CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Developing Calibration Tools for Microscopic Traffic Simulation Final Report Part 1: Overview Methods and Guidelines on Project Scoping and Data Collection

Michael Zhang, Jingtao Ma
University of California, Davis

California PATH Working Paper
UCB-ITS-PWP-2008-3

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department Transportation, Federal Highway Administration.

Report for Task Order 5308

January 2008

ISSN 1055-1417

T.O. 5308

DEVELOPING CALIBRATION TOOLS FOR MICROSCOPIC TRAFFIC SIMULATION

FINAL REPORT

PART I: OVERVIEW OF CALIBRATION METHODS AND GUIDELINES ON PROJECT SCOPING AND DATA COLLECTION

Michael Zhang, Jingtao Ma
Institute of Transportation Studies
University of California
Davis, CA 95616

ABSTRACT

This report, the first of a three-part series, documents the findings of the first two tasks of Task Order 5308, "Developing Calibration Tools for Microscopic Simulation", namely a review of literature and the development of certain guidelines for properly scoping a microscopic simulation project and coding its network to minimize coding errors. A wide range of transportation applications of microsimulation is reviewed, paying particularly attention to their calibration efforts. The review revealed that many studies paid little attention to model calibration, or at least not documented it if a detailed calibration effort was carried out. And among the studies that performed model calibration, the calibration procedures employed are quite ad hoc, often relying on trial-and-error. The report identified three calibration issues to be addressed in future work: the lack of a systematic calibration procedure, the lack of automated calibration tools, and the lack of reliable O-D trip demands.

This report also examined four important aspects of model development, namely project planning, network coding, data collection and processing, and traffic demand estimation, Guidelines for project planning, network coding, and data collection and preparation, synthesized from various sources including our own calibration experiences, are also provided .

Keywords: Microscopic simulation, micro simulation, calibration, calibration guidelines.

EXECUTIVE SUMMARY

Microscopic traffic simulation (microsimulation) has seen more and more applications in the formulation and assessment of transportation policy alternatives. Being high fidelity traffic models, a microsimulation model has numerous parameters model that affect traffic flow in very complex ways. It is vital to the validity of the conclusions drawn from a microsimulation study to calibrate these parameters against local traffic conditions before the simulation is applied. Calibration also serves as an additional check of the validity of the built-in traffic models in a microsimulation.

This report first presents the findings of an extensive review of up-to-date microsimulation applications. Four broad categories of these applications were identified, including evaluation of infrastructure performance, assessment of Advanced Traffic Management and Information System (ATMIS) strategies, studies of travel behavior and environmental impact. Being more traditional of the four, the first two categories of applications are more numerous and continue to expand their scopes as new ITS elements are being researched, tested and implemented in the transportation system. The remaining two categories are emerging application areas of microsimulation. It was found that model calibration is the weakest link in all application categories.

In Chapter 3, four important aspects of model development are analyzed, namely project planning, network coding, data collection and processing, and traffic demand estimation. Project planning is the first step encountered by an analyst and also a step often being overlooked. Guidelines synthesized from various sources, including our own calibration experiences, are provided for a complete project planning process. Coding accuracy and consistency, treatment of road capacity variations between sections are identified as important to model calibration.

By first assessing the merits of important calibration practices, Chapter 4 summarizes the calibration techniques found in the literature. An error-checking list is provided by dividing the issues into different categories to streamline the checking process. Issues in traffic demand calibration are also discussed, and three calibration methods are reviewed.

The last chapter summarizes the gaps in current practices and outlines the work to be performed in the remainder of this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Background

Microscopic traffic simulation (microsimulation) models treat individual driver vehicle unit (DVU) as the basic modeling object and describe its detailed movement through the road network. Although many models call themselves microscopic simulation models, some of them are either simulating people's daily travel pattern (travel simulators), or conducting in-laboratory test of people's reaction to stimuli from both in-vehicle devices and on-road traffic surroundings (driving simulator). In this project, we specifically focus on traffic simulation models which study the operational performance of traffic flowing over the network.

In the past decades microsimulation has seen more and more applications and is now becoming an indispensable analysis tool for transportation analysts (Jeannotte et al 2004). Because microsimulation models record the trajectory of each DVU along its journey, they virtually provide all the information for traffic analysis. Moreover, microsimulation models introduce randomness into their components including the DVU releasing, the DVU movements with reference to the surroundings, the departure time and route choices. The randomness partly captures the variation of the traffic patterns they modeled. Traditionally microsimulation has been used to design transportation infrastructure at a single location, but nowadays both the temporal and spatial scopes of microsimulation have been considerably expanded to go beyond a freeway section (Cheu et al 1998, Lee et al 2001) or an isolated location such as an interchange or an intersection (ISAC 1999) to include corridor networks (Gardes and May 1993; Gomes, May and Horowitz 2004; Lee and Kim 2004) and city or region wide transportation networks (Bridges 2003; Smith 2006). Furthermore, the capabilities of microsimulation have also been extended to accommodate most up-to-date ATMIS strategies, such as coordinated signal control systems (Liu et al 2001), ramp metering (Zhang et al 2001), HOV lanes (Gardes et al 2002) and many more.

High fidelity as they are, microsimulation models are both data and labor intensive. They require large amount of detailed input data and sub-model parameter data so as to describe the interaction between traffic demand and network supply. Therefore, building a microsimulation application often takes several logical steps, including project planning, data collection, network coding, baseline model calibration and validation, model application and project documentation. It is not uncommon that even a medium size network could take months to build (Gardes and Bloomberg 2003).In all these steps, calibration of the baseline model is crucial, because only a well calibrated model can provide the right basis for further applications. Applying the model without good calibration could lead to distorted or even wrong conclusions. In addition, microsimulation models (or their sub-models) have been verified and calibrated against real traffic conditions at certain locations, and the model parameters are provided as default values in the model. Since driving behavior and network characteristics change from location to location, it is necessary to adjust these parameters to suit local conditions.

1.2 Scope and Objectives

In general, two types of data are needed to build a reliable microsimulation model, namely input data and model parameters. The first type includes the network layout, road facilities such as markings and controls, vehicle fleet and traffic demands. The other type refers to the parameters that comprise the microsimulation model (and its sub-models). In the calibration process, one does not only need to check the first type of data against the local situation to eliminate possible errors, but also need to fine-tune the second type such that the microsimulation model replicate the local drivers' behavior.

This document is the first deliverable of the PATH project TOU 5308. This report summarizes the calibration experiences documented in the literature. First we categorize the successful microsimulation applications, and then we proceed to provide guidelines regarding calibration aspects including project planning, network coding, data collection and processing and traffic demand estimation. Next we describe the calibration steps and a few calibration methods that will be deployed in the study. Lastly a brief summary points out the gaps in the current calibration practices and outlines the work to be performed in this project, which will also be documented in a parallel Year-1 report.

CHAPTER 2 SUCCESS STORIES IN MICROSIMULATION APPLICATIONS

Applying Microsimulation to investigate complex traffic phenomena can be traced back to the 1950s (Webster 1958), but its real growth is a consequence of computational development in terms of both hardware and software advances. Nowadays microsimulation applications have advanced to modeling more complex networks to evaluate a wide array of transportation management measures. In this section we classify the microsimulation practices into four categories and briefly describe the typical applications and their calibration aspects.

2.1 Evaluation of Transportation Infrastructure Improvement

2.1.1 Design or Redesign of Transportation Infrastructure

The early microsimulation applications mainly focused on the design or redesign of traffic engineering infrastructures. For example, an earlier work used Paramics to help evaluate the redesign of road markings and other traffic engineering elements at the motorway interchange near Munich, Germany (ISAC 1999). There was a high level of weaving and merging traffic on site, and the loop detector data are ample enough to allow for the link headway factor (LHF) varying from one road section to another (ISAC 1999). An iterative process was used to adjust the mean target headway and mean reaction time, which were obtained as 0.7 and 1.0 second, respectively. For the specific links, the iterative process had been applied again to adjust the LHF, and the researchers visually checked the overlapping parts of the plotted volume-speed diagram to determine appropriateness of the LHF. Because of the inadequacy of Paramics lane changing models in reflecting the German driving rules at the modeling time, the gap acceptance behavior in lane changing was not adjusted.

Another typical work was done on the U.S. Highway 50 at Missouri Flat Road interchange at Placerville, CA. The project was to test the operational performance of an urban interchange improvement: single point urban interchange (SPUI) (Kurumi 2004). Three microsimulation models, CORSIM, PARAMICS and VISSIM, were all used to compare their capability of modeling simple urban networks. No systematic calibration process was reported to adjust the default parameter values in these simulation models. Their simulated traffic performance results were understandably different, but they still provided acceptable description of the SPUI improvement, while both Paramics and VISSIM matched the field observations and user expectations better.

2.1.2 Freeway operational assessment (FSOA)

The FSOA projects simulate the network in a large scale for the purpose of evaluating various types of candidate freeway assets improvement alternatives (Shaw 2002). In general, the state DOTs select and scope the reconstruction projects based on both cost-benefit analysis and engineering judgment from expert panels. While the treatment methods for facilities such as pavements or bridges are taken care of during the selection process, other traffic engineering issues such as safety, environmental and traffic impact will "not be evaluated until Preliminary Engineering begins"(Shaw 2002). As recognized by Wisconsin DOT, the above commonly applied process of reconstruction project selection may run into the risk that those operational problems can change the scope and cost of the project significantly. Thus, one major concern is how to conduct the “oranges and apples” comparisons among dissimilar options, for instance, the different combination of multiple elements: not only pavements and bridges, but also geometry changes, road network expansions, ITS infrastructures, signal system or sound walls, etc. Microsimulation tools are used to evaluate the proposed improvement alternatives. Meanwhile the researchers compared the capabilities of the existing microsimulation software, and recommended Paramics for further FSOA analysis.

2.1.3 Rehabilitation work zone traffic impact analysis

Although it seems a natural idea of using traffic simulation to estimate the queues and delays caused by road works, microsimulation models did not become one major tool until practical needs arise for a detailed traffic management plan (TMP) to deal with traffic peaking and detours during the construction period (Lee and Kim 2004), especially when innovative construction measures such as the long-life pavement rehabilitation strategies (LLPRS) program are being tested and applied by Caltrans. Commonly used tools of demand-capacity analysis and macroscopic simulation such as FREQ can estimate freeway queuing delays caused by the work zone. However, when the reconstruction work takes more than a single traffic peak period, for example, the 55-hour continuous weekend closure in I-10, Panoma, CA (Lee et al 2000), the impact of drivers’ rerouting onto urban streets can hardly be evaluated from Highway Capacity Manual (HCM) and similar models. Analyzing the drivers’ rerouting effect becomes another application area of microsimulation.

Moreover, microsimulation allows the users to evaluate other traffic management alternatives to alleviate the congestion caused by reconstruction activities. In the I-15 Devore reconstruction project (Ma 2003), Paramics model was used to investigate whether the queue spill-back due to the reconstruction lane closures could block the system interchange upstream of the reconstruction site, and whether the domino effect could lead to the grid lock in the adjacent local street network. Detailed traffic management plans, such as using movable barrier to split traffic of different destinations or restricting and rerouting trucks from entering the work zone during the peak hour, could only be evaluated in the microsimulation model.

Trial and error calibration process was conducted in this application. Empirically observed on the I-10 Pomona project and I-710 Long Beach project (Lee et al 2002), it was agreed that in California the CWZ lane capacity of a 2-lane by 2-lane (counter flow traffic) will reduce from the normal condition of 2,100 vehicle/hour/lane (vphpl) for a 4-lane freeway (each direction) to 1,500 vphpl. Link headway factor (LHF) of the work zone links in the Paramics model was searched from the default 1.0 to as high as 2.5 and an LHF of 2.0 was found to reproduce the observed capacity and thus selected. Paramics Version 4.0 used for the I-15 project and this version does not introduce link reaction factor (Quadstone 2003a), only LHF was manipulated to calibrate the capacity of work zone sections.

2.2 Traffic Management System Evaluation

Evaluation of various traffic management systems might be the most widely used application area of microsimulation models (Leeds 1999a). With the rapidly increasing ATMIS features deployed, the functionalities of microsimulation models have been correspondingly expanded and enhanced greatly. For instance, Baher et al (1999) presented a list of features that are necessary or desirable for microsimulation and evaluated an early version of Paramics (Version 1.5). Many of the features that were weak or not incorporated in the early version are now being enhanced or added by later researchers, such as actuated or coordinated signal control (Liu et al 2001; Quadstone 2002), various ramp metering control algorithms (Zhang et al 2001). The researchers at University of Leeds in UK conducted a model developer and user survey of thirty-two available microsimulation software in the SmarTest project. By analyzing the developers' response and publicly available documentations, the researchers identified the gaps of these models that need to be filled so as to "quantify the benefits of Intelligent Transportation Systems primarily in Advanced Traveler Information Systems and Advanced Traffic Management Systems"(Leeds 1999a). Four models were chosen to enhance their modeling power by adding more ITS features such as adaptive signal control, public transport priority, dynamic route guidance, incident management and so on. The SmarTest project also listed the traffic phenomena and ITS functionalities concerned by microsimulation users, as shown in Table 1.

