

ABSTRACT

WAN, BAOHONG. Traffic Simulation Failure Detection and Analysis. (Under the Direction of Dr. Nagui M. Roupail.)

Microscopic, stochastic traffic simulation may yield simulation failures under multiple replications. The failed runs are not valid in the estimation of traffic performance and should be excluded from the final simulation output analysis. On the other hand, these failure runs provide important clues to perform a simulation flaw diagnosis. An unconventional failure detection and analysis methodology was proposed to comprise three layers: time series inspection, spatial analysis, and causal analysis. The process of time series inspection traces the variation of indicator variables over the time domain for the purpose of detection of simulation failures. The spatial analysis identifies failure occurrence patterns, and the subsequent causal analysis judge contributing factors to simulation failures using a tabular method in combination with other tools.

A widely-used traffic simulator, CORSIM, is used as the test-bed simulator. Three real-world traffic networks were simulated as the case studies for the proposed method. The study results indicated that the proposed failure detection and analysis method is valid and effective to improve traffic simulation from multiple perspectives. Its application in the evaluation of networks testified its utility in multiple aspects. The proposed procedure helped uncover the existing deficiencies in the current simulation models, and, therefore, provide important guidance for the organized model improvement efforts. On the other hand, the procedure was also applied in the analysis of a projected traffic scenario to testify its value in the identification of critical sites on the network from the traffic engineering perspective.

Traffic Simulation Failure Detection and Analysis

Dissertation

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EXECUTIVE SUMMARY

Microscopic, stochastic traffic simulation may yield unrecoverable traffic gridlock (referred to as simulation failures in this research) under multiple replications. The failed runs are not valid in the estimation of traffic performance and should be excluded from the final simulation output analysis. On the other hand, these failure runs provide important clues to perform a simulation flaw diagnosis.

The detection and diagnosis of failure runs is a challenging task, particularly when conducting a large number of replications. In contrast to the traditional methods of failure detection, we propose a times series analysis method to identify the occurrence of simulation failures through traffic flow anomaly detection. The observed phenomenon is a severe malfunction of one or more internal traffic links where outgoing vehicles can no longer discharge.

Once failure replications are identified, they are examined to determine the contributing factors to their occurrence. These factors can be attributed to three components, namely simulator-related, simulation-related, and network-related. If the right category can be determined, users can take appropriate actions to mitigate simulation failures by rectifying the choice of simulator (for simulator-related factors), improving user modeling process (for simulation-related factors), or proposing traffic improvement plans (for network-related factors).

The proposed analysis procedure is thus based on a time series inspection as well as a

spatial analysis. The process of time series inspection traces the variation of indicator variables over the time domain for the purpose of detection of simulation failures, while the spatial analysis identifies failure occurrence patterns and is the basis for the subsequent causal analysis using a tabular method.

A widely-used traffic simulator, CORSIM, is used as the test-bed simulator. Hence, the proposed methodology is actually implemented with CORSIM's particular features. Three real-world traffic networks were simulated as the case studies for the proposed method. The first and the second network were geometrically identical to each other, except that they had different traffic demand features and traffic control plans. The first network testified to the utility of the failure detection method as a pre-calibration procedure, while the second network demonstrated its application for the purpose of network analysis. The third network had considerably different features from the previous two networks in both geometry and traffic demand features. These differences enabled us to test the transferability of the method between different networks.

The study results indicated that the proposed failure detection and analysis method is valid and effective to improve traffic simulation from multiple perspectives. Its application in the evaluation of networks testified its utility in the analysis of simulator features. In the network studies, the proposed procedure helped uncover the existing deficiencies in the current simulation models, and, therefore, provide important guidance for the organized model improvement efforts. Assuming a valid model and a competent simulator, the procedure was applied in the analysis of a projected traffic scenario to

testify its value in the identification of critical sites on the network from a traffic engineering perspective.

In conclusion, the method is valid and effective to help simulation users and model developers alike to identify existing flaws and deficiencies in the simulator, the modeling process, and the study network. The current findings led us to believe that continuing research along this direction is necessary and rewarding.

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Simulation is a key tool widely used in transportation engineering analyses. In order to properly reflect the random nature of traffic in the real world, most microscopic simulations are stochastic in nature. That is, traffic movements are described by statistical distributions as opposed to having fixed values. Correspondingly, repeated runs are necessary to explore the behavior of the system being studied.

Reliable use of traffic simulations is limited by a lack of methods for the assessment of their validity. Decision-makers frequently ask: can simulation fully represent the real world traffic situations? The answer to such a sweeping request is usually “no” (Bayarri, et al., 2002). Nevertheless, simulation can be used for making reliable predictions of traffic performance in particular settings.

