PM. Such delays can be accounted for by the time spent on the way to reach the current road. The intercity flows on those two roadways have significant impact on the traffic conditions. For instance, in figure 4.5, even though the local flow is relatively low from approximately 2:00 PM to 4:00 PM, the road travel time keeps increasing due to the

significant increase in the intercity flow during this period. A similar situation is demonstrated in figures 4.3 and 4.6. Since both of the roads are classified as freeways, the emissions of THC, CO, and NOx are functions of speed only. Note that the speeds on both roads are greater than 60 mph, and as shown in figure 3.4, the emission rates (gram/mi) are almost constants for the three emissions in this case. Moreover, the emission of CO2 is assumed to be constant (371.2 gram/mi) too. Therefore, the total emission rates (v-gram/h) are functions of VMT rate (v-mi/h). This also can be observed from the similarity of the dynamic patterns between VMT rates and emission rates.

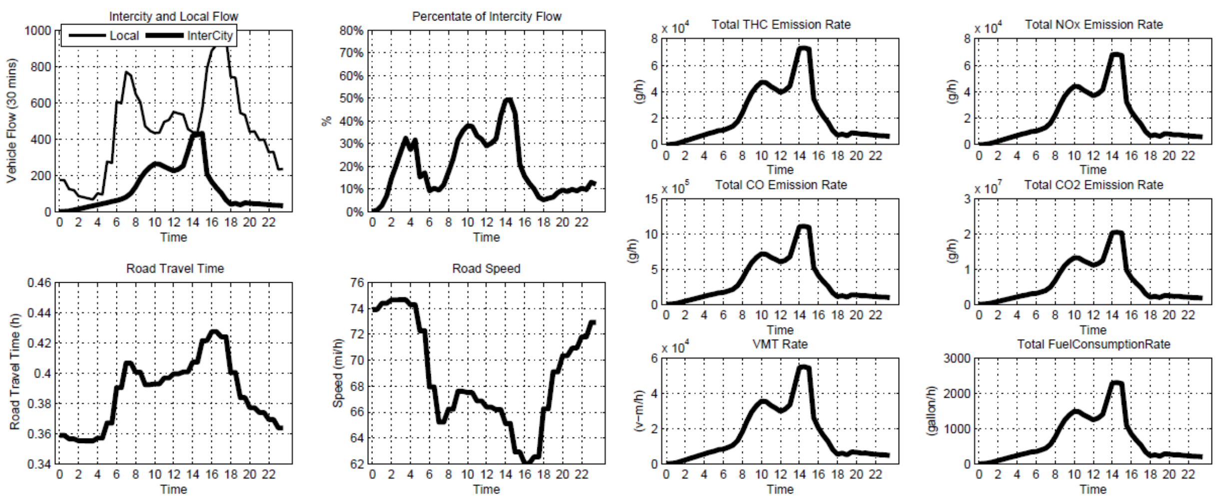


**Figure 4.3** Direction A of Road 144891 (Rural Freeway)

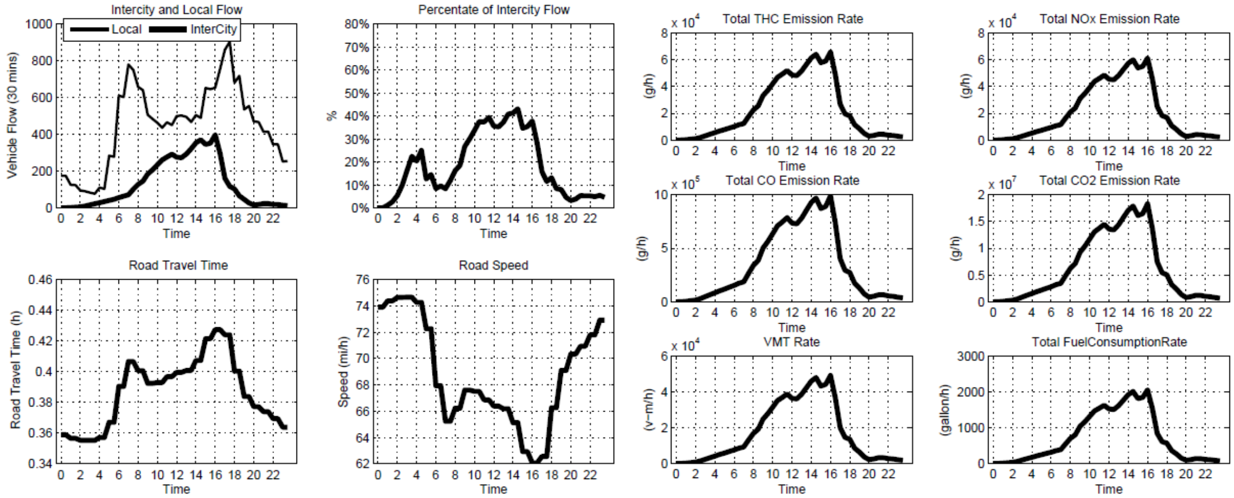