Table 1 Microsimulation User Desired Traffic Phenomena-Object and ITS features

ITS features	**Traffic Phenomena-objects**
Vehicle detectors	Queue spill back
Adaptive signal control	Weaving
Coordinated traffic signals	Incidents
Ramp metering	Commercial vehicle
Static route guidance	Roundabouts
Dynamic route guidance	Public transport
Incident management	Parked vehicle
Probe vehicles	Pedestrians

Priority to public transport vehicles	Weather conditions
Motorway flow control	Elaborate engine model
Variable message sign	Search for parking space
Adaptive cruise control	Bikes/motorcycles
Zone access control	
Automatic debit and toll plazas	
Congestion pricing	
Automated highway system	
Automomous vehicles	
Parking guidance	
Regional traffic information	
Support for pedestrians and cyclists	
Public transport information	

Source: SmarTest Microsimulation review report (Leeds 1999)

In California, evaluating corridor ATMIS strategies using microsimulation can be dated back to the end of 1980's (Gardes and May 1993a). To assess the potential benefits of traveler information, PATH researchers built an INTEGRATION model for the nine-mile Santa Monica freeway corridor (Interstate-10), and tested various strategies including ramp metering, real-time signal control, route guidance and the combinations(Gardes and May 1993a, 1993b). The microsimulation model was later expanded to cover larger local areas (Bacon, Windover & May 1995), but the expanded model posed great difficulty upon calibration and only part of the project goals were met due to unexpected time put into calibration. Other microsimulation such as CORSIM was also used to model the ATMIS benefits (Skarbardonis, Dalhgren & May 1998; Skarbardonis 2002), adjusting the default driving behavior parameters, e.g., car-following sensitivity factor, lane changing aggressiveness factor, was recognized to be necessary to accurately simulate freeway facilities in California. A more recent two-year study on the I-680 corridor (Gardes et al 2002, Gardes et al 2003a) investigated the application of high occupancy vehicle (HOV) lanes and local ramp metering strategies using Paramics model, and extensive calibration efforts were put to replicate both the road capacities at typical locations and the contour map of travel speed spatially and temporally. Although there have been meso-scopic simulation studies on relatively larger scale networks (Jayachrishnan et al 1993; Jayachrishnan et al 1996), corridor simulation studies are also greatly expanded to cover areas beyond the freeway mainline and a few parallel streets. Some studies covered city or region wide area to fully assess the impact of ATMIS strategies upon the city or the region (Gardes et al 2003b), and experiences have been accumulated for conducting the calibration process (Gardes et al 2001).

2.3 Travel Behavior Studies using Microsimulation

Examples of travel behavior studies using microsimulation are modeling users' response in Advanced Traveler Information Systems (ATIS) applications, integration of travel forecasting and traffic operations, and user-machine interaction for in-vehicle devices. Similar to the simulators used in the military or auto industry (Jones et al 1985; Leeds 1999a) where the drivers' reaction to certain stimuli such as braking/information provisions was tested, these models study people's responses under certain circumstances, from driving maneuvers at signalized intersections to route diversion propensities under ATIS information and guidance.

2.3.1 Evaluation of ATIS Effectiveness

Understanding users' responses to potential or existing ATIS services is critical to the deployment of such services and the evaluation of their effectiveness (Koutsopoulos 2003). In general, the data to support such analysis are expensive to obtain, and researchers have to resort to travel simulators to investigate user behavior under certain traffic circumstances. Three distinct categories of research related to the applications of microsimulation of ATIS are: i) in-vehicle behavior concerning the drivers' response to in-vehicle devices; ii) driving behavior concerning the driving tasks such as car following, overtaking, gap acceptance and other driving maneuvers; iii) travel behavior concerning the drivers' choices of mode, route, diversion, and compliance with ATIS advices (VMS messages, highway advisory radio broadcasting, route guidance system displays and so on) (Axhausen 2004).

Except for a few research such as DYNASMART (Jayachrishnan et al 1994), most ATIS simulation studies used highly simplified models and rarely apply a generalized microsimulation model such as AIMSUN, Paramics, CORSIM, VISSIM. Recently, Dia (Dia 1999) comes up with a framework to incorporate the users' response models into microsimulation. Behavioral surveys were analyzed to provide the user-information-traffic interaction model, and this model was incorporated into the microsimulation via application programming interface (API) functions1. However, these studies are mostly pilot studies of investigating the effectiveness of ATIS, where calibration of the microsimulation models was not their focus and not fully addressed.

2.3.2 Combining travel demand forecasting with Microsimulation

In contrast to microsimulation, travel demand forecasting models usually apply to large scale networks and model traffic flow on the network much more coarsely. Table 2 shows the time and space scales that these models typically apply to. As commonly found in the

---

[1] Several commercially available microsimulation packages, including Paramics, VISSIM, AIMSUN and CORSIM, provide such library of functions which allow the users to access, modify and enhance the microsimulation core algorithms *via* designated programming languages, such as C/C++ or JAVA.

results produced by travel demand forecasting models, some road sections could have unrealistically high traffic volumes (Nagel 2001). Researchers then begin to cross these cutoff boundaries, and examples of this are mesoscopic models such as DYNASMART (Mahmassani 2000) and microsimulation models such as TRANSIMS (http://transims.net; Nagel et al 1996), combining the travel demand analysis with mesoscopic or microscopic simulation. For example, in a case study in the Dallas area (Nagel 2001), the conventional four-step transportation planning models were applied to evaluate two panel reviewed network improvement project plans. TRANSIMS was then used to re-do the analysis and was able to obtain traffic flow conditions consistent with the observations.

Table 2 Prototypical Breakpoints between Models in Simulation Systems

Module	Typical Time Scale	Typical Spatial Scale	Typical Entity
Traffic flow	1 sec	1 meter	Intersection
Route choice	1/4 hour	100 meters	Corridor
Demand generation	1 hour	1 km	City
Land use	1 year	10 km	Region
Economy	1 year	100 km	Country

Source: Nagel (2001)

2.4 Environmental Impact Study

Emissions from mobile sources, vehicles in particular, account for a major part of urban air pollution, and estimation of the emission from the transportation sector has ever been an important area. Traditionally the estimation work first takes the travel demand forecast model results, i.e., the vehicle miles travel (VMT), from the network flow pattern obtained from the traffic assignment. The emission rates are then calculated from the speed estimated from the link volume statistics. However, this method essentially applies the static modeling method and thus suffers from the errors of various sources such as the travel demand model process and post process of travel speed estimation (Bai, Nie & Niemeier, 2005). To overcome this problem, some Microsimulation models incorporate the emission estimation module (Williams 2000). The emission rate from the driving cycle, that is, the mathematical function between certain pollutants discharge rate such as CO2 or greenhouse gas (GHG) versus velocity-acceleration of a certain vehicle, are associated with the simulated driver vehicle unit (DVU). Many environmental impact studies have been conducted at a specific project level, such as the electronic toll collection (ETC) plaza (Saka 2002), signalized intersection (Hellinga 2001), and freeway section level (Lemessi 2001). Nevertheless, the nature of practical and realistic emission study requires applying the model to a region level network, which is now exploring the potential limit of the modeling capability of microsimulation models (Bai 2003).

2.5 Summary

Four broad categories of microsimulation applications have been reviewed in the chapter. The first two categories, the evaluation of infrastructure performance and that of traffic management systems, are traditional applications of microscopic traffic simulation. But their application areas are becoming broader as various new ITS features have been continuously developed and required extensive evaluation before their implementations. So is the fourth category, environmental impact study. The third category of applications, travel behavioral studies and combining simulation with travel activity models, is relatively new and its number is expected to increase in the future.

Despite the success applications of microsimulation in various types of transportation projects, model calibration remains the weakest aspect in nearly all applications we found. Their documentation touched little on how the models are calibrated to suit local traffic conditions. Most calibration effort is rather ad hoc, often relies on trial-and-error. This state of affairs in model calibration could undermine the credibility of the conclusions drawn from such studies. In the next chapter, we will look into the calibration issues and summarize current practices in the calibration of microsimulation models, so as to gain insights on how to develop a systematic calibration procedure for such models.

CHAPTER 3 MODELING ASPECTS FOR A SUCCESSFUL CALIBRATION

3.1 Project Planning

A traffic simulation project generally takes the following steps: project planning, data collection, network coding, model calibration and validation, analysis of results, and presentation of key findings. Once a microscopic traffic simulation tool is selected, the first task of the analyst is to plan for the application, i.e., having a big picture of what is going to be done, what can be done and what can be expected from the simulation tool, and what is expected by the targeted audience. The project planning step has been emphasized by experienced model users and model developers in many documents (Dowling et al 2002; Quadstone 2004). However, this important step has been overlooked by many users, often resulting in either too ambitious or too narrow project scopes, numerous repetitions, or much prolonged calibration processes.

This section provides guidelines for setting up the framework of any microsimulation application towards an effective and efficient modeling process. In sum, it is necessary and helpful for the analyst to discuss and clarify the following items before the network coding and data collection tasks start:

- project purposes and needs
- limitations of analysis
- temporal and spatial scopes
- data requirements
- level of effort in modeling
- timeline and milestones

3.1.1 Identify Project Purposes and Needs

Microsimulation applications can vary from high level planning studies to detailed engineering design, as reviewed in Chapter 2. At the project planning stage, specific objectives such as model outputs are unlikely to be defined, but the analyst needs to clarify the expectations from the modeling work in general. The following considerations can help pinpoint the project purposes and needs:

Expected Objectives. What does the analyst want to get from the simulations? For example, if the microsimulation is mainly used as a public outreach tool, accurate geometric representation of the current traffic and proposed changes will be important for marketing purposes. Usually the development and evaluation of design, operation and traffic management alternatives[2] are the most common microsimulation applications. For such applications, the ability to model these alternatives and their traffic impact faithfully and accurately is a must and a large amount of effort is expected to be devoted to data preparation, model building and calibration, and processing and analysis of simulation outputs.

Resource Constraints. This refers to the availability of time, monetary and personnel resources. Compared to modeling tools at macroscopic levels, microsimulation is much more fine-grained and often requires a great deal more of input data. Although varying from simulation package to simulation package, building a microsimulation application (preparing input data, coding the network, and calibrating the simulation model) for a medium sized network can take several months to complete. It is not uncommon that the available time budget determines the spatial and temporal scope of the project. Another important factor affecting project time and scope is the project personnel's proficiency in the specific software used. Users familiar with the software normally take much less time than novice users since the latter often have to climb a steep learning curve to master the microsimulation software. The modeling skills of the project staff, therefore, have to be taken into account at the project scoping stage.

Future usage. The life cycle of a microsimulation application usually spans at least a short-term planning period of five years. Future projects may significantly change the traffic pattern in the area of interest. In terms of resource savings, it may be desirable to have one microsimulation model that can be also used for the evaluation of future projects. If this is the case, one may enlarge the project scope in anticipation of future usage.

Data availability Sufficient and quality data are fundamental to the success of any microsimulation. At the project planning stage, it is not necessary for the analyst to prepare the data for coding and calibration, but the analyst should identify all the possible sources of data and estimate their coverage and quality. Dowling et al. (2002) has listed the following data sources and their quality for microsimulation applications:

---

[2] Mostly, microsimulation application aims to evaluate the performance of certain projects proposed to improve some aspects of the transportation network. For example, better control strategies, advanced information system, or simply improving the current facilities. Here the terms 'policy options', 'ATMIS alternatives', and 'network changes' all refer to these proposed projects to be evaluated in microsimulation.

Table 3 Data Sources and Usage

Category	Sources, Fidelity and Usage
Geometry data	▪ Aerial photos: Node and link alignment ▪ As-Built plans: Lanes and detailed horizontal and vertical curvatures
Control data	▪ Field inspection: sign and stripping inventories ▪ Operating agencies: city traffic engineers, TMCs ▪ Available models: Synchro models, TRANSYT, etc.
Demand data	▪ PeMS, HPMS: point specific traffic counts ▪ Existing planning models: zoning system and coarse trip tables
Calibration data	▪ Field inspection: capacity and saturation flow rate, delay and queue ▪ Floating car runs: travel time, queue length and duration ▪ PeMS & HPMS: point speed and traffic counts, travel time
Future Demand data	▪ Planning models: a rough estimation, need to be inspected

Source: collated from (Dowling et al 2002)

It is noted that when field data are scarce, they can also be supplemented with data produced by existing models, such as regional planning models (e.g., EMME/2, TP+/Viper), traffic control models (e.g., TRANSYT, Synchro) and macroscopic traffic models (e.g., FREQ, HCS)..

Targeted Audience. Different end users have various focuses and concerns on the simulation results. Performance evaluation and calibration criteria are different to various groups, ranging from advanced technical panel, DOT traffic operations staff, to the general public. Ideas to be conveyed to technical panel and general public may be the same, but the presentation will be quite different. Simulation focuses and corresponding project scopes and modeling efforts must be adjusted accordingly.

3.1.2 Quantify Spatial and Temporal Boundaries

It is one major step to determine the spatial and temporal boundaries of a microsimulation project, and perhaps it is also the most difficult step at the project planning stage. This is also called project scoping in some documents (Quadstone 2004). Ideally, a larger network with good calibration can predict even the marginal effect of any proposed network changes or ATMIS features, but this will undoubtedly call for a larger investment in data collection and modeling effort. In many cases it relies on the analysts' experiences or "engineering judgment" to perform this task. In a broader sense, project scoping involves all information available at the project planning stage, and is largely determined by project objectives, data availability, and project budget.

Federal Highway Administration (FHWA) initiated a study to assist users selecting appropriate traffic analysis tools for different aspects of traffic and transportation analyses (Alexiadis et al 2004; Dowling et al 2004; Jeannotte et al 2004). The study area of traffic analysis is classified into four types, as listed in Table 4.