When a simulation needs a large number of replicates, the problem becomes more complicated since some replications may result in unrealistic traffic congestion (herein called simulation failures). Obviously these failure runs (runs containing simulation failures) should be excluded from a traditional statistical analysis for the estimation of means and variances of particular traffic performance measures. Further, the occurrence of simulation failures may indicate flaws in the simulator or unaccounted factors in the simulation. The question is then how to sort out the possible explanations for these. Specifically:

- 1) What is the role of simulation failures in a stochastic simulation?

2) How can the consequences of simulation failures be addressed?

Detection and analysis of simulation failures should be a primary task in the successful use of traffic simulation. However, traditional traffic simulations are incapable of executing process surveillance and control in this field. Observation of animation files is commonly used to diagnose simulation. However, with the increased use of a large sample size, animation observation of many replicates may turn to an infeasible task.

This research is intended to providing quantitative solution paths for these questions. Specifically, the phenomena of simulation failures are to be studied to clarify the definition and patterns of them. In contrast to traditional methods (such as animation observation, etc.), a new method is to be devised that utilizes time histories of measured traffic variables to detect traffic anomalies for each simulation replication. This method identifies 1) the occurrence of failure and 2) the time of occurrence. The failure occurrence patterns are then aggregated across replications to derive 3) the critical places of failure occurrence. Occurrence patterns including factors 1), 2) and 3), are to be analyzed in an attempt to relate failures to potential contributing factors.

The significance of this research is threefold. First, successful detection of simulation failures can help simulation users to ascertain the validity of stochastic simulations and, therefore, improve the quality of simulation analysis by excluding bad data. Second, successful analyses of unexpected simulation failures (failures due to user/simulator errors) can provide hints to improve simulation by uncovering existing problems in the model and its use. Finally, successful analyses of expected simulation failures (failures

due to network capacity problems) can provide an alternate approach to the analysis of transportation capacities, which is often one of the major objectives of a simulation study.

1.2 Simulation Failure Study

Definition of Simulation Failures

To clarify the scope of this study, we define simulation failures as follows. In a stochastic traffic simulation, traffic gridlock may appear at one or more locations in the network. If these traffic gridlocks cannot recover in a reasonably short period, incoming traffic to the problem areas will contribute to added congestion and finally form “permanent” gridlocks on the network. Since the occurrence of permanent gridlocks contradicts engineering knowledge of real world traffic behavior, it is seen as unusual and referred to as simulation failures.

Simulation failures can be caused by a variety of factors, such as simulator algorithms, user coding errors, inadequate calibration, network capacity limits, etc. According to these different possibilities, the occurrence of simulation failures can be seen as unexpected and expected. Different contributing factors call for different user actions, as described below.

If the subject network under study is known to have no traffic gridlocks, the occurrence of simulation failures is seen as unexpected. In this case, failure occurrence is mostly due to inadequate, inaccurate, or even incorrect information in the process of simulation model development. Accordingly, the analysis of unexpected simulation failures is

intended to locate the contributing factors of simulation failures. The elimination of these factors can help to improve the validity of the subject simulation model.

On the other hand, if the subject network is known to have capacity problems, the occurrence of simulation failures is seen as expected. In this case, the goal of failure analysis is to find out critical locations on the network that are experiencing capacity problems, based on which specific traffic improvement plans can be proposed to rectify them.

Basic clues about the expectations of failure occurrence are obtained from the status of the subject simulation. Conventionally, the procedure of traffic simulation contains a series of stages such as simulator selection, data preparation, model construction, model calibration, model validation, and model application. If failures occur in an early stage of simulation (e.g., prior to model calibration), users should first assume the occurrence of simulation failures as unexpected, and then utilize the failure analysis results to improve their modeling efforts. In the study of a late stage simulation model, by contrast, users should assume the model as correct, and attribute simulation failures to capacity problems of the study network.

In reality, however, the occurrence of simulation failures is mostly due to a combined effect. That is, part of simulation failures is due to inadequate or incorrect modeling efforts, while others may be due to the network capacity problems. This is a common situation when an insufficiently calibrated model is used to predict a projected traffic scenario. In such cases, the failure occurrence patterns need to be studied to associate

them to different possible causes. This process begins with and is based on the successful detection of simulation failures.

Detection of Simulation Failures

By definition, simulation failures are both error-inducing and irrecoverable. Thus, the occurrence of simulation failures will yield invalid results in a stochastic simulation. Successful detection of simulation failures, therefore, can be used to refine a simulation by identifying these failures and evaluate the impact of them.