**Figure 4.4** Direction B of Road 144891 (Rural Freeway)

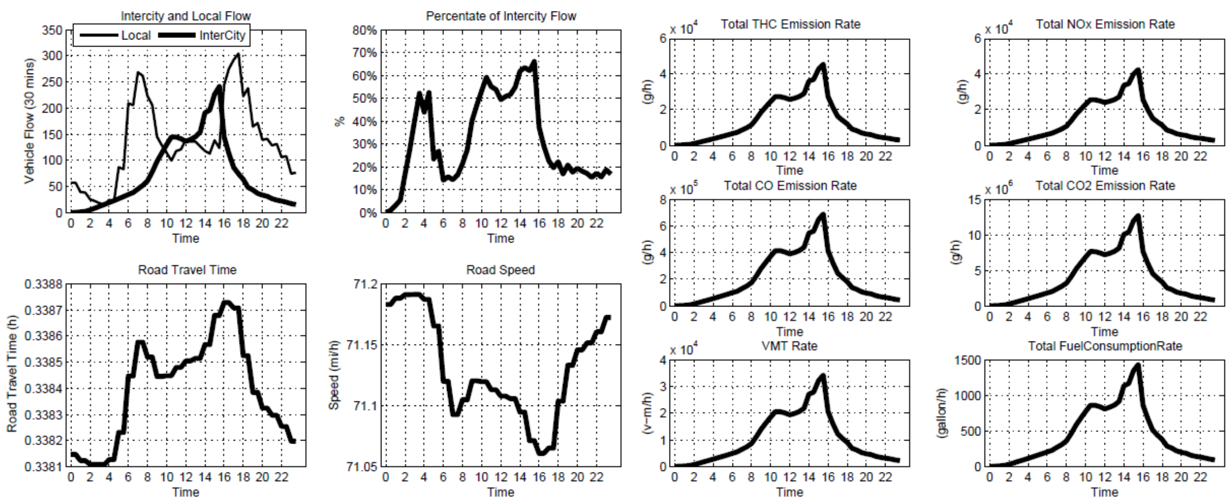


**Figure 4.5** Direction A of Road 12494 (Urban Freeway)

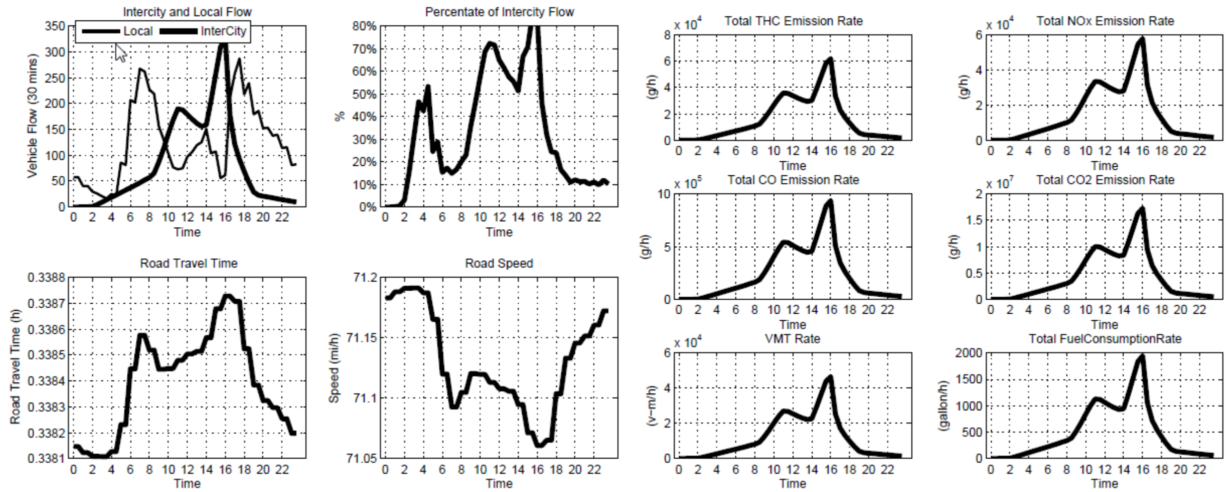


**Figure 4.6** Direction B of Road 12494 (Urban Freeway)

The third (7807) and fourth (12417) roads are classified as rural and urban arterial, respectively. Their time-dependent road flows and emission rates are illustrated in figures 4.7, 4.8, 4.9, and 4.10,. Two differences can be observed when compared to the two roads (144891 and 12494) previously discussed. First, the occurrences of intercity flow peaks are very close to those of intercity demand. This is an indication that there may be trip origins around the roads. Second, there is a smaller percentage of intercity vehicles than found on roads 144891 and 12494, which complies with the reasonable notion that intercity travelers are more willing to take the freeways which are generally faster than the arterial roads. Similarly, the emissions and fuel consumptions are dominated by the VMT rate because of the relatively high speed on roads 144891 and 12494.