Table 4 Microsimulation Network Classification

Network Category	Geographic Coverage
Isolated Location	Limited study area, such as a single intersection or interchange
Segment	Linear or small-grid roadway network.
Corridor Network	Expanded study area that typically includes one major corridor with one or two parallel arterials and their connecting cross-streets, typically less than 520 square kilometers (km^2) (200 square miles (mi^2)).
Region/Strategic	Citywide or countywide study area involving all freeway corridors and major arterials, typically 520 km^2 (200 mi^2) or larger.

Source: FHWA Traffic Analysis Toolbox study (Jeannotte 2004)

Project scoping first needs to identify the geographic coverage of the network to be built in microsimulation, and then it can use specific techniques or other types of models (e.g., HCM or sketch planning models) to help decide both the spatial and temporal scopes.

3.1.2.1 General rules for Determining Spatial and Temporal Boundary

<u>Spatial boundary</u>

Deciding the spatial boundary of the microsimulation is highly case-specific. It depends greatly upon engineering judgment of local conditions. Some general rules for considering the local conditions include (Quadstone 2004):

1. Ensuring the boundary traffic is not disturbed. A rule of thumb, the simulated traffic impact due to proposed network changes is marginal at the

boundary of the simulated network. It is the so-called ‘Free-flow-in, free-flow-out’ rule. The redistribution and rerouting of traffic shall be estimated when quantifying the overall size of the simulated network.

2. Estimating the available resources**.** Similar to Section 3.1.1, the time and staff resources can largely determine the size of the studied network. Besides, the model calibration and validation work will increase drastically when the network size increases. Thus the model development efforts are not linearly proportional to the network size.

3. Taking adjacent critical or congested area into account. If there are critical traffic attraction or production facilities adjacent to the area of interest, it is better to incorporate the critical facilities into the simulation network so as to evaluate their impact upon the area. Adjacent congested area could possibly cause queue spilling back to the area of interest, and this is critical to the quality of the microsimulation model. This rule applies to networks of all sizes.

4. Identifying possibly available data sources. If the transportation network has very sparse data collection locations, a tradeoff has to be decided on whether to accept a bigger simulated network with relatively low-quality input or to have the network size cut down to match the available data. Data availability also refers to the ability to collect further data. If the network has very limited data collection locations that may meet the current needs but no further data can be expected, the network size will be constrained to the current status.

5. Future land use and politics. Rapidly growing metropolitan areas can have dramatic land use changes even in the foreseeable future, and result in unavoidable transportation network changes. Taking the land use and regional development plan into consideration will avoid future waste of the coded microsimulation model work. Politics for local municipality development plays a similar role in the transportation network evolution, so it must also be considered in determining the project scope.

These general rules apply to networks of all sizes and various application objectives. Nevertheless, the spatial boundary of the microsimulation application depends largely on the objectives of the projects.

<u>Temporal scope (length of simulation period)</u>

Many factors affect the selection of the length of the simulation period in a simulation study. The selection process is also highly case-specific. First, it depends on the study purpose. For instance, investigation of peak hour traffic conditions would require modeling of the whole peak period (usually three hours long). If the application is to study the effectiveness of high occupancy vehicle (HOV) lanes, the simulation will span the entire HOV restriction period as well as a warm-up and cooling-down period.

Besides the study purposes, other considerations to help decide the length of the simulation period include:

1. Local traffic patterns. Traffic patterns may well be influenced by the local activity patterns, for example, local back-to-school season, yearly/monthly/weekly traffic cycles, special events (sports, holidays), and etc.

2. Warm-up and cooling-down period. The objective of setting up a warm-up and a cooling-down period before and after the main period of concern is to provide proper initial conditions for the modeling period. The warm-up period is often set to span the longest trip that would occur in the network. In this way all the simulated traffic would be loaded onto the network during the main simulation period.

3. Major trip purposes. Commuting and recreational trips are fundamentally different. While peaking may well reflect the work trips, recreational trips may have a much wider span of departure times. When mixed, trip of various purposes may affect the modeling period as well as the overall demand structure.

   Major trips of the simulated traffic generally determine the modeling period. Similar to the setup of warm-up period, the modeling period cannot be shorter than the longest trip time, taking the en route delay and traffic condition into account.

4. Changes in demand. Traffic demand data are hard and expensive to obtain. Furthermore, traffic demand may change even in a short simulation period. Special events such as sporting matches with large traffic attraction/production can drastically change the traffic demand pattern. Microsimulation needs to adapt to these changes in both the overall modeling period and different time slices in the demand profile.

   Traffic composition may also change at certain places and this must also be considered. For example, some places have restrictions on freight vehicles' access to city centers and the simulation would be distorted if the modeling period crosses the restriction periods.

5. Data and resource availability. If the available data and other resources are not enough to support an expectedly longer simulation period, the simulation period may be cut short.

3.1.2.2 Some Scoping Techniques for Determining Spatial and Temporal Boundaries

The abovementioned rules are general guidelines for laying out further analysis. Indeed many scoping work has relied heavily on engineering judgment based on the analysts' knowledge of the local network situations. Besides such heuristic methods, a few scoping techniques have been mentioned in the literature. They mainly use other available models to help decide the spatial or temporal boundaries of a microsimulation application. These techniques include:

Demand-capacity analysis and macroscopic simulation

High fidelity simulation is a double-edged weapon. On one hand, it can help the analyst study a transportation problem in great detail. On the other hand, it also burdens the analysts with a great amount of coding, data preparation and calibration work. In contrast, some simpler macroscopic models such as the deterministic queuing model (also known as the demand-capacity model) offer a coarser description of traffic but require much less inputs and are much easier to apply. Whenever it is possible, one can use such macroscopic models to perform a sketch study to estimate the temporal and spatial scope of the simulation project before further work begins. For example, if one wants to study the traffic impact of a construction work zone on a freeway using microsimulation, one can use the deterministic queuing model to estimate the maximum queue length and duration of congestion caused by the work zone based on historical demand data and estimated work zone capacity. This would provide a reference frame for the temporal and spatial scope of the microsimulation that may also include arterial streets and neighboring freeways as diversion routes. Other macroscopic models, such as FREQ, offer greater modeling flexibility than the deterministic queuing model by considering entry/exit flows and traffic on parallel routes, and can also be used to help determine the temporal/spatial scope of a microsimulation project.

Planning models

Software that implements travel demand forecasting models (e.g., EEME/2 and TP+Viper) can provide the origin-destination information for both current and future traffic conditions and a coarse representation of road geometry. As such they can also estimate the influence area of certain network changes, such as facility improvements (adding interchanges, ramps, and etc.) as well as new ATMIS elements. Moreover, planning models can also predict the incurred demand pattern changes in the sub area of a microsimulation study, hence providing a rough demand estimate for the microsimulation.

It should also be noted that planning models are much more coarsely grained in both temporal and spatial resolutions. Therefore changes must be made to the demand structures and other data produced by planning models before applying them to set up a microsimulation. For example, the traffic analysis zones (TAZ) used in planning models are often too big to be used in microsimulation models, and they have to be broken down into smaller ones to avoid artificial traffic jams created by large amount of traffic released from the large TAZs.

3.1.2.3 Characteristics of Networks of Different Geographic Coverage

Besides the general network classification (Section 3.1.2.1) and scoping rules and methods (Section 3.1.2.2), some specific methods and guidelines are often used for networks with special features, and they are summarized as follows.

Networks of isolated location or segment

In these networks, the analysts are usually interested in the performance of one or two adjacent facilities, where the impact of traffic route selection is minor. The typical applications involving such networks include:

- Evaluation of the performance of isolated systems, such as intersection control systems, and freeway facility improvements (e.g., adding an interchange or a ramp);
- Single road facility design and redesign;
- Traffic behavior in a critical area (e.g., weaving sections).

The key to decide the spatial boundary of this type of networks is to locate the boundaries where the traffic influences from adjacent facilities are marginal.

For example, Minnesota Department of Transportation (MnDOT 2003) uses separate criteria for rural areas and metropolitan areas in deciding the spatial boundary of its CORSIM based simulation studies. Rural areas have relatively far distanced interchanges, therefore the boundary for simulating one subject interchange is to have one *service interchange* (on-off ramps connecting local streets) on either side. For studying an interchange in urban areas, however, one *system interchange* (freeway-freeway) on either side of the subject interchange has to be included in the simulation model.

The simulation period of this type of applications is largely determined by the length of the peak period. Since the facilities to be designed or improved usually has a life span of 20 years or more, when deciding the length of the simulation period, one should also consider the spread of the peak period in future years as demand grows and congestion worsens.

Corridor networks

Corridor networks of medium size are the most commonly seen networks in microsimulation applications. Example applications in such networks are ramp metering studies (e.g., Gardes et al 2002; Gardes et al 2003; Gomes et al 2004), HOV lane studies, studies of coordinated signal control and traveler information systems (e.g., Gardes et al 1993; Ben-Akiva et al 2002), as well as work zone traffic impact studies (e.g., Ma et al 2003).

In all these applications, whether it is investigating various types of traffic control strategies (e.g., adaptive, coordinated signal control, ramp metering, route guidance), or developing effective management plans for construction work zones, it is essential to identify the bottlenecks in the corridor network, and geographical scope of the network should cover the areas affected by these bottlenecks, which can be crudely estimated by the deterministic queuing model. In practice, however, the modeling scope is also constrained by the availability of traffic data, particularly those from arterial streets.

Strategic/Regional networks

Computational advances in PCs in recent years have enabled microsimulation to be applied to large transportation networks, usually the application domain of planning models. Some microsimulation applications to date even cover a whole metropolitan area (Bridges 2003). For networks of this size, key factors affecting the simulation quality are: local driving behavior, departure time and route choice decisions, O-D demand estimation, and travelers' response to various types of traffic management strategies.

Although modeling strategic network using microsimulation is a daunting task for any analyst, determining the spatial boundary for such applications may not require as much technical analysis as other applications concerning smaller size networks. This is because 1) political and economic concerns often dominate in deciding the modeling scope in such studies, and 2) it is sometimes even desirable to cover a whole area for future use. When technical analysis is required to decide the project's coverage area, planning models can be used to help make this decision.

3.1.3 Estimate Data Requirements

The availability of good quality data affects both the scope and reliability of microsimulation studies considerably. We refer to Table 3 for a summary of data sources commonly used in California; and Chapter 4 of (Dowling et al 2002) for a detailed description of data categories, and Section 3.2 of this document for data collection guidelines.

3.1.4 Estimate Level of Effort

The level of modeling effort is important to all personnel related to the microsimulation project. The project manager needs to estimate modeling effort to convey the expectations and constraints to DOT (Caltrans) personnel. The level of effort depends more or less on the complexity of the simulated network. Nevertheless, several months are usually needed to conduct a medium sized network simulation starting from scratch. The time does not translate into staff hours because of two factors: (1) various levels of staff experiences with certain microsimulation software and (2) there may be delay due to the waiting time for input data to be available or re-coding of part of the network.

One easy way to estimate the level of effort is to identify the major tasks and how much effort should be put into to those tasks. It requires good knowledge of the network, the simulation software, the availability of resources and data. Even though there are general time frames for each modeling step (See Figure 5 of MnDOT 2003; or Figure 1 of

Dowling et al 2004), the percentages of each model development step vary among different models. Estimation of the level of effort is usually combined with setting timelines and milestone tasks, which will be discussed in the next section.

3.1.5 Set Timelines and Milestones

After estimating the modeling effort, the analyst usually sets up reasonable deadlines for major tasks before proceeding to next modeling steps. Without a time table for major tasks, the project lacks structure and cannot be well organized, raising the risk of unmet project goals.

The general rules of setting reasonable timelines are summarized as follows (Quadstone 2004):

1. Identify major tasks. The major steps in a microsimulation project include data preparation, network coding, model calibration and validation, and model application (Dowling et al 2002). Along with these, specific tasks, such as data collection for certain locations, or calibrating the performance for critical areas, shall be identified beforehand.

2. Identify critical steps. Critical tasks and milestones need to be taken special care of, as any delay on these tasks will affect the project completion date.

3. Overall schedule. Several months are often needed to build a microsimulation model. A realistic setup for the entire schedule should also allow for slack times at certain steps. A general estimation is to buffer 20% of a tight schedule for possible time overruns.

3.1.6 Summary of the Project Planning Process

We discussed the project planning process in Sections 3.1.1 to 3.1.5. As strongly recommended by experienced microsimulation users and model developers, a brief project scoping report (PSR) containing the following information helps structure the later simulation work:

- Purposes and needs: model objectives, major concerns of the network, deliverables;

- Spatial and temporal scopes: network size, coverage, modeling period, major bottlenecks;

- Data requirements: data availability, possible sources, expected data collection effort, discrepancies between data requirements and availability as well as remedies;

- Level of effort: expectation of model fidelity, rough estimation of percentages of different tasks, overall estimated developmental effort;

- Timelines and milestones: timeline of major tasks, and their sub-tasks as detailed as possible, and expected dates of completion.

Such a PSR would be a useful document for checking the progress and updating the project tasks in later modeling steps. It is very often that the microsimulation project would be modified to accommodate changes not predicted before the project starts. A good documentation of important changes is also necessary. It is also a good practice to check the progress against the PSR after each major task has been accomplished.