Use of conventional methods (such as animation observation) is infeasible if there are many replications to examine. In this research, we propose a new method to utilize the time histories of key link performance in order to quantitatively identify the occurrence of simulation failures. The proposed method and two conventional methods are discussed below.

❖ Animation Observation

Modern simulators are typically equipped with animation tools to allow for a visual examination of vehicle trajectory details. With a close examination, users can utilize these simulation animations to visually identify traffic anomalies and simulation failures in a simulation. However, when a stochastic simulation requires a large sample size, it is tedious and laborious to visually examine the extensive animations for all replications.

Further, in case of a large sample size simulation experiment, batch-mode running is frequently used to accelerate the simulation process by skipping the generation of large animation files. In this case, the method of animation observation consumes simulation

efficiency since analysts need to re-run the simulation in a normal mode using saved random number seeds.

In all, for a large-sample-size simulation, animation observation is not considered a practical approach since simulation animations are not only hard to generate, but also difficult to analyze. On the other hand, simulation animations are typically considered the “reality” of simulation. Observation of them is often seen as the final and most reliable way to solve any complicated problems in simulation. Therefore, when the occurrence of simulation failures is detected using another method, animation observation can serve as a supplementary tool for the purpose of failure analysis

❖ Outlier Detection

The second method, outlier detection, identifies simulation failure runs by finding out their corresponding distributional outliers during the process of simulation output analysis. The success of this method is based upon the assumption of a one-to-one correspondence between failure replications and outlier data in simulation outputs. In other words, the outlier detection method assumes that all failure runs generate outlier simulation outputs, and, conversely, all outlier simulation outputs are generated by these failure runs. As long as this assumption holds true, failure runs in a simulation can be identified using this method.

The techniques of outlier detection are mature in the sense that there are currently some standard statistical methods, such as Dixon’s Test (e.g., Han, 2001), etc., that are readily available for the detection of distributional outliers. Other simplified methods exist, as well. For example, as an effective and easy-to-apply approach, a histogram can be

constructed to allow for the visual identification of outliers on a graphical plot.

Although the method of outlier detection is straightforward and easy to apply, its disadvantages are obvious as well. First of all, the outlier detection method is only capable of identifying failure replications. It needs supplementary methods to locate the site and the onset time of failure occurrence. Thus, the method alone is incapable to execute a high-level causal analysis which is based on such information.

Also, the assumption that the method is based upon is sometimes unrealistic. For example, simulation failures may occur very late in a simulation period; in such cases, they may have only minimal effects on the final simulation outputs (appearing not to be outliers). Conversely, some non-failure simulation runs may generate very poor traffic performance (appearing to be outliers) simply because of the coincidence of some adverse factors. The method of outlier analysis is inflexible in differentiating these extreme situations since it is based on the analysis of final simulation outputs only. Thus, this method would generate inaccurate results if such cases exist in a simulation.

❖ Traffic Anomaly Detection

By definition, the occurrence of simulation failures can be signaled by unrecoverable traffic gridlocks that will result in abnormal traffic behaviors (e.g., severe vehicle blockages, low speeds, fewer trips, high traffic densities, etc.) in the problem areas. Thus, the occurrence of simulation failures can be indicated by the onset of such traffic anomalies. In light of this, we propose a method of traffic anomaly analysis to detect simulation failures by identifying abnormal traffic performance at specific times and locations.

In essence, the method of traffic anomaly analysis traces the time history of selected indicator variables, and relates changes in an indicator variable to the occurrence of simulation failures. With the setting of appropriate indicator variables, once a detection function is satisfied, simulation failures will be reported.

Standard methods for detecting a change in a time series (e.g. Law & Kelton, 2000) may be useful in detecting traffic anomalies, but the role of such methods here is unclear. This is largely because of the complications of traffic networks where the space-time interactions and dependencies need to be considered among the multiplicity of performance measures at the link level. In this research, a series of thresholds are derived directly from the definition of simulation failures, and from the intention to avoid pitfalls of false alarms. These thresholds are then used to formulate a mathematical function that is able to identify the occurrence times and locations of simulation failures in a quantitative way.

One concern of the method of traffic anomaly analysis is that it may require substantial computation. This is due to the complexities in data acquisition (the derivation of traffic performance data at a specific resolution of time and space) and anomaly analysis (automatic analysis of variations of an indicator variable over time). As long as the application procedure is standardized, a computer program can be coded as an application program interface (API) for traffic simulation to save user calculation efforts.

1.3 Analysis of Simulation Failures

Since the occurrence of failures in a simulation model often implies the presence of unaccounted factors in it, once simulation failures are detected, the analysis of them can

provide an important approach to the flaw diagnosis of the simulation. Specifically, an effective simulation failure analysis can help users to improve simulation development and/or to enhance network analysis by identifying the different contributing factors of simulation failures. The key to perform such an analysis is to sort out the possible causes of simulation failures.