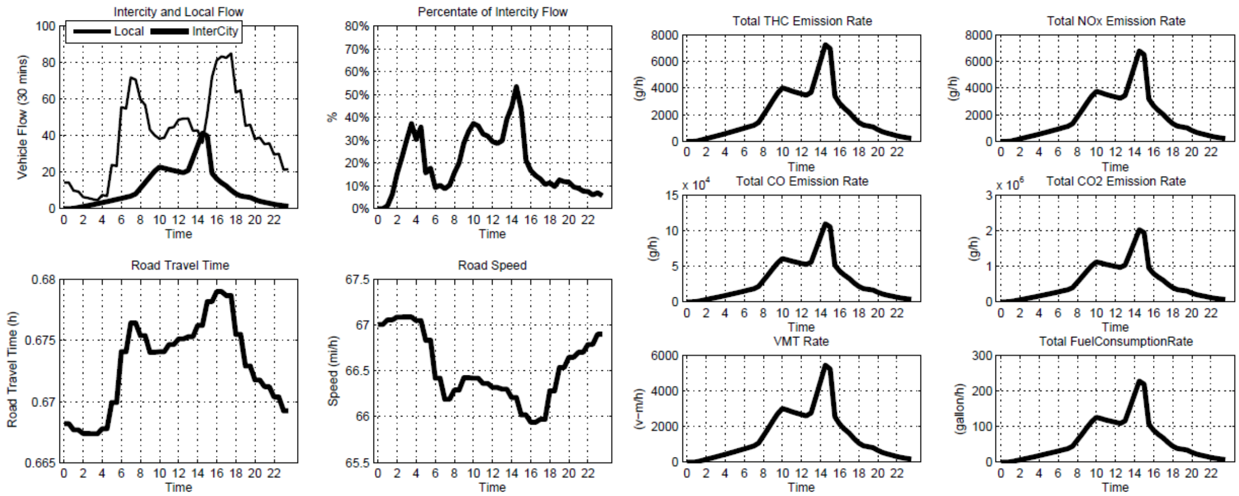


**Figure 4.7** Direction A of Road 7807 (Rural Arterial)

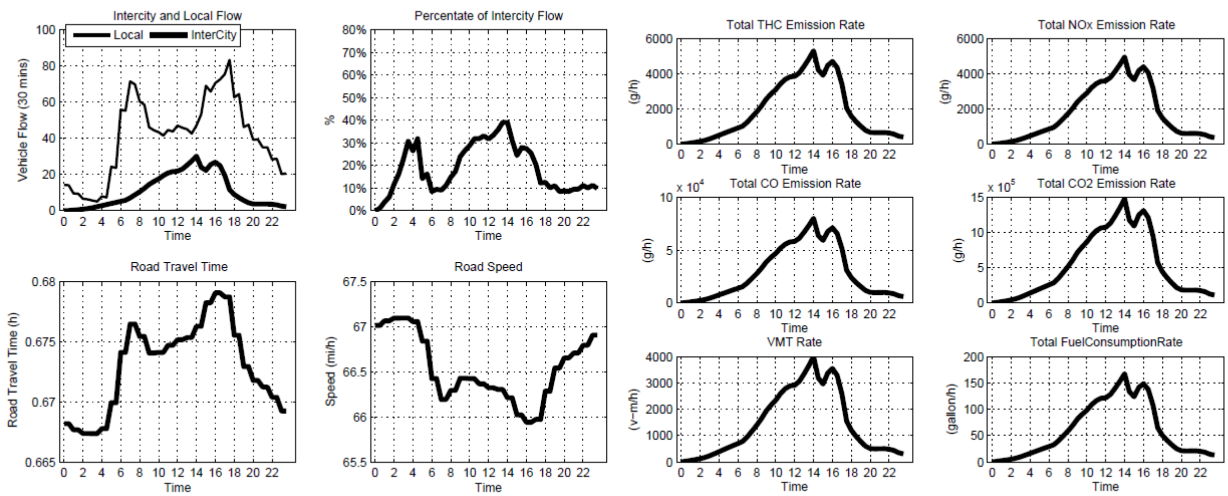


**Figure 4.8** Direction B of Road 7807 (Rural Arterial)

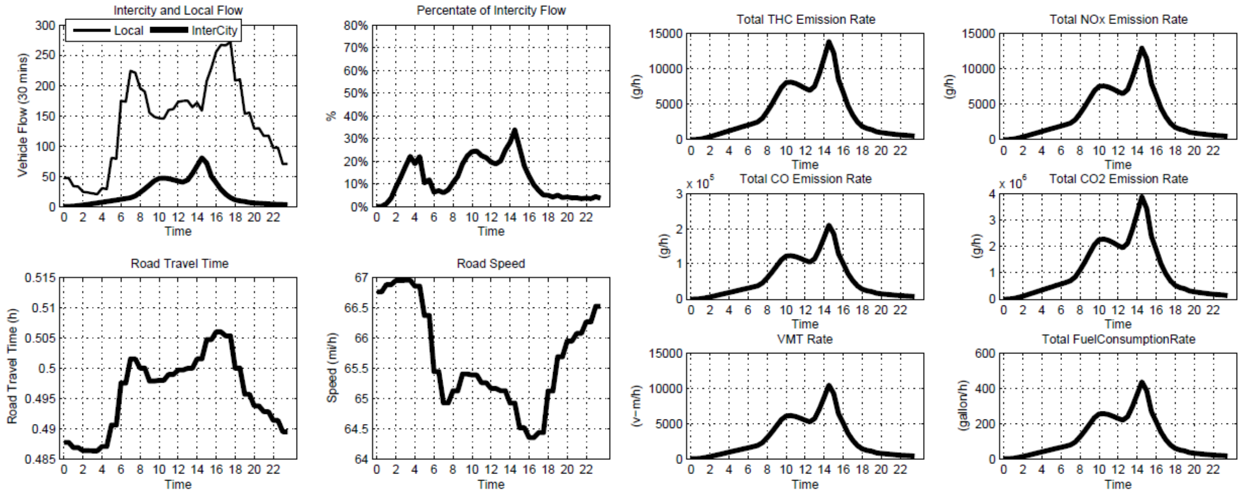


**Figure 4.9** Direction A of Road 12417 (Urban Arterial)

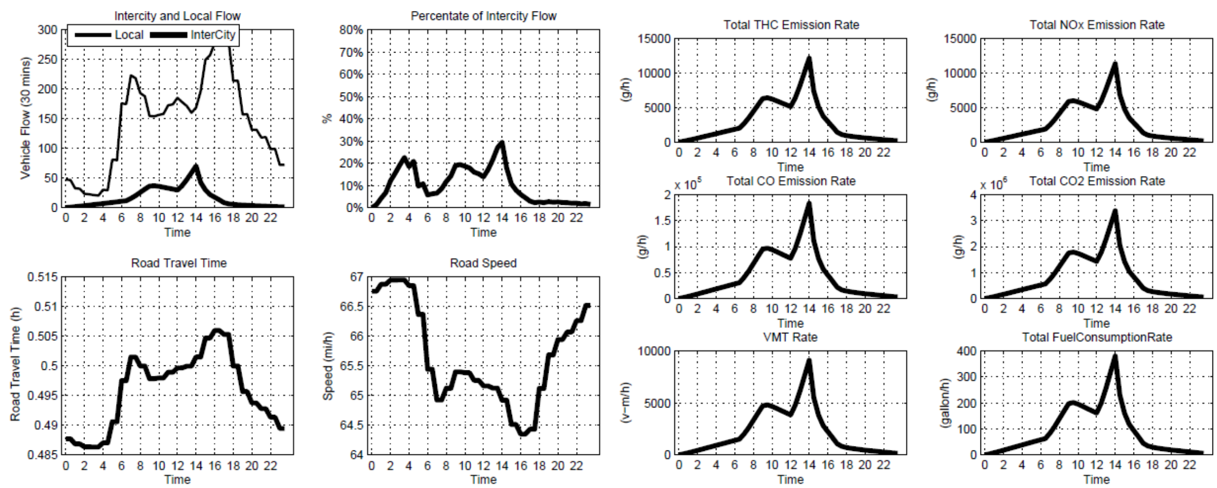


**Figure 4.10** Direction B of Road 12417 (Urban Arterial)

The last two roads 181719 (urban collector) and 24194 (rural minor collector), are classified as local in table 3.4. Figures 4.11 and 4.12 present the time-dependent intercity and local flows and figures 4.13 and 4.14 offer the corresponding emissions and fuel consumption rates. Relatively small amount of intercity flow can be seen and they have little influence on the traffic condition in those cases. Roads of this kind are not preferred by the intercity travelers because of their low capacities and low speed limits. The patterns of total emission rates are similar to that of total VMT rates since the emission rates are constants for the roads of local type.