3.2 Network Coding

Building a baseline simulation needs three categories of input data, namely network geometry, traffic control data, and traffic demand. Coding up input data accurately in a microsimulation is the first step towards developing a reliable simulation project. Microsimulation models commonly take the node-link (arc) network representation; but network coding techniques vary between different software implementations of the models. Herein we mainly focus on the coding issues related to model calibration.

3.2.1 Coding Accuracy

Microsimulation is data-intensive, and it is important to ensure the coded network represents the real world network as faithful as possible. Guidelines on improving coding accuracy found in the literature are summarized as follows:

- Geometric accuracy. Overlaying aerial photos or as-built plans as the coding background is a common technique when coding the skeleton network. At critical locations such as key intersections and ramps, detailed geometric design plans should be used to fine tune the lane usage and node positions. Recently, several studies have converted networks coded for planning models or geographical information systems (GIS) into networks for microsimulation (TSS 2000; Church & Noronha 2003; Gardes et al 2004), but the converted primitive network needs further refinement in things like road alignment and curb positioning before it can be used in microsimulation.

- Coding templates. Templates such as link category files can help building the network quickly by standardizing the facility and area types. Using templates also helps error checking and calibration work in later stages.

- Demand structures. Traffic demand is a complex set of input data. In a broader sense, traffic demand includes vehicle fleet mix, driver population and their behavioral characteristics, and the OD trip table. At the stage of network coding, some inputs, such as parameters related to driving behavior or route choice behavior, are not known with certainty, and their default values have to be accepted as is. They will be updated in the calibration stage. Other inputs, such the vehicle fleet mix and the physical and performance characteristics of the vehicles in the fleet, including acceleration/deceleration characteristics, dimensions, fleet composition and driver-passenger occupancy, should be gathered from various sources as completely and accurately as possible, for they can significantly affect the simulation results.

3.2.2 Bottleneck Sections

Networks to be simulated usually cover some sites that have special features such as sharp curvatures, steep up/down grades, lane drops, and so on. These features affect driving behavior and often result in capacity reductions in these road locations. Driving behavior parameters related to these sites should be fine tuned to capture the traffic flow characteristics unique to these bottleneck locations. A good example of such efforts is a VISSIM study by Gomez et al (2004), where car following model parameters were adjusted to replicate the traffic flow characteristics at a sharp curve and on-ramps with large incoming demands on a stretch of congested I-210 in Pasadena, CA.

3.3 Data Collection and Processing

Five categories of data are needed when building a microsimulation model (Dowling et al 2002):

1. Geometry (lanes, lengths, curvature and grade)
2. Control (signal timing, signs)
3. Existing demand (turning counts, O-D trip table)
4. Aggregate data for calibration (speeds, link volumes, link or path travel times)
5. Future demand in the projected time horizon.

Categories 1, 2 and 3 are required for coding the baseline network. Together with the first three categories, Category 4 are used for the calibration of the network, and Category 5 for evaluating policy and ATMIS alternatives designed to cope with future traffic growth. Dowling et al. (2002) has described each category briefly. Our report focuses the collection and processing of data used in model calibration.

3.3.1 Assembling Microsimulation Input Data

The five categories of data are integral to a successful microsimulation application. A good set of data in categories 1-4 is vital to build a solid baseline simulation and future demand data are essential to investigating the effectiveness of proposed network changes to accommodate the demand growth. Once the scope of the project has been decided (see Section 3.1), one needs to collect all five categories of data to be used in different stages of a simulation project. Data requirements differ according to network sizes (see Table 4) because key issues of interest vary by network sizes.

Small-size networks:

The main modeling concerns for small-size networks are the operational characteristics of its critical elements, such as merging or diverging sections, intersections and lane-drop segments, thus it is important have accurate geometric and traffic control data for such networks, including:

- Lane grouping, stripping, markings, interchange/ramp shapes and lengths;
- Intersection signal control type, control plan;

In addition, the relevant calibration data include:

- flow rate, travel speed and occupancy
- Queue length;
- Intersection saturation flow rate for certain movements;
- Control delay, stop time.

Medium-size networks

Driving behavior at critical locations, route choice behavior as well as traffic demand are important factors to consider in medium sized networks. In addition to data used in calibrating driving behavior as in small networks, one should collect additional data for the calibration of route choice and adjustment of O-D demands:

- Traffic counts along critical routes, e.g., traffic counts on the freeway as well as on/off ramps; turning counts at major intersections.
- Travel time along certain routes. Different demand patterns may produce similar traffic counts but differing travel times on selected routes. Travel time measurements along routes of interest can help refine the O-D trip table so as to achieve better calibration accuracy.

Large-size (strategic) networks

Data requirements for strategic networks are more extensive than the networks of smaller sizes. In addition to data such as traffic counts, travel speeds and travel times, other data that can improve the accuracy of the generalized travel cost function, such as trip time, trip distance, and tolls, as well as data that reflect the behavioral differences among different groups of users, such as driver types and fleet composition, also need to be collected for large-size network simulation studies.

One general rule of data collection and processing is to reduce the difficulty for later baseline calibration and future year model application. Bad data often lead to unreliable simulation results and hence misinformed policy or management decisions. Thus, one should always check the accuracy and consistency of collected data before coding them up into the simulation. There is no substitute for the collection of all needed data from the field, but this may not always be feasible due to resource constraints. Below are a few techniques that can be used to supplement field data collection efforts and eliminate errors and inconsistencies presented in the assembled data:

- Synthesize data from various data sources. Input data for a network may have been collected for other studies and exist in various forms. One can extract relevant data from these existing sources. For example, one can extract crude geometry and O-D information from existing planning or GIS applications, turning movements and signal timing plans from existing Synchro or TRANSYT applications, and turning movements, ramp merge/diverge volumes, intersection layout and timing from existing HCS or FREQ applications (Dowling et al 2002). Synthesizing these data with field measurements can considerably reduce data collection costs.

- Eliminate inconsistent data. The following inconsistencies are often observed: (1) traffic counts far exceed the estimated flow capacity; (2) ‘floating car’ travel times do not match with travel speeds measured along the same route/link; (3) travel times and speeds are inconsistent with observed traffic conditions. In many cases the errors are easy to spot while in some cases it may not be easy to identify them. In the latter case, more data, either from historical sources or supplemental field measurements, should be obtained to help screen out the bad data. Otherwise, one has to abandon the inconsistent data..

3.3.2 Types of Calibration Data

As high fidelity as they are, microsimulation models can provide all kinds of traffic information, ranging from micro scale data such as the moment by moment acceleration and speed of a vehicle, to macro scale data such as flow rate, average travel speed on a road section, and travel delay at a road junction. In theory, one can calibrate a microsimulation model up to the scale of individual vehicle movements, but this would require a great deal amount of data that is practically impossible to collect for even a small network, and is often unnecessary. In fact, it is the macro scale measurements that we are mostly interested in such studies, not the minute details of vehicle movements, because we are primarily interested in the congestion patterns occurring in the network, and such patterns can be adequately and more clearly depicted by macro level data. Such measures include flow rate, link/path travel times, delays or queue sizes at bottleneck locations. For the sake of reference, we list in Table 5 the measures of effectiveness (MOEs) commonly used to quantify the goodness of fit of the outputs from a calibrated simulation model. These MOEs are often used as criteria for judging the quality of model calibration.

Table 5 Commonly Applied MOEs in Microsimulation Calibration

Measure of Effectiveness	**Description**	**Typical Application Context**
Stop time	Or stopped delay, is the stop time per vehicle stopped. Usually this occurs at signalized intersections, and is a portion of the control delay. Stop time is easier to measure and serves as a basic MOE.	Signal control: vehicle actuated control, coordinated control, adaptive signal control, and so on.
Travel time	Usually the trip durations obtained from floating car runs conducted in the area of interest. It comprises of trip times on the links of the measured route.	Strategic and corridor network studies
Queue length	Number of queued vehicles.	Signal control, freeway bottleneck analysis
Traffic counts	Usually in the unit of an hourly or quarter-hourly flow rate.	Strategic and corridor network studies
Travel speed	Average travel speed, measured for a fleet of vehicles, for trips between an O-D pair, or for certain road sections.	Any network studies
Delay time	Average delay per vehicle compared to free-flow travel time, computed at the intersection or link level	Signal control and ramp metering systems
Speed profile	Plot of successive speed data at the same location over time.	Freeway performance studies

In addition to these measures, two simple techniques can also be used to assess the calibration outcome for certain applications, one is the speed contour plot and the other is the speed-flow plot. The contour plot of the average travel speed over time and space can reveal the formation and dissipation of the congestion pattern on a segment of road and is particularly suited for bottleneck analysis of a linear network, and the speed flow plot can tell us the traffic flow characteristics at a location and whether the underlying driving behavior models and their parameters are set up properly.

3.4 Issues in Traffic Demand Estimation

With a few exceptions like MITSIM, which estimates traffic demand automatically from link counts (Ben-Akiva et al 2002), most microsimulation models need exogenously provided traffic demand. The O-D trip table can be obtained from household surveys or license plate matching surveys, but these surveys are usually costly and carried out infrequently, usually every five to ten years for a city network. As a common technique to obtain more up-to-date O-D trip tables, estimation methods using observed traffic counts and/or travel times are often employed to supplement the more expensive survey methods. Several issues, however, exist with these estimation methods:

1. Estimating the O-D trip table from observed link counts is an under-constrained problem, that is, many different O-D tables can produce the same set of observed link counts. Therefore additional information about the traffic in the network is necessary to determine the most likely O-D trip table.

2. O-D trip tables used in most microsimulation applications are usually externally obtained from models that are inherently different from microsimulation models, for example, macroscopic models. Paramics OD Estimator fixes this problem by applying the same simulation engine in the O-D estimation process. However, since the O-D estimation process is highly tied to traffic assignment and some assignment methods do not consider the dynamic evolution of the simulated traffic, there are still discrepancies between the field measurements and the simulation results obtained under the estimated O-D trip tables. For instance, because the all-or-nothing and stochastic assignment methods in Paramics neglect the possible turning delays at the signalized intersections, some drivers in the simulation may favor certain paths but in reality they may behave differently.

3. In a large (strategic) network, most O-D pairs have numerous alternative routes and the existence of this great number of routes often causes the greatest difficulty in calibrating a strategic network. When the route cost is very sensitive to certain route choice factors (such as cost function, specific link cost, driver behavior, and so on), a minor change in any of the parameters can make the flows oscillate among routes so drastically that both the simulation and estimation processes become unstable. A common technique used to avoid such oscillations is to assign flow on a limited number of key routes, but this may lead to unrealistic trip distributions in the network.

4. Drivers' route choice characteristics, such as their perception of travel costs and familiarity with the network, collectively have significant influences on demand estimation but are usually unobservable. This also adds to the difficulty in obtaining a reliable O-D trip table.

5. The estimation of O-D demand in the "future year" is even more difficult than that in the baseline year, for there are even no link counts or travel times available to estimate future year demand. Typically future year demand is obtained through projecting the baseline year demand in some way. Here by 'future year' demand we not only mean the projected demand into the modeling horizon, but also the induced demand changes caused by implemented traffic management strategies or other improvements made to the network. Examples

of the latter include the demand changes caused by the addition of an HOV lane, or the implementation of ramp metering, and so on. Estimating such demand changes prove to be difficult and sometimes huge estimation errors are made.

We will discuss further in the next chapter the topic of refining O-D demand in the calibration process.

CHAPTER 4 CURRENT CALIBRATION PRACTICES

4.1 Reviews on the Dowling Report

The Dowling report (Dowling et al 2002) draws a relatively complete picture about every aspect of applying microsimulation, from planning the simulation project, preparing input data, to presenting the results to the audience. Its major contributions in model calibration can be summarized as follows:

- It clarifies the terminologies and distinguishes the eight steps in developing a microsimulation application, namely determining the project time and network size, data collection, network coding, error checking, baseline model calibration, alternative/policy options evaluation, documentation and presentation of results. Before a microsimulation model is used to investigate management or policy scenarios, the model itself shall be validated and the default parameters adjusted against the selected traffic situations, the so-called “theory validation”. For example, the Paramics model is validated against the UK’s traffic conditions (Cameron and Duncan 1996) and VISSIM against German traffic conditions (hubschneider 1983). However, when the models are applied to places where traffic conditions are significantly different from those of the theory validation sites, “model application calibration”, or simply “model calibration”, must be conducted to tailor the model to the local situation. This is also the focus of our project. The process is vital because an ill calibrated simulation may lead to misinformed transportation policy decisions.

- It develops a systematic calibration process, a set of calibration criteria. The calibration procedure suggested in the report is as follows: A generally
    1. Check for and eliminate obvious coding errors;
    2. Calibrate the capacity related factors;
    3. Calibrate the demand related factors;
    4. Review of the realism of the model results.

  By breaking down the calibration process into several steps, one can apply the procedure in an iterative way until the gap between simulated and field measured MOEs falls into an acceptable range.

- It emphasized the importance of checking coding errors. Coding errors can lead to distorted parameter values in the calibration stage. For example, if a specific link is assigned an inappropriate cost factor or wrong category, the calibration procedure would artificially manipulate the parameters related to vehicle route choice = in order to obtain a good fit between simulated and observed traffic measures. That is, the calibration procedure, without the knowledge of the coding error, would adjust the parameters in a skewed way so as to compensate for the errors caused by coding mistakes.