Causes of Simulation Failures

There are a variety of contributing factors that can lead to simulation failures. In general, these factors are classified into three categories, simulator-related, simulation-related, and network-related. The details of these categories are discussed below.

❖ Simulator-Related Factors

Simulator-related factors refer to the errors and limitations of the traffic model algorithms in a simulator. These factors are often pre-decided and unchangeable once users have chosen a simulator. Thus, the choice of simulators often predetermines the role of simulator-related factors in the process of failure analysis for a traffic simulation.

Choosing an appropriate simulator is not as simple as it appears. Currently there are many simulators available in the field of traffic simulation. These simulators are based on different traffic flow theories and, therefore, can result in different results when modeling the same traffic phenomena. It is the user's responsibility to understand the features of each simulator and apply them wisely. In the process of choosing a simulator, major considerations include the modeling capabilities of a simulator, current traffic data availability, the cost of simulation, individual experience, etc. In fact, it is rare for users

to find an ideal simulator that can satisfy all their requirements. Consequently, users often need to seek a balance between different considerations.

Once a simulator is chosen, users should be aware not only of the strengths of the simulator, but also of its weaknesses. For example, one known constraint of a widely-used simulator, CORSIM (CORridor SIMulation Model), is its inability to simulate roundabouts. On the other hand, CORSIM is favorable to many simulation users since it allows for inputting traffic demand in the form of traffic counts, which is relatively inexpensive and easy to collect in the field. If users decide to use CORSIM because of the data availability in the field, they may have to approximate the geometry of a roundabout and its operation by modeling several consecutively curved links and intersections.

User knowledge about a simulator is mainly acquired through user experience and a review of the literature. Once users decide to use a simulator, they may have already been familiar with its strengths and weaknesses. In case that any unusual phenomenon occurs in a simulation run, users can easily judge the likelihood of simulator-related contributing factors based on their knowledge in this field.

❖ Simulation-related Factors

Simulation-related factors refer to incorrect or inadequate modeling during the process of simulation model development. Some common factors in this category include data collection errors, incorrect coding, inadequate calibration, etc. Correspondingly, the analysis of simulation failures can serve as an important tool to locate these contributing factors, and their removal can enhance the validity of any subsequent process (e.g.,

output analysis) in a simulation.

It is noted that lack of knowledge about traffic behavior is often the most common reason to lead to a poorly calibrated simulation. Simulation failures may occur as the result of it. Also, traffic simulation is such a complicated process that users often need to define multiple driver and vehicle parameters at the same time. Most simulators fail to provide guidance for the calibration of traffic parameters. When multiple parameters have a common effect on the same traffic behavior model, the problem of choosing the right parameters alone may become over complicated for normal users.

The analysis of simulation-related factors can be assisted by observing different patterns of failure occurrence. For example, if simulation failures are caused by the incorrect coding of a local element (e.g., number of lanes on a link), they are most likely to focus on the miscoded link. By contrast, if simulation failures occur as the result of insufficient calibration of global parameters (e.g., left-turn gap acceptance parameters), they are expected to occur at intersections throughout the network if their performance is affected by these inappropriate parameters.

❖ Network-Related Factors

Network-related factors refer to capacity constraints on the study network, which may be caused either by inadequate network geometry, or by a high level of projected traffic demand. These factors are commonly seen in simulation practice, particularly when simulation is used to predict traffic performance in a projected traffic environment. The analysis of factors in this area, thus, can help users gain awareness of the capacities of the study network, which forms the basis for the development of traffic improvement plans

(TIP).

In the study of a traffic network, it is an important task for simulation to identify a marginal demand level which denotes the capacity of the network. Under such a demand level, simulation failures are very likely to occur at the bottleneck areas on the network. Based upon such a failure analysis, users can then propose specific traffic improvement plans to improve these discovered bottleneck areas. Thus, failure analyses can benefit traffic engineers in answering at least two important questions: 1) under which circumstances should a traffic improvement plan be implemented; and 2) where should a traffic improvement plan be aimed at?

In summary, traffic simulation failures may be caused by a variety of contributing factors. In order to distinguish between these factors and use the information to benefit simulation development and network analysis, a causal analysis should be performed based on failure occurrence patterns, as discussed in the next section.

Causal Analysis

The fundamental motivation for a causal analysis is to determine the categories of contributing factors based on the failure occurrence patterns, specifically, the types, time, and locations of failure occurrence discovered in the stage of failure detection.