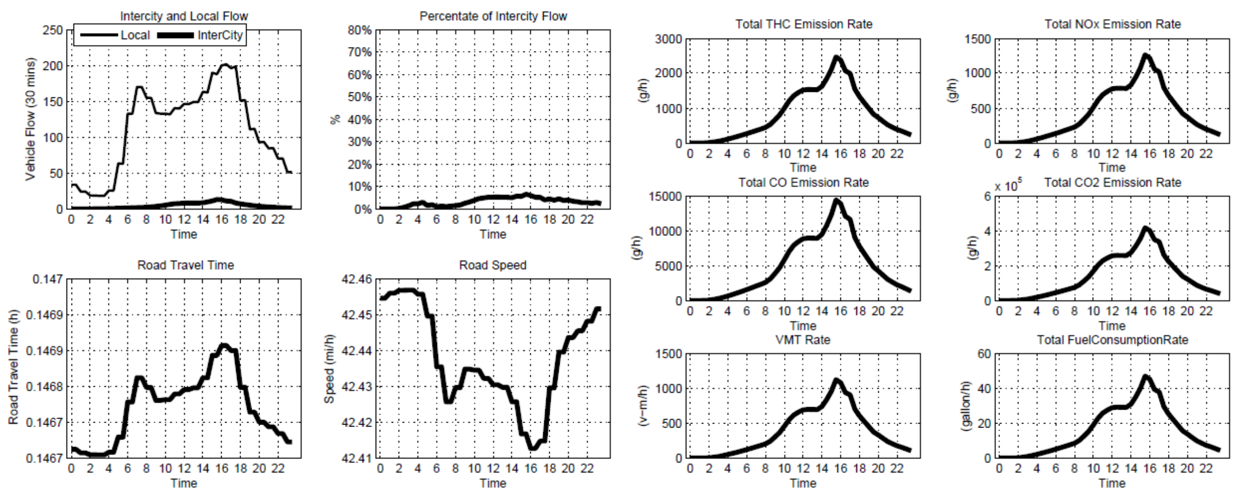


**Figure 4.11** Direction A of Road 181719 (Rural Local)

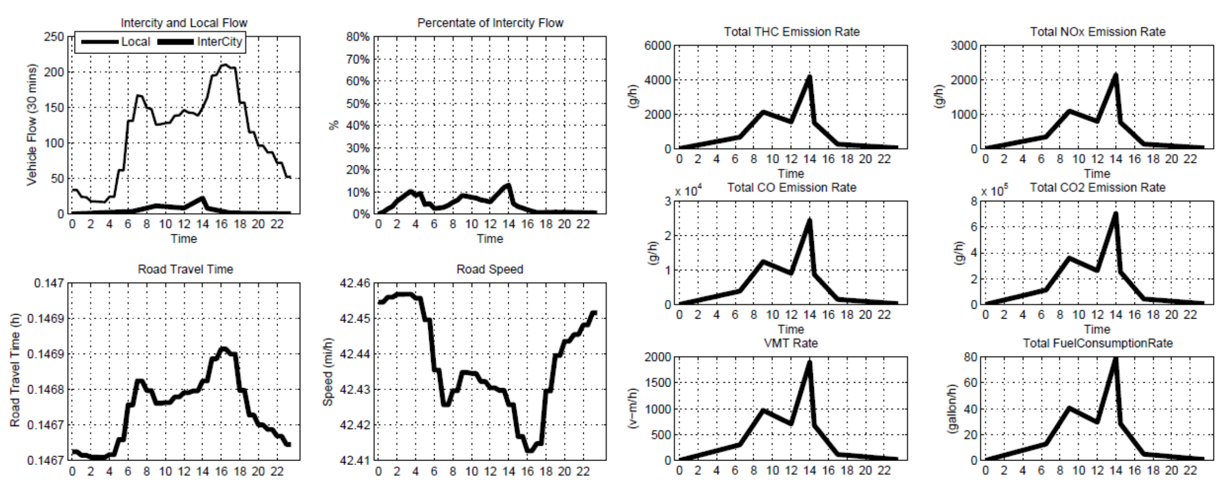


**Figure 4.12** Direction B of Road 181719 (Rural Local)

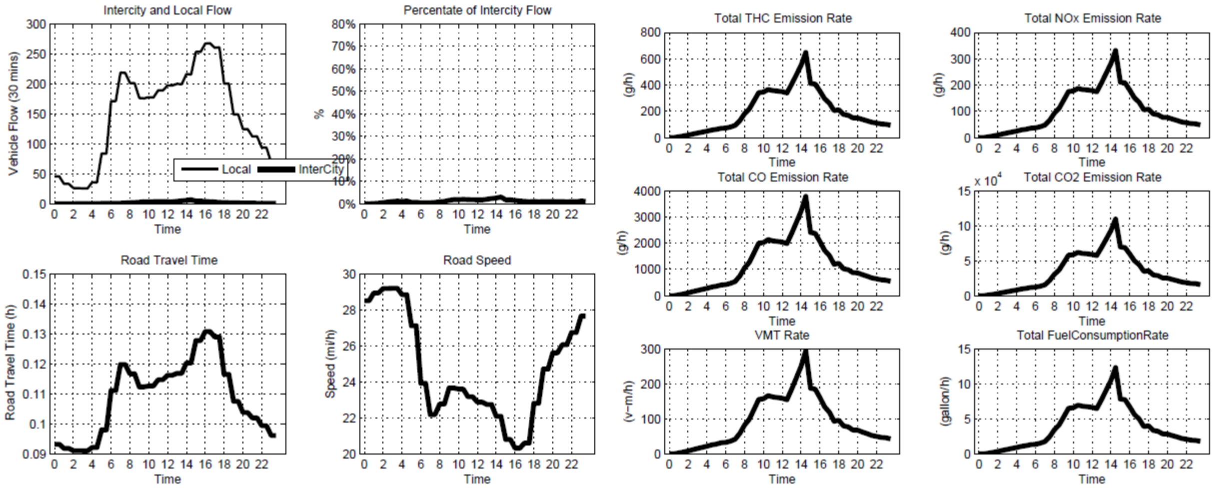


**Figure 4.13** Direction A of Road 24194 (Urban Local)

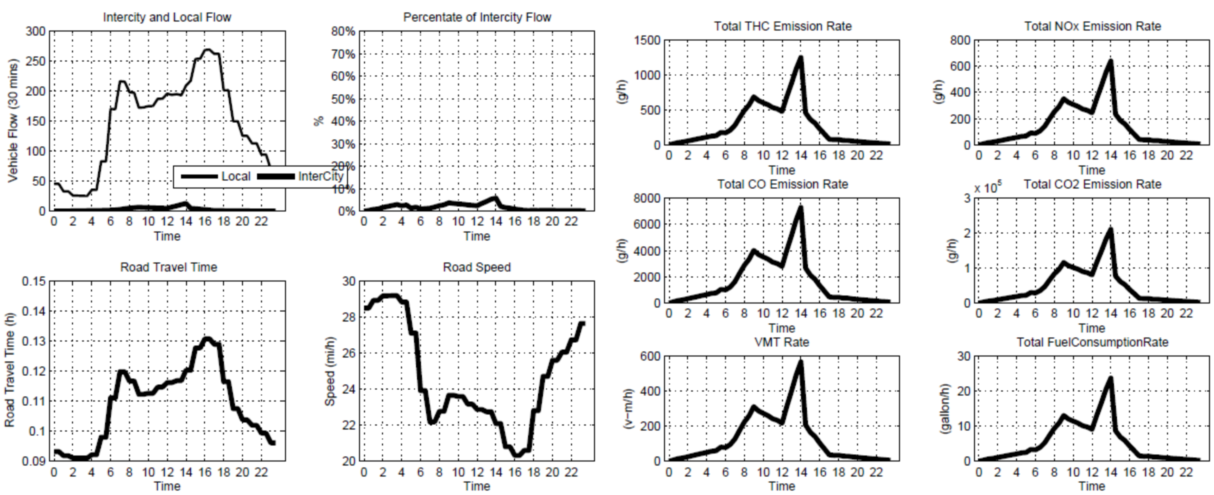


**Figure 4.14** Direction B of Road 24194 (Urban Local)

Figures 4.15, 4.16, 4.17, and 4.18 illustrate the intercity vehicles and total vehicles on the roads with FClass 1, 2, 11, and 12 every 6 hours. Relatively fewer vehicles can be observed from 0:00 AM to 6:00 AM and 6:00 PM to 0:00 AM on the map for both groups which fulfills common sense expectations that a relatively small number of travelers will be on the road during those time periods.  Meanwhile, a large number of vehicles are on the road from 6:00 AM to 12:00 PM and 12:00 PM to 6:00 PM. Observable differences exist in the intercity vehicle volume for those two time periods. The volume from 12:00 PM to 6:00 PM is greater than from 6:00 AM to 12:00 PM because the largest peak in the departure for the intercity travelers happens in the afternoon. Note that the intercity vehicle volume from 0:00 AM to 6:00 AM is smaller than the one during 6:00 PM to 0:00 AM even though a higher percentage of departures occur during the former time period. This is because some of the intercity travelers that departed in the afternoon or even morning may still be in the network in the evening, which contributes to the intercity volume during this time period. The total vehicle volume within those two intervals of 6 hours exhibits a very similar pattern because of the relatively symmetric movement of morning and afternoon local traffic. However, due to the intercity flows, the total vehicles volume in the afternoon on certain roads is higher than the volume in the morning.