- It classifies the model parameters from the supply and demand sides into two categories: global and site-specific. On the supply side, microsimulation models do not directly provide any capacity as in the HCM. Rather the capacity of a road segment is in indirectly decided by driving behavior parameters such as mean target headway. One therefore calibrates these driving behavior parameters to match the capacities observed at various types of road segments. On the demand side, the parameters to calibrate are those related to driver and traffic characteristics, including the demand patterns (trip rate and the time variation), their familiarity with the network and their individual groups' route cost criteria. These parameters are calibrated against measurements of traffic counts and/or travel times.

- It emphasizes the use of microsimulation animation to check for model realism. Besides looking at the MOEs of interest (e.g., link counts, travel times, queue lengths), one should also perform visual inspections when running the simulation to spot problems that can be averaged out or hidden in the numerical results.

In the next few sections, we will summarize the findings and experiences about error-checking, and calibration of supply and demand parameters found in the literature to-date, including the Dowling report.

4.2 Checking Coding Errors

The coded network should be carefully checked for possible coding errors. It should be noted that the specific process of checking coding errors varies from one simulation software to another. In this report, our discussions will be focused on Paramics, , but some of the techniques discussed here can also be applied to checking coding errors in simulations using other software packages. The Dowling report suggests seven general error checking techniques:

1. Consulting simulation software website/forums/technical support;
2. Using an overlaid digital map to fine tune the network geometry at key locations;
3. Eliminating redundant nodes and links;
4. Auditing the link characteristics by coloring different link categories[3];
5. Tracing a single vehicle running through the network in very low demand to visually audit its movement;

---

[3] In Paramics, *link audit* is one error checking tool, which can color the network links by: category, major/minor, highway/urban, speed limit, number of lanes, link type, cost factor and headway factor. See Quadstone (2003). Paramics V5-Modeller Reference Manual. Edinburgh, Scotland, Quadstone Ltd. pp 58.

6. Running the model at a low demand level (50%, for example) to investigate any unexpected congestion;
7. Coding simple test networks to confirm possible software bugs.

The above seven error checking techniques are referenced in Table 6 by their corresponding index number. In addition, engineering judgment is often called for when specific knowledge about the local network is required. We name engineering judgment as error checking technique No. 8.

In this report, we have identified ten error checking categories. They are:

- General rules
- Software updates
- Network layout
- Global simulation parameters
- Data availability and accuracy
- Supply
- Traffic demand
- Site specific supply and demand factors
- Control systems
- Traffic assignment related factors

It should be noted that many of the parameters in Table 6 may not have satisfactory values until the whole calibration has been completed. A check list as in Table 6 serves as a reminder to the analyst to examine the coded network as well as to think of the calibration needs and work load.

TABLE 6 Error Checking List

Category	**Detailed item**	**Comments**	**Techniques used**
General rules	Number of simulation runs	At each parameter adjustment step, there should be enough number of simulation runs for accumulating output statistics (Ref. MnDOT 2003; Dowling et al 2004).	
	Documentation	Ideally, each calibration step and parameter change should be documented for later reference.	
Simulation theoretical model updates	Availability of new model release	New features of ATMIS infrastructure or new simulation user tools might be available. The baseline network should be upgraded with these latest tools/models before checking for errors.	Dowling (1)
	Model bugs fix-up patches	Special functions may be added into the missing ATMIS features, such as various adaptive control systems and updated behavioral modeling.	Dowling (1)
Network layout	Geometry, detail plan	Inspect - Link alignment - Curb positioning - Lane usage at lane drop/widening sections and intersections against aerial photos or as-built plans	Dowling (2)
	Network connectivity	Availability of paths between each O-D pair	Route inspection[4]
	Link audit	Check - Network hierarchy - Link category definitions (number of lanes, speed limit, freeway or urban street, headway factors, cost factors) - Abnormality of link characteristics on a continuous facility	Dowling (4)
	Time step	Time step affects the vehicle movement calculation, and the simulation run-time. The constraint is freeway traffic volume[5].	Simple calculation[3]

---

[4] In PARAMICS, the route from an origin zone to a destination zone can be shown visually in the Modeller, with assignment method manipulations.

Global simulation parameters	Speed memory	The number of time steps during which an individual vehicle remembers its speed (affecting driver reaction time)	
	Queue speed and queue distance	Key MOE statistics, usually checked against one’s experiences and local knowledge	
	Data availability and coverage	The following data categories should be obtained to assess traffic performance: - Link counts - Average speed - Travel time and their coverage over the network	(8)
Data availability and consistency	Data accuracy	Correct some obvious errors in the aggregate data, e.g., too long or too short travel time over a certain road, too high traffic volume compared to capacity, and etc.	(8)
	Data consistency	Two main sources: - Link counts on adjacent road sections - Travel time and related average travel speed over certain paths	Validate Data tool[6]
	Category headway factor	Identify critical locations and road sections where driving behavior might be different, e.g., car parks and stadium, and then specify certain headway factors. These categories and locations are subject to further calibration.	(8)

---

[5] In PARAMICS, vehicles make transitions from one link to the successive link only at each time step. If the time step is too large, say 2 for example (i.e., every 0.5 second the model updates the vehicle positions), there will be large errors in the calculation of vehicle positions and movement of vehicles, especially when the traffic is running near free flow condition. For example, if a driver vehicle unit (DVU) is running at 65 mph, the positions will be

$$65*\frac{5280}{3600}=96\,ft$$

in one second. If the time step is 2, it means that Paramics DVU moving rule will hold it in front of a transition point for waiting to move into the next link and thus an error of 48 ft occurs. If there are large volumes of traffic on the freeway, it will cause both computational error and artificial congestion. With the increase in time step, this error will be reduced. The analyst must make the tradeoff calculation here.

[6] The data consistency check tool “Validate data” is available in Paramics O-D Estimator. See Quadstone (2003b) pp 22.

Infrastructure supply	Category cost factor	Identify the roads which are favored or not favored by travelers in the study period, and assign proper cost factors to them. These factors are also subject to further calibration when one calibrates route choice parameters.	
	Zoning structure and O-D	A microsimulation model for a strategic network usually obtains traffic TAZs from planning models. A planning model TAZ is often too big for microsimulation and thus it may be necessary to break those TAZs into smaller zones.	(8)
	Zone characteristics	External origin zones for freeways are different from the internal zones of residential or employment areas, in the sense that traffic entering from freeway external zones has high speeds. Freeway external zones are generally treated as 'zone connectors'7.	
Traffic demand	Traffic composition	Check the vehicle mix and their proportions with the most up-to-date fleet data	
	Critical sites	Identify the locations where traffic significantly differs from its surroundings. Examples of such locations include HOV entries and exits, places of special events, and so forth.	
	Site specific adjustment	Identify the characteristics of critical sites in terms of traffic behavior. The parameters to be adjusted include headway and cost factors. These factors are subject to further calibration.	
Site specific parameters	Control types	Check the control types and make sure they are correctly represented in the coded network: pre-timed, semi-actuated, fully actuated signals, traffic responsive signals, coordinated signal systems (OPAC, RHODES, and etc.); ramp meters.	

---

[7] The initial speeds are different for the vehicles released from a general zone and a zone with a zone connector node. When a vehicle is released from a general zone, the vehicle starts from a speed of zero. But if released from a zone with a residing zone connector node, the vehicle will have a speed at the speed limit, See Quadstone (2003a) pp51.

Control systems	Control parameters	Check the control parameters of the individual control systems. For pre-timed signals, check: - Phasing sequence - Green split - Cycle length For vehicle actuated signals, check: - Minimum and maximum green times - Phase combination and sequencing - Detectors' positioning For traffic responsive controls and ramp metering algorithms, check their specific parameters.	
	Lane usage	Check the lane usage at the signalized intersections and ramps, especially those locations without turning bays.	
Traffic assignment	Link cost function	Define a cost function based on the local conditions. The function could be based on travel time, travel distance, tolls, or combinations of these cost factors.	
	Assignment method	Select an appropriate assignment method: all or nothing, stochastic or dynamic assignment, or their combinations.	
	Drivers' classification	If a combination of assignment methods is used, define the approximate proportion of travelers who follow each assignment rule, based on the knowledge of travelers' familiarity with the network, and their travel habits.	

The Dowling report emphasizes checking the validity of the traffic composition data, since the default values for vehicle mixes in the simulation software or their national/state averages rarely reflect local conditions. It is recommended to obtain an up-to-date traffic composition in the study network from local agencies, including weigh in motion (WIM) stations, or sample measurements made by the analysts themselves. Although vehicle characteristics, such as dimension and acceleration/deceleration performances, seldom deviate from the software default values, it is still desirable to have those checked against local fleets as well.

It should be noted that error checking is often performed in the early stage of the project and on a coarsely built network. At this stage, many parameters are not calibrated yet, so some of the problems found in the simulation results at the error-checking stage may not be caused by coding errors. The analyst thus has to make a judgment as to when to move on to the next stage. Nevertheless, error-checking guidelines tabulated in this report provide a good check list and a few techniques to spot and correct the most commonly found coding errors, particularly for a novice user of microsimulation.

4.3 Supply-side Calibration: Obtaining the Right Flow Capacities

In a microsimulation, the capacity of a road section is indirectly determined by the car-following and lane-changing rules built into the driving behavior model. Except the developer’s initial verification, very rarely a microsimulation user would calibrate the driving behavior models against micro-scale traffic measurements, that is, calibrating the driver behavior model against vehicles’ detailed movement trajectories. At the calibration stage, one assumes that these models have been validated by the developers and the objective of calibration is to adjust the model parameters so as to make the model reflect local traffic conditions. An important measure of how well the driver behavior model is calibrated is its ability to reproduce observed flow capacities at various road locations. In this report, the calibration of driving behavior parameters to obtain the right capacities for typical freeway sections, signalized intersection approaches, and lane drop sections, are elaborated.

- ✧ Capacities can be estimated from the flow-speed or flow-density curve for freeway sections. Field data of speed and volume at typical road sections are easily observed via loop detectors, and a variety of other measurement devices. Microsimulation software such as PARAMICS, AIMSUN and VISSIM also has modules to gather the simulated flow and speed data via simulated detectors. The concave curve of flow-speed is plotted for both field measurements and microsimulation outputs. The car-following and lane-changing parameters in the simulation model are then adjusted until the speed-volume curves obtained from both the simulation and field observations match each other fairly well, with their peak volumes at the same level.

- ✧ Queue discharge rate and control delay at a signalized link are two major MOEs used to calibrate the approach capacity of an arterial link. Since the capacity of an approach depends also on the green time it receives, one usually calibrates against the saturation flow rate of an approach. A simple sub-network concerning the studied intersection can be set up to simulate the observed conditions of lane usage, control settings and arrival flows. Driving behavior model parameters are adjusted to replicate the observed queue discharge rate at the link of interest, until a satisfactory match is obtained between the simulated and observed saturation flow rates. One can follow the same procedure if one calibrates the driving parameters against control delays (Tian et al 2002).

- Work zone lane closures usually cause significant reductions in roadway capacity (Maze 2000). Traffic capacity in a work zone area is observed to range from 1400 veh/hr/lane to 1600 veh/hr/lane in some studies (Ma 2003). The link headway factor for the narrower sections at a work zone thus has to be adjusted to reflect those commonly accepted or observed capacity values. Other locations with lower capacities, such sections with sharp curves or steep grades, should also be calibrated against the observed field measurements in a similar manner, although sometimes with additional help from a speed contour map (Table 5).

4.4 Demand-side Calibration: Reproducing Observed Traffic Conditions

Demand-side calibration is probably the most daunting part in the whole calibration process. Parameters to be calibrated in the demand side include trip input, link/route cost functions, network hierarchy, driver familiarity, traffic assignment methods and perturbation factors over available routes.

4.4.1 Trip Input

In a microsimulation, the trip input usually comes in one of the following two forms:

- An O-D matrix that defines the trip rate between every pair of traffic analysis zones, and a flow profile that defines the variation of the trip rates over the entire simulation period;
- Link traffic counts coupled with turning proportions at intersections.

The first form of trip input can easily accommodate time-dependent O-D demands with trip rates vary from one time slice to another. Commonly used time slices within which demand is treated as constant are 15 minutes, 30 minutes or 1 hour. Since this form of trip input is the most commonly used input form for microsimulation, we will use this form in our discussions of demand calibration.

Network topology and size are deciding factors for the amount of effort needed to obtain a satisfactory O-D trip table. For networks with simple topologies and small size such as a short stretch of freeway with on/off ramps, O-D trip tables can be obtained relatively easily from macroscopic models such as FREQ. The process is as follows. One feeds successive 15-min link counts into FREQ for the entire study period. FREQ will then transform the counts into O-D trip tables for successive time slices. O-D trip tables for other types of simple networks, e.g., those with one single intersection or a linear arterial with no route choice, can also be obtained in this way with the help of appropriate software tools.

When a network is large and most O-D pairs in it have numerous connection routes, obtaining a reliable O-D trip table for such a network would be extremely hard. While O-D trip tables obtained from household surveys or planning models can serve as seed O-D tables for microsimulation applications, they are usually inadequate and needs further adjustments. These "historical" O-D trip tables, however, can be used together with up-to-date traffic measurements from the network to derive an improved estimate of the O-D trip demands. Although there are various estimation methods for dynamic O-D demands proposed by researchers (e.g., Sherali and Park, 2001), a mature and proven method suitable for large networks has yet to emerge.