It is noted that simulation failures often result in vehicle spillback and cause vehicle blockages at many locations in a relatively short time. In order to identify the most critical link(s) among them, the time sequence of failure occurrence on these links should be analyzed first. As a general rule, those locations that have the earliest failure

occurrence will contain the most relevant information about simulation failures. An aggregation of the failure leading frequencies of these critical locations can then be performed across replications. Finally, a spatial distribution of critical sites can be derived upon which judgment of failure causes can be made.

The spatial distribution of simulation failure initiation locations is able to provide important hints about the types of simulation failures and their causal factors. For example, the above-mentioned simulator-related causes often lead to a scattered pattern of the critical failure-leading (in the time domain) sites, while a network-related cause typically leads to origination of simulation failures at critical links and corridors only. In consideration of this, a tabular method is a good way to summarize different failure contribution factors together with the likely features of their resulting failure occurrence patterns. The details of this approach are discussed in the methodology chapter.

1.4 Objectives of Research

The major technique used in this research is traffic anomaly detection that analyzes time histories of key link performance in order to detect simulation failures. A follow-on spatial analysis is then proposed to accumulate failure occurrence frequencies over critical network sites. The information gathered is used as the basis to execute a causal analysis that is aimed at diagnosing the contributing factors of failure occurrence. The final goal is to utilize the failure analysis results in order to effectively improve simulation development and network analysis, the immediate purpose being the mitigation of any unexpected failure occurrence.

The procedure is helped by the (unlimited, except for time) availability of simulation

output data. This brings in the possibility of an advanced failure analysis without considering the cost of data collection. Another advantage of simulation is its ability to duplicate an experiment even with the application of different test procedures. In this research, this denotes the availability to testify the effectiveness and features of the proposed detection method.

Specifically, the objectives of this research are listed below.

1. Develop a failure detection method that is practical, effective, and efficient;
2. Compare the proposed failure detection method with traditional methods, including animation observation and outlier detection, to demonstrate its advantages and weaknesses;
3. Develop a method that can effectively derive failure patterns and diagnose the contributing factors of failure occurrence;
4. Identify the role of the failure detection method in the framework of a conventional simulation process, particularly with the issues of simulation verification and validation;
5. Apply the methods to specific cases, summarize application results, and develop conclusions and recommendations for further research.

1.5 Organization of the Dissertation

This dissertation paper is currently comprised of ten chapters. The research problem has been introduced in Chapter One. Other highlights in this chapter include an overview of the study problems as well as a definition of research objectives.

A literature review is described in Chapter Two. Literatures from two fields are respectively discussed: the first covers existing techniques in the field of traffic anomaly detection in several analogous problems, and the second is about emerging research in the detection and analysis of simulation failures within the large framework of simulation model validation and verification.

Chapter Three focuses on the description of the proposed methodology, which is categorized into three layers: a time series inspection, a spatial analysis, and a causal analysis.

The implementation of the proposed method is introduced in Chapter Four. The test bed simulator chosen is CORSIM. Therefore, the realization of the method implementation is illustrated with the particular features of CORSIM simulator.

Chapter Five demonstrates an application of the proposed methodology in the evaluation of simulators. This is illustrated by comparing different versions of CORSIM, which has undergone significant upgrading in some of its traffic behavior models.

The study results of two case study networks are discussed in Chapters Six and Seven. These case studies consider a sub-network of downtown Chicago in the PM and AM peak, respectively. Chapter Eight discusses the application of the method to a different network on the NCSU campus in order to test its transferability across various networks. Each of the three chapters includes a discussion of the network features, a description of the case study design, the case study results, and a summary and discussion of these results.

Chapter Nine synthesizes the research results on the simulator evaluation and network

evaluation, summarizes key research findings, and provides research conclusions and recommendations for the future research.

Chapter Ten includes a list of bibliography. The appendices of this dissertation include VBA program codes, and three CORSIM input files that have been used in the case studies in this research.

CHAPTER 2: LITERATURE REVIEW

The literature review is carried out in two areas. The first one focuses on existing traffic anomaly detection technologies in some analogous fields to this research. It provides a technical background for the development of an effective failure detection methodology in this research. The second covers current research efforts in the field of simulation failure detection and analysis. It clarifies the role of failure detection and analysis in a framework of simulation validation and verification.

2.1 Traffic Anomaly Detection Technologies

Traffic anomaly detection is a predominant task in the field of network surveillance and management. Successful traffic anomaly detection has many meaningful applications in the studies of different types of traffic networks. In particular, traffic gridlock detection in communications networks and traffic incident detection in transportation networks have many similarities to the flaw detection issues addressed