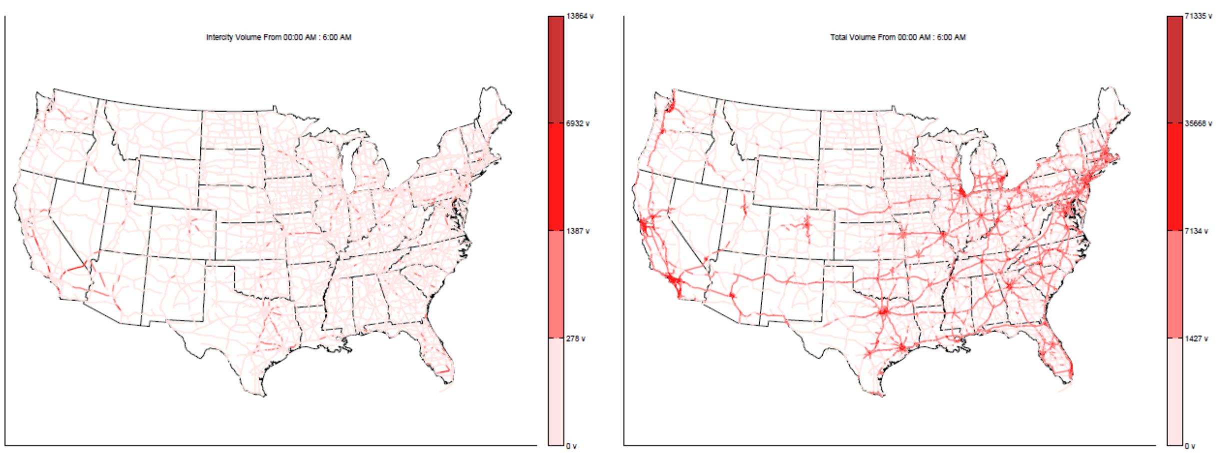


**Figure 4.15** Total Volume of Intercity Travelers and All Travelers from 0:00 AM to 6:00 AM

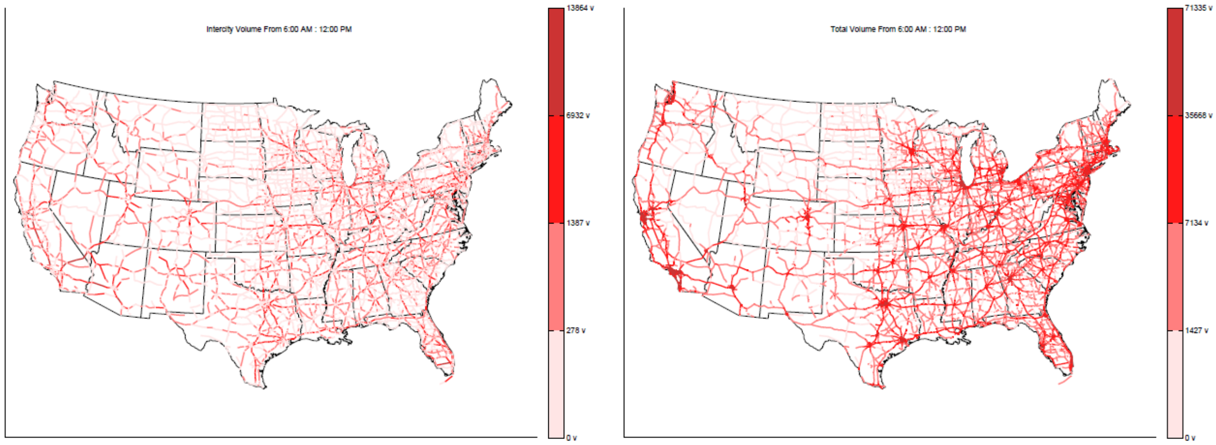


**Figure 4.16** Total Volume of Intercity Travelers and All Travelers from 6:00 AM to 12:00 PM

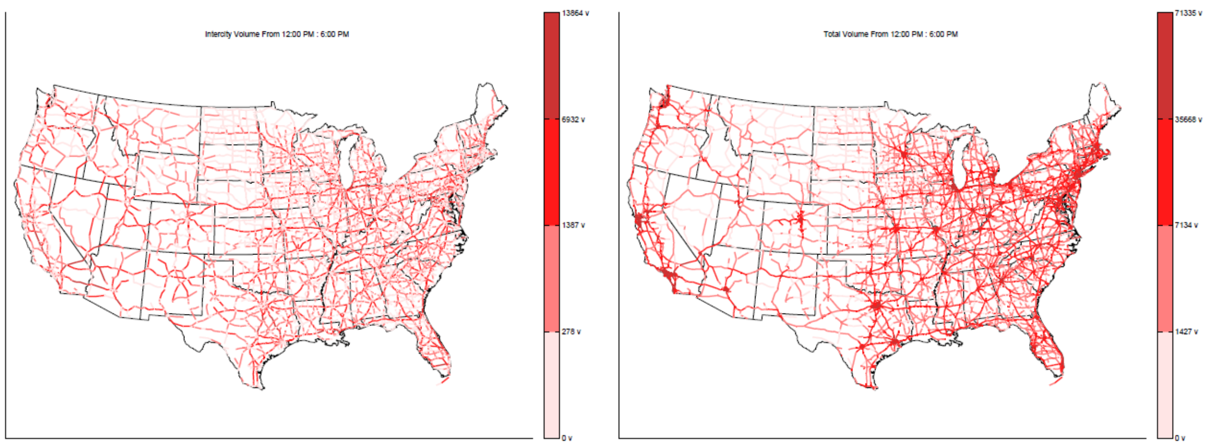


**Figure 4.17** Total Volume of Intercity Travelers and All Travelers from 12:00 PM to 6:00 PM

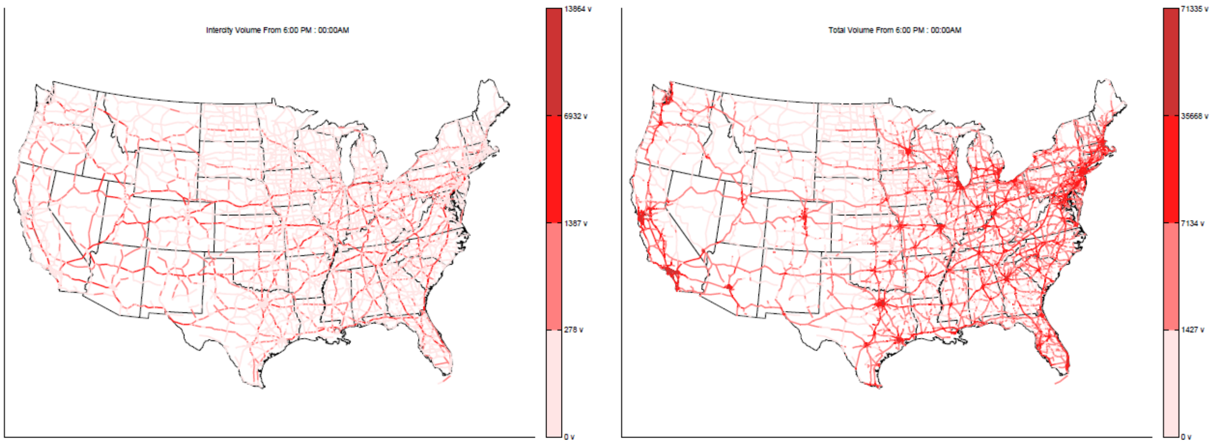


**Figure 4.18** Total Volume of Intercity Travelers and All Travelers from 6:00 PM to 0:00 AM

Figure 4.19 shows the CO2 emissions from the intercity link flows on roads with FClass 1, 2, 11, and 12 every 6 hours. Clearly, the CO2 emissions from 12:00 AM to 6:00 PM is the highest followed by the CO2 emissions during 6:00 AM to 12:00 AM.