A common practice is to first obtain an O-D trip table from a planning model. For reasons stated below, this O-D table cannot be used directly by a microsimulation:

- Zones used in a planning model usually cover too big an area for microsimulation purposes and thus the limited capacities of outgoing links cannot accommodate the traffic generated from the these zones if the same zoning structure were used in a microsimulation;

- Planning models can produce link volumes much higher than the corresponding link capacities, which cannot be simulated by microsimulation models (section 2.4).

However, the O-D trip table obtained from a planning model can be refined externally. Quadstone's Paramics O-D Estimator is one of the most recent technological developments specifically designed for estimating trip demand in a micro simulation. It applies the same simulation engine as the simulator itself and allow users to start with a seed O-D trip table, such as the one obtained from a planning model, and change the O-D trip rates iteratively until a certain convergence criterion is met. Initial applications of the O-D Estimator (Gardes et al 2003b; Ma et al 2003) to refine a seed O-D obtained from planning models showed good results. Experiences with the O-D Estimator led to the following application tips (Quadstone 2004), including:

- Analyze the input data (seed O-D, link traffic counts, turning volume counts) and weigh them properly according to their accuracy (confidence level);

- Select appropriate estimation parameter settings (minimum/maximum trip rate, calculation period for one iteration, flow intensity to assign proper network traffic load, break points to stop);

- Decide when to stop the estimation process based on both resource constraints and estimation performance (i.e., one can terminate the process if the study objective is fulfilled, a good fit is achieved in critical areas and critical road sections, or too much time has been consumed by the estimation process);

- Intervene when justified. For example, check the output at key locations; check if the link volume match the total of the turning movements incoming from upstream intersection into this link; check the flows across the cordon line, or the totals of flows in and out of a particular zone or a group of zones (called sector analysis); check the overall shape of the estimated matrix to see if parameter values need further refinement).

- Avoid drastic network changes in the later stage of modeling process. For example, the estimation process will have to be restarted if the number of zones, zone sizes, zoning structures change. If these changes must be made, they must be done at the early stages of the estimation process or more desirably, at the project planning and scoping stage.

In the documented O-D estimation practices, however, two key issues have not been clearly addressed:

- When there are multiple time slices in the simulation period, O-D trip rates for each time slice are usually estimated independent of those in the other time slices, hence ignoring the interaction of traffic between different time slices. If all trips started in a time slice also ended in the same time slice, this would not create a problem. But if the time slice is short, such as 5 or 15 minutes, many trips begin in a time slice are not likely to end in the same time slice, and this would lead to poor fits between simulated and observed data when the demand estimated this way is loaded into the network.

- A good seed O-D trip table can considerably speed up the estimation process and improve its accuracy. Efficient methods need to be developed to obtain such seed O-D trip tables for microsimulation.

These problems will be addressed in our subsequent work and documented in our later reports.

4.4.2 Network Hierarchy

A general road network usually presents itself in a hierarchical structure: freeways, major arterials, secondary arterials and connectors. Local drivers usually have good knowledge of the levels of service provided by different types of facilities and choose the routes with higher speed limits, or better signal synchronization and less interference from side streets. In modeling drivers' behavior, failure to notice such natural driving preferences over the hierarchical network can result in many more repeated adjustments of myopic settings through trial and error. In calibrating the route preference in a large network, these adjustments proved extremely tricky (Gardes et al 2003b). Thus a clear definition of network hierarchy is strongly recommended. For example, the following hierarchy is used in the calibration of a PARAMICS network along a freeway corridor in northern California (Gardes et al 2003b):

Major Primary	Link Cost Factor 0.8
Major Secondary	Link Cost Factor 1.0
Minor Primary	Link Cost Factor 0.8
Minor Secondary	Link Cost Factor 1.0

It is believed that a clear definition of network hierarchy with appropriately assigned cost factors stabilizes the route choice behavior in a large network.

4.4.3 Departure time and Route Choice: Cost Function, Demand Profile, Drivers' Familiarity, Perturbation over Route Alternatives

Parameters concerning cost function, demand profile, drivers' familiarity, perturbation over route alternatives are related to the drivers' departure time and route choice propensities. They are among the most difficult set of parameters to be calibrated because these parameters affect traffic flow in myriad and complex ways.

The route cost function defines the route choice propensity globally, through a suitable combination of travel time, distance and toll. The demand profile specifies how the total demand or the demand for certain O-D pairs is released onto the simulation network over the time slices. Drivers' familiarity affects their choices over routes. Familiar drivers may choose a minor route while the unfamiliar ones are assumed to always choose a major route between an O-D pair. In Paramics, generally only familiar drivers update their cost tables by considering turning penalties under dynamic feedback assignment, unless designated otherwise. In several PARAMICS applications in California, the proportion of 5% or 15% of familiar drivers have been used, without sufficient justification. The perturbation factor pertains to the stochastic assignment method, allowing the route cost to be randomly manipulated within the predefined range. In the calibration process, these parameters are often adjusted in a trial-and-error manner.

4.4.4 Traffic Assignment Methods

Three traffic assignment methods are provided in Paramics, namely all or nothing, stochastic and dynamic feedback assignment (Quadstone 2003a). When using Paramics, one needs to specify both the assignment method and its corresponding parameters based on his own knowledge of the network and its travelers. These would include, for instance, the perturbation factor for stochastic assignment and feedback time interval as well as smooth/decay factors for dynamic assignment. The predominant approach used to calibrate these parameters found in the literature is trial-and-error, which is often tedious and time-consuming.

Two types of mechanisms exist in current prevalent microsimulation models. One type adjusts the trip cost table and resulting path flows automatically to achieve some stability, e.g., static or dynamic user equilibrium flow pattern. Examples are VISSIM's dynamic assignment module (PTV 2003), AIMSUM (TSS 2000) and MITSIM (Ben-Akiva et al 2004). The other type allows the analyst to decide the factors that influence the path flows, and Paramics belongs to this latter type.

Both types have their advantages and disadvantages. The first type of models could mask some important network features during the automatic updating process, while these features could possibly lead to a distorted model. This problem is particularly critical for microsimulation applications, because there are a great number of parameter settings that could twist the drivers' route choice behavior in the model if improperly coded. On the other hand, models such as Paramics need more intervention from the analyst and consequently require more calibration efforts.

4.5 Visual Check

Researchers also recognized the importance of visually checking the realism of simulation runs. Key congestion spots present in the simulation but not observed in the field usually warrant further investigation. The Dowling report has suggested four types of possible errors to be noted:

- Error in the analyst's expectations. Further field check is needed before asserting that the animation does not show realistic behavior, because some important features in the field may not have been identified when collecting the data.

- Error in coding. Some spotted simulation problems may be caused by coding errors. One should always remember that a microsimulation model can only be as good as the input data, so check one's coding carefully.

- Error in animation. Unrealistic vehicle movement may be caused by software and display bug, and should be checked with the software developers.

- Error in vehicle behavioral models. Absurd simulation results may be due to some improper assumptions made in the models themselves. This error should also be checked with the software developers.

Visual check alone cannot serve as the final criterion for accepting a calibrated model, but it can help spot modeling problems at different stages of calibration.

4.6 Calibration Targets and Statistics

Calibration of the baseline model can be a long drawn process. However, when improvements become marginal and model outputs become acceptable in terms of meeting study needs, one may consider stopping the baseline calibration.

Virtually, all observable performance indices listed in Table 5 can be used to develop calibration targets, provided that reliable field measurements of these index variables exist. However, field measurements of some traffic variables (for example, the stops and delay at signalized intersections) may be hard to obtain. Some commonly used calibration targets and statistics found in literature are summarized in Table 7.

Table 7 Microsimulation Application Model Calibration Criteria

Measures and Stopping Criteria	Acceptable Targets
Hourly Flows, Model vs. Observed	
Individual Link Flows	
Within 15%, for 700 vph <Flow<2700 vph	>85% of cases
Within 100 vph, for Flow < 700 vph	>85% of cases
Within 400 vph, for Flow > 2700 vph	>85% of cases
Total Link Flows	
Within 5%	All Accepted Links
GEH Statistic – Individual Link Flows	
GEH < 5	85% of cases
GEH Statistic – Total Link Flows	
GEH < 4	All Accepted Links
Travel Times, Model vs. Observed	
Journey Times	
Within 15% (or within one minute, if higher)	85% of cases
Travel Speed, Model vs. Observed	
Average Travel Speeds: Routes	
Within 5% (or one mile per hour, if higher)	85% of cases
Individual Link Speeds	
Visually acceptable speed-flow relationship	To the analyst's satisfaction
Speed Contour: Network	
Bottleneck location	All
Bottleneck congestion duration	All
Within ± 2 Analysis periods (often 15 min)	
Bottleneck congestion spillback	All
Within ±1 Analysis sections (often freeway sections between ramps)	

Signal Control System performance, Multiple Model Runs vs. Observed	
Total Time in Queue Within 90% confidence interval	All approaches
Delay Time per Vehicle Within 90% confidence interval	All
Maximum Queue Length Within 90% confidence interval	85% of cases
Percentage of Vehicles Stopped Within 90% confidence interval	All

Source: adapted from FREEWAY SYSTEM OPERATIONAL ASSESSMENT, Technical Report I-33, Paramics Calibration & Validation Guidelines, DRAFT, Wisconsin Department of Transportation, District 2, June 2002, cited by(Dowling 2002) .

Besides these MOEs, other MOEs for the calibration process are also found in the literature. For example, the difference between the observed and modeled speed profile has been used to calibrate the driving behavior parameters (Lee et al 2001, Cheu 1998; Fellendorf 2001; Kim 2004).

4.7 Parameter Calibration Methods

A conceptual model calibration procedure is illustrated in Figure 1. This calibration procedure can be regarded as a combinatorial optimization problem: finding the combination of concerned model parameters such that the selected outputs from the simulation can best (optimally) match the corresponding field measurements. In the literature, three major calibration methods have been documented, namely trial-and-error, genetic algorithms and simulated annealing. Herein we will review the applications of these three methods.

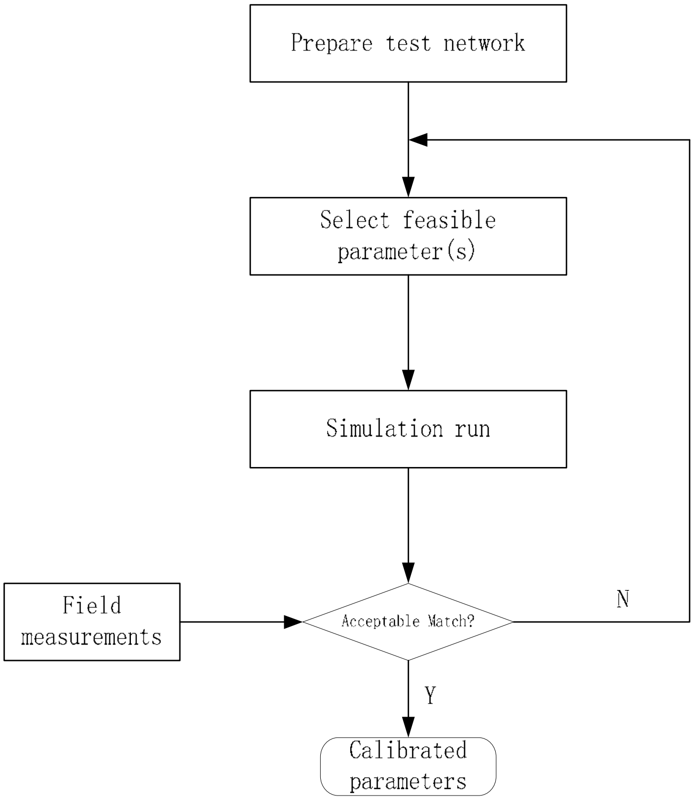


Figure 1 A General Framework of Model Parameter Calibration

4.7.1 Trial-and-Error Heuristics

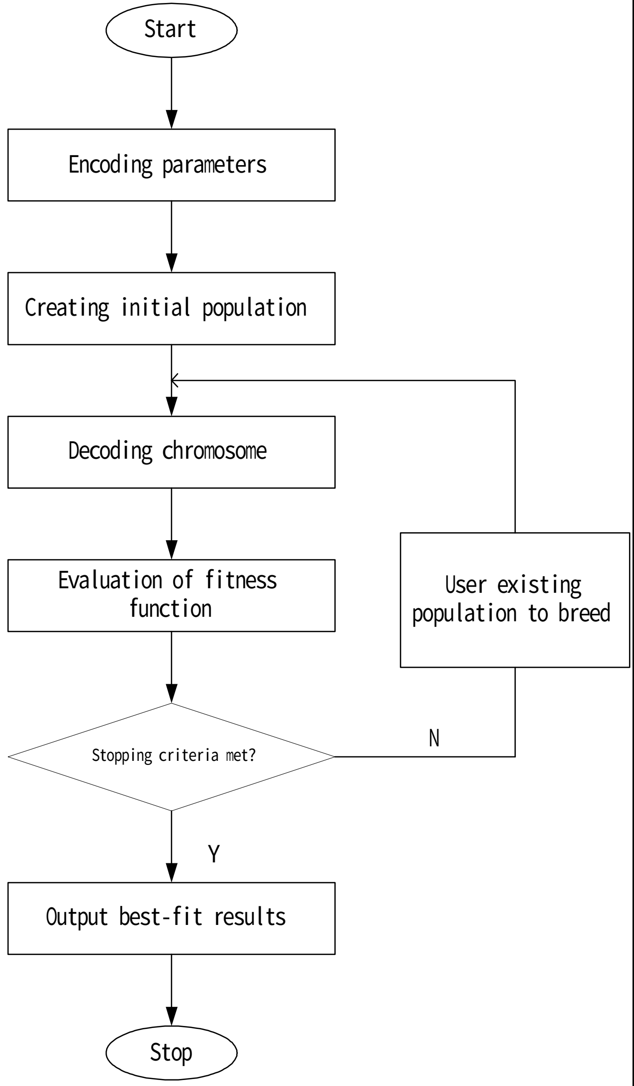
Conventional optimization algorithms make use of the gradient information to aid their search of the optimal solution(s), often in an iterative manner. The gradient of a function, being the first order derivative with respect to its arguments, provides the direction of the steepest ascent in functional values. For well behaved functions, various methods exist to determine the search direction and moving step size towards the global or local optima (e.g., Luenberger 1973). However, because of its complexity and stochastic nature, one usually cannot compute the gradient for the optimization problem formulated for model calibration. Thus, many calibration efforts (Gardes et al 2001; Ma et al 2003; Ben-Akiva et al 2004; Gomez et al 2004) rely on trial-and-error to find a suitable set of model parameters.

The trial-and-error method involves an iterative adjustment process. One first enumerates the feasible solutions by dividing the feasible regions into equal intervals and picking a value from each interval, then runs the simulation based on combinations of selected parameter values, often one parameter at a time. One can make the intervals smaller to increase the precision of the calibration. This process continues until both precision requirements and performance target are met. This method is simple and easy to apply, but the choice of the feasible range and incremental steps of each parameter is quite ad hoc, often relies on the analyst's modeling experience and judgment to make a good choice. The calibration process using trial-and-error is usually carried out manually, which becomes impractical when the number of parameters to be calibrated becomes large.

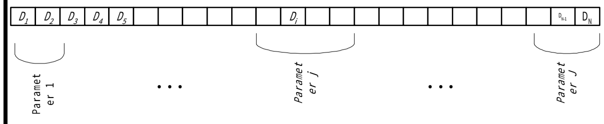
4.7.2 Genetic Algorithm

Genetic algorithm (GA) is a popular method used in microsimulation calibration. Three reasons are the most frequently cited for the choice of GA. First, GA does not require gradient information, which usually is not available from a microsimulation due to its complex model form. Second, GA has been considered robust because it always maintains a set of feasible solutions rather than a single solution as in conventional optimization algorithms in its intermediate steps. Third, GA avoids exhaustive enumeration in the search of the global optima, thus can save significant amount of computational resources.

Genetic Algorithm is a heuristic optimization method emulating the “survival of the fittest” mechanism in the biological evolution process (Goldberg 1989). A typical GA computation process is illustrated in Figure 2. First, the parameters to be calibrated are selected and coded into the so-called chromosomes (see Figure 2b). A chromosome is a string of numbers resembling the genes of an individual in the population. Usually, the parameter values coded in the chromosome are represented by a series of unsigned decimal or binary digits. The GA process starts by randomly generating a number of individuals in the population, each bearing a string of chromosome representing a feasible solution. These individuals form the initial population or the first generation in the evolution. From here GA evaluates each individual of its fitness which, in the case of model calibration, is the objective function measuring the difference between the observed field measurements and simulation outputs under the corresponding parameter values. In this stage, each chromosome is first decoded into the actual parameter values. Then, the microsimulation model is run with these values and the MOEs, such as traffic counts and/or travel times, obtained from the simulation are used to evaluate the fitness of this individual.



(a) GA flow chart



(b) Structure of chromosome

Figure 2 Genetic Algorithm (GA) Computation Process

To emulate the evolution process, the individuals with better fitness in the existing population will “mate” to produce offspring. Usually a rank selection scheme is applied, in which those individuals with higher fitness values have higher chances to produce offspring. In GA, the chromosomes of parents undergo crossover and mutation operations to exchange or modify their gene codes. The crossover operation exchanges the parents' gene codes at randomly selected locations of the chromosome string, while the mutation operation modifies the randomly selected gene codes in small numerical magnitudes. In addition, an elitism strategy is often used in the reproduction process to keep the chromosome with the highest fitness value for comparison with those computed from the next generation. If all the individuals in the next generation fail to outperform the elite individual, the later will be reinserted into the population of the subsequent generation. The reproduction cycle repeats itself until the stopping criteria are met.

GA has been applied to calibrate the driving behavior model parameters in microsimulations. Kim and Rilett (2004) use the GA method to calibrate both CORSIM and TRANSIMS models for two corridor systems in Texas. CORSIM has 11 car following sensitivity parameters, two acceleration/deceleration parameters and six lane changing parameters. The authors used the binary coding method to code the 19-parameter set into a 121-bit binary string as an individual's chromosome, resulted in a search space of 2^{121} permutations. The large search space illustrates the importance of using an efficient optimization method. In the TRANSIMS study, there were only three parameters to be calibrated, but due to the binary representation of the range of parameter values, the search space is still as large as 2^{30}. The MOE used was the mean absolute error ratio (MAER) between the simulation results and field measurements.

In an earlier research done in Singapore (Cheu et al 1998), GA has been used to calibrate the car-following parameters in FRESIM for a 5.8 km long section of expressway towards the Singapore city. In that section the closely positioned on/off ramps generate frequent weaving maneuvers. The driving behavior model parameters were calibrated for those locations since the simulation results obtained using the default parameter values were unacceptable. Altogether 10 parameters related to the embedded car-following and lane-changing models were encoded in a GA's chromosome with 40 decimal digits. Simulation runs with the calibrated parameter values produced a close match for the verification data set in terms of the 15-minute flow rate at the mainline and on/off ramps, and the 30-second point speed at loop detectors.

Lee et al. (2001) also used GA to calibrate two driving behavior parameters in PARAMICS, i.e., the mean target headway and mean reaction time. Traffic volume and occupancy were the MOEs used to compare the fitness of each chromosome in every generation, and the fitness function was the summation of the average relative errors of the two MOEs over all detection stations and the whole simulated period.

4.7.3 Simulated Annealing

Similar to GA, simulated annealing (SA) employs a stochastic approach in the search of global optima. As a departure from GA's stochastic manipulation of a whole pool of candidate solutions, the SA algorithm avoids being trapped in the neighborhood of a local optima by allowing for temporary increases in the "cost", namely the difference between the simulated outputs and their corresponding field measurements in the case of calibrating a microsimulation model.

The SA algorithm emulates the annealing process in condensed matter physics

(Kirkpatrick 1983). Annealing is known as a process of obtaining the steady states of low energy for a solid object in a heat bath. It includes two steps: (1) increase the temperature of the heat bath to the value at which the solid melts; (2) decrease carefully the temperature of the heat bath until the material arranges itself into a ground state. At the ground state the particles of the solid are arranged in a highly structured lattice so that the energy of the system is at the minimum and thus the solid object possesses very stable properties (Aarts and Korst 1989).

In emulating the physical annealing process, SA treats the feasible solutions as the possible energy states in a physical system, and the cost in the optimization problem as the energy of a physical system.

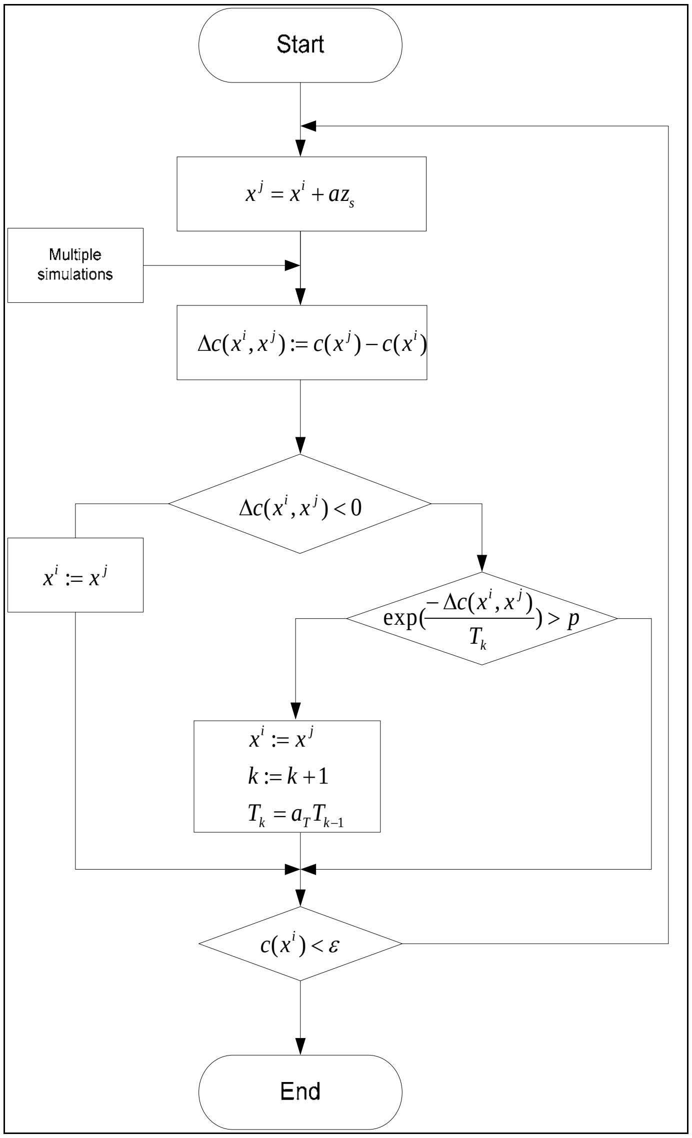


Figure 3 The Computation Process of the Simulated Annealing (SA) Algorithm

A typical flow chart for applying SA is shown in Figure 3. The parameters to be calibrated are denoted by vector x_i, and $c(x_i)$ is the associated cost function, i.e., the index measuring the gap between the simulation outputs and the observations, and *i* is the iterative index. The current solution is randomly manipulated to obtain a new feasible solution x_j. And the new solution will be accepted with a probability of p_k^j

$$p_k^j = \begin{cases} 1 & if \quad c(x^j) \le c(x^i) \\ \exp(\frac{c(x^j) - c(x^i)}{T_k}) & otherwise \end{cases} \qquad (1)$$

T_k is a monotonically decreasing scalar sequence, emulating the cooling of temperature in the physical annealing process. As the sequence number *k* increases, the probability of accepting an inferior solution (compared with the previous solution) will decrease.

Since SA accepts an inferior solution with a non-zero probability in each iteration, it has the ability of getting out of the neighborhood of a local optimum. The SA process is shown to asymptotically converge to the global optima (Aarts and Korst 1989).

Not many calibration studies use the SA method. In a pilot study, Fellendorf (2001) used SA to calibrate the traffic queuing positions against the field measurements for a roundabout area using VISSIM, and reported good calibration results.

CHAPTER 5 A WORKING SUMMARY

Calibrating a microsimulation to reflect local driving conditions is a crucial first step in its application to various transportation problems. But the calibration process itself is often a challenging and time consuming task. Both the literature and our own experiences revealed that one can code a network and carry out simulation runs under various study scenarios relatively quickly once the baseline model is calibrated, but calibrating the baseline model often takes a big chunk of project time. Yet, the calibration procedures developed to date are quite ad hoc, often rely on manual trial-and-error or make limited use of optimization techniques. Such calibration procedures are usually tedious to carry out, and do not guarantee that the desired calibration objective will be met. In this review, we documented existing calibration practices and their limitations, and identified three general calibration issues to be addressed in the subsequent stages of this research project. These three issues to be addressed in our research are briefly summarized as follows.

The Need of a Systematic Calibration Procedure. A clearly defined calibration process is needed to avoid calibration spurious results and unnecessary repetitions. In the current process, the roles of parameters in a simulation are not clearly distinguished such that they can be calibrated several times. In some instances, calibration and validation have been mixed together. Some calibration procedures calibrate parameters of different categories together, which makes it difficult to assess the calibration outcome because these parameters affect traffic flow in different ways and their errors may compensate each other, that is, the wrong combination of parameters values can also provide a good model fit. To avoid these pitfalls, we need to group the parameters by their functions and influence scope, identify appropriate performance measures to gauge their effects on traffic flow, and decouple the calibration process as much as possible so as to reduce calibration complexity and improve calibration accuracy.

Automate the Calibration Process. The calibration of a group or all model parameters in a microsimulation requires numerous simulation runs and manually performing these runs in a trial-and-error calibration procedure is a tedious and time consuming task. The calibration process needs to be automated to the greatest extent possible. Some efforts were already made to automate some calibration steps, such as employing GA or SA algorithm to calibrated driving behavior parameters. But an overall streamlined calibration procedure with clear usage guidelines and a well designed user-interface to carry out the complete calibration process is still needed.

Overcome the Difficulties in Calibrating Route Choice and Traffic Demand. The calibration of route choice and trip demand is perhaps the most difficult components of the calibration process. This is especially true for medium or large size networks, since traffic demand and route choice couples together to affect traffic conditions on a network together with other factors such as bottleneck capacity, and traffic control. What adds to the challenge is the lack of reliable seed O-D patterns. A good seed O-D matrix often helps the estimation of dynamic O-D trips tables and ways to obtain them should be further explored. We shall also look into combining macroscopic dynamic O-D estimation tools with the built-in O-D estimation tools in a microsimulation to obtain reliable baseline O-D trip tables for microsimulation studies.

REFERENCES

Aarts, E., J. Korst. 1989. Simulated Annealing and Boltzmann Machines, A Stochastic Approach to Combinatorial Optimization and Neural Computing. Wiley-Interscience.

Alexiadis, V., K. Jeannotte K., A. Changdra. 2004. Traffic Analysis Toolbox Volume I: Traffic Analysis Tools Primer. Report FHWA-HRT-04-038, Federal Highway Administration.

Axhausen, K. 2004. Driving Simulators and Behavioral Travel Research. Transport Studies Unit, University of Oxford, U.K.

Bacon, V.W., J. R. Windover and A.D. May 1999. Investigating the intelligent transportation sytems strategies on the Santa Monica freeway corridor, PATH Research Report UCB-ITS-PRR-95-38, Institute of Transportation Studies, University of California, Berkeley.

Baher, A. et al. 1999. Simulation of ITS on the Irvine FOT Area using PARAMICS 1.5 Scalable Microscopic Traffic Simulator: Phase I:Model Calibration and Validation. PATH Research Report UCI-ITS-TS-WP-99-1, Institute of Transportation Studies, University of California, Irvine.

Bai, S. 2003. Application of dynamic traffic simulation models in mobile source emission estimates. PhD Dissertation Proposal, Department of Civil and Environmental Engineering, University of California, Davis.

Bai, S., Y. Nie, and D. Niemeier. 2005 The impact of speed post-processing methods on regional mobile emissions estimation. Proceedings of the 84th annual meeting of the Transportation Research Board, CD-ROM.

Ben-Akiva, M. et al. 2002. Calibration and evaluation of MITSIMLab in Stockholm. Proceedings of the 81st Annual Meeting of the Transportation Research Board, CD-ROM.

Ben-Akiva, M. et al. 2004. Calibration of microscopic traffic simulation models with aggregate data. Proceedings of the 83rd Annual Meeting of the Transportation Research Board, CD-ROM.

Bridges, M. et al. 2003. TRANSIMS-DOT. Proceedings of the 82nd Annual Meeting of the Transportation Research Board, CD-ROM.

Cameron, G. and G. Duncan 1996. PARAMICS:parallel microscopic simulation of road traffic. Journal of Supercomputing, 10(1), 25-53.

Cheu, R. et al. 1998. Calibration of FRESIM for Singapore expressway using genetic algorithm. Journal of Transportation Engineering, 124(6), 526-535.

Church, R. L., V. Noronha 2003. Translating GIS street network files for use with Paramics. Final Report, CALTRANS/CA/TO-03/02, California Department of Transportation (Caltrans), Sacramento, CA.

Dia, H. 1999. Modeling the impacts of advanced traveller information systems using intelligent agents. Proceedings of the 20th Conference of Australian Institutes of Transport Research, Sydney, Australia.

Dowling, R. et al. 2002. Guidelines for Applying Traffic Simulation Modeling Software. Dowling Associates Inc., Oakland, CA.

Dowling, R., A. Skarbardonis, V. Alexiadis 2004. Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Software. Report FHWA-HRT-04-040, Federal Highway Administration.

Fellendorf, M. and P. Vortisch. 2001. Validation of the microscopic traffic flow model VISSIM in different real-world situations. Proceedings of the 80th Annual Meeting of the Transportation Research Board, CD-ROM.

Gardes, Y. and A. D. May. 1993a. Simulation of IVHS on the Santa Monica Freeway Corridor using the Integration model. Phase 1: Initial Investigations. PATH Working Paper UCB-ITS-PEP-93-3, Institute of Transportation Studies, University of California, Berkeley.

Gardes, Y. and A. D. May. 1993b. Simulation of IVHS on the Santa Monica Freeway Corridor using the Integration model. Phase 2: Preliminary ATIS and ATMS Experiments. PATH Working Paper UCB-ITS-PEP-93-6, Institute of Transportation Studies, University of California, Berkeley.

Gardes, Y. et al. 2001. Freeway calibration and application of the PARAMICS model. Proceedings of the 80th Annual Meetings of the Transportation Research Board, CD-ROM.
Gardes, Y. et al. 2002. Bay Area Simulation and Ramp Metering Study. PATH Research Report UCB-ITS-PRR-02-06, Institute of Transportation Studies, University of California, Berkeley.

Gardes, Y. et al. 2003a. Bay Area Ramp Metering Study-Year 2 Report. PATH Research Report UCB-ITS-PRR-03-09, Institute of Transportation Studies, University of California, Berkeley.

Gardes, Y., et al. 2003b. Advanced Simulation Tools for Freeway Corridor Management. PATH Working Paper UCB-ITS-PWP-03-15, Institute of Transportation Studies, University of California, Berkeley.

Gardes, Y. and L. Bloomberg. 2003. Devore/I-15 Traffic Simulation Analysis Report-Level 1 Network Investigations. Institute of Transportation Studies, University of California, Berkeley.

Gardes, Y. J. Ma, C. Kim, H.M. Zhang 2004. Implementation of vehicle radiation detection system for New Jersey Turnpike. Proceedings of Intelligent Transportation Systems Safety and Security Conference, Miami, FL.

Goldberg, D. E. 1989. Genetic Algorithms in Search Optimization and Machine learning. Addison-Wesley.

Gomes, G. et al. 2004. A Microsimulation model of a congested freeway using VISSIM. Proceedings of the 83rd Annual Meeting of the Transportation Research Board, CD-ROM.

Hubschneider, H. 1983. Mikroskopisches Simulationssystem fuer Individualverkehr und Oeffentlichen Personennahverkehr. Schriftenreihe des Instituts fuer Verkehrswesen. Karlsruhe, Germany, Karlsruhe Technical University.

ISAC Ltd. 1999. Experiences with PARAMICS. Presented at ISAC in winter 98-99. http://www.paramics-online.com/ tech support /reports.htm, accessed Jul. 2003

Hellinga, B. 2001. Analytical emission models for signalized intersections, Department of Civil Engineering, University of Waterloo.

Jayakrishnan, R. et al. 1993. A Simulation-Based Framework for the Analysis of Traffic Networks Operating with Real-Time Information. PATH Working Paper UCI-ITS-TS-WP-93-8, Institute of Transportation Studies, University of California, Irvine.

Jayakrishnan, et al. 1994. An evaluation tool for traffic information and management systems in urban networks. Transportation Research, 2C(3), 129-147.

Jayakrishnan, R. et al. 1996. Enhancements to a Simulation Framework for Analyzing Urban Traffic Networks with ATIS/ATMS. PATH Working Paper UCI-ITS-TS-WP-96-1, Institute of Transportation Studies, University of California, Irvine.

Jones, E. R. et al. 1985. Human factor Aspects of Simulation. National Academy Press.

Jeannotte, K. et al. 2004. Traffic Analysis Toolbox Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools. Report FHWA-HRT-04-038, Federal Highway Administration.

Kim, K. and L. R. Rilett. 2004. A genetic algorithm based approach to traffic micro-simulation calibration using ITS data. Proceedings of the 83rd Annual Meeting of the Transportation Research Board, CD-ROM.

Kirkpatrick, S. et al. 1983. Optimization by simulated annealing. Science, 220, 671-683.

Koutsopoulos, H. N. et al. 2003. Travel simulators for data collection on driver behavior in the presence of information. Transportation Research, 11C(2), 143-159.

Kurumi. (2004). Single point urban interchange. http://www.kurumi.com/roads/interchanges/spui.html, accessed Jul. 2004

Lee, E-B. et al. 2000. Construction productivity and constraints for concrete pavement rehabilitation in urban corridors. Transportation Research Record 1712, 13-22.

Lee, E.B., J.T. Harvey, C.W. Ibbs, and J. St. Martin. 2002 Constructability Analysis for Asphalt Concrete Pavement Rehabilitation in Urban Corridors, Transportation Research Record 1813, pp. 285-294.

Lee, E-B and C. Kim. 2004. Validation of a microscopic traffic simulation study on urban freeway reconstruction project with high-traffic volume. Proceedings of the 84th Annual Meeting of the Transportation Research Board, CD-ROM.

Lee, D-H. et al. 2001. Parameter calibration for paramics using genetic algorithm. Proceedings of the 80rd Annual Meeting of the Transportation Research Board, CD-ROM.

Leeds. 1999a. SmarTest Project:Review of Micro-Simulation Models. Research Report, Institute for Transport Studies, University of Leeds.

Leeds. 1999b. SmarTest Project:Final Report. Research Report, Institute for Transport Studies, University of Leeds.

Leeds. 1999c. SmarTest Project:Simulation Report. Research Report, Institute for Transport Studies, University of Leeds.

Lemessi, M. 2001. An ALX-based Microsimulation for a two-lane road section. The 33rd Winter Simulation Conference, Arlington, Virginia.

Liu, H. X. et al. 2001. PARAMICS API Development Document for Actuated Signal, Signal Coordination and Ramp Control. Working Paper UCI-ITS-TS-WP-01-03, Institute of Transportation Studies, University of California, Irvine.

Luenberger, D. G. 1973. Introduction to Linear and Nonlinear Programming. Addison-Wesley.

Ma, J. et al. 2003. Work Zone Traffic Impact Analysis:Simulation-Based Case Study of the Interstate 15 Devore Reconstruction Project. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley.

Maze, T. et al. 2000. Capacity of freeway work zone lane closures. Paper presented at the Mid-Continent Transportation Symposium, Ames, Iowa.

Mahmassani, H. et al. 2000. Micro-assignment of travel demand with activity/trip chains. Proceedings of the 9th International Conference on Travel Behavior Research, Queensland, Australia.

Nagel, K. Ed. 2001. Microsimulation. Travel Behavior Research: The Leading Edge.

Nagel, K., C. Barrett, and M. Rickert. 1996 Parallel traffic microsimulation by cellular automata and application for large scale transportation modeling. Technical report, TSA-DO/SA, Los Alamos National Lab, New Mexico, USA

MnDOT. 2003. Advanced CORSIM Training Manual. Technical Report, Department of Transportation, Minnesota.

PTV. 2003. VISSIM 3.70 Users Manual. PTV Ltd, Karlsruhe, Germany.

Quadstone. 2002. Quadstone Paramics to interface with scats adaptive traffic control system. News Release, http://paramics-online, accessed July 2003. Quadstone Ltd, Edinburgh, Scottland.

Quadstone. 2003a. Paramics V4-Modeller Reference Manual. Quadstone Ltd, Edinburgh, Scotland.

Quadstone. 2003b. Paramics V4-OD Estimator Reference Manual. Quadstone Ltd, Edinburgh, Scotland.

Quadstone. 2004. Project Scoping/Project Cycle Training Course. Quadstone Ltd, Edinburgh, Scotland.

Rickert, M. 2001. Dynamic traffic assignment on parallel computers in TRANSIMS. Future Generation Computer Systems 17: 637:648.

Saka, A. A. et al. 2002. An Estimation of Mobile Emissions Reduction from using Electronic Toll Collection in the Baltimore Metropolitan Area: A Case Study of the Fort Machenry Tunnel Toll Plaza. Center for Transportation Studies, Michigan State University.

Shaw, J. W. 2002. Microsimulation, freeway system operational assessment, and project selection in southeastern Wisconsin: expanding the vision. Proceedings of the 81st Annual Meeting of the Tranportation Research Board, CD-ROM.

Sherali, H. D. and T. Park. 2001. Estimation of dynamic origin-destination trip tables for a general network. Transportation Research, 35B(2), 217-235.

Skarbardonis, A., J. Dahlgren, A.D. May 1998. Modeling the Santa Monica freeeway corridor: a feasibility study. PATH Research Report UCB-ITS-PRR-98-37, Institute of Transportation Studies, University of California, Berkeley.

Skarbardonis, A., 2002. Modeling the Santa Monica freeeway corridor: simulation experiments. PATH Research Report UCB-ITS-PRR-2002-1, Institute of Transportation Studies, University of California, Berkeley.

Smith, M.C., Adel W. Sadek. 2006 Challenges in calibrating large-scale microscopic simulation model of diverse urban, suburban, and rural networks: practical guide. Presented at 85th TRB Annual Meeting. 2006. Washington D.C.

Tian, Z. et al. 2002. Variations in capacity and delay estimates from microscopic traffic simulation models. Transportation Research Record 1802, 23-31.

TRB. 2003a. Signalized intersection. In Highway Capacity Manual, Chapter 1, Transportation Research Board.

TRB. 2003b. Simulation and other models. In Highway Capacity Manual, Chapter 31, Transportation Research Board.

TSS. 2000. AIMSUN Users Manual. Transport Simulation Systems, Barcelona, Spain.

Webster, F. V. 1958. Traffic Signal Settings. Road Research Laboratory, Berkshire, UK.

Williams, M. D. 2000. Recent Developments in the TRANSIMS Approach to Emission Estimation. Los Alamos National Laboratory.

Xu, M. et al. 2003. A microsimulation model of travel behavior for use in urban transport corridor analysis. Proceedings of the 10th International Conference on Travel Behavior Research, Lucerne.

Yonnel, G, et al. 2004. Implementation of a vehicle radiation detection system in microsimulation for the New Jersey Turnpike. Presented at the 1st Intelligent Transportation System Safety and Security Conference, Miami, Florida.

Zhang, M. H. et al. 2001. Evaluation of on-ramp control algorithms. Institute of Transportation Studies, UC Berkeley. PATH Research Report, UCB-ITS-PRR-2001-36, Berkely, CA.