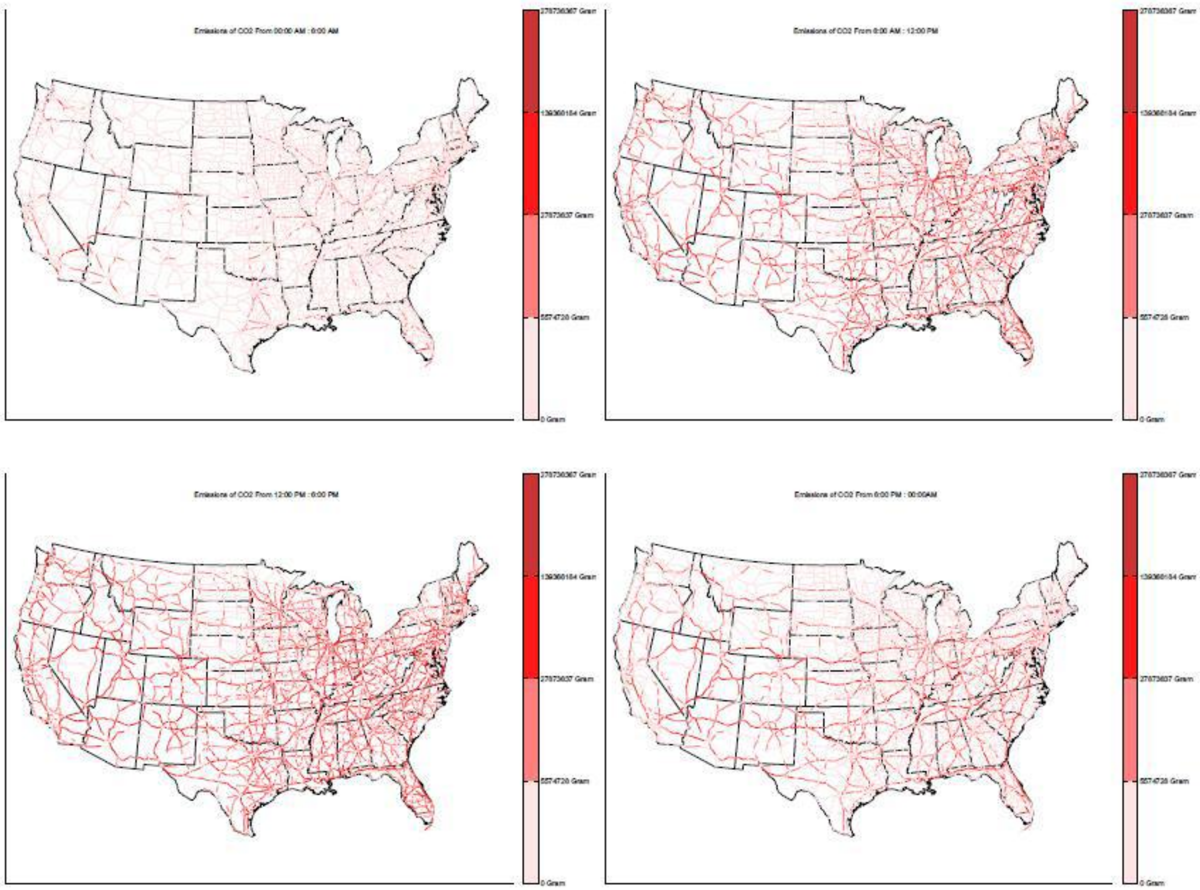


**Figure 4.19** Total CO2 Emissions from Intercity Travelers Every 6 Hours

# Chapter 5 Conclusions and Recommendations for Future Research

In this report, a Pseudo-DTA simulation model is proposed to estimate the time-dependent intercity flow from the intercity demand across the whole U.S. Also, the fuel consumption and emission rates are estimated based on the simulation results and data from EPA's Mobile-6. Results analysis shows that our simulations model gives a reasonable estimation of time-dependent intercity flow in an efficient way. However, the following issues deserve further investigation in the future to improve our method.

First, the US territories span six time zones; therefore, the time-dependent intercity demand of each OD pair and non-intercity traffic flow on each road should be estimated according to its local time instead of under the same time horizon.

Secondly, more detailed data on the FAF2 network is expected from the Highway Performance Monitoring System (HPMS). The road capacity, speed limit, and other related parameters should be estimated or calculated in a more accurate way.

Thirdly, the traffic counts data used to estimate the time-dependent link flow were collected from the St. Louis area only, which may not be representative. The use of a more general traffic counts data set should be considered.

Fourthly, since the time-dependent local flow is known a priori, a dynamic shortest path algorithm may be considered, which is more reasonable than the one we are currently using.

Lastly, the AADTT in FAF2 includes intercity truck flows, and those trucks are converted to passenger car unit to be treated as non-intercity flows. Our model may be improved to better estimate the time-dependent intercity truck and passenger car flow and their related fuel consumption and emissions.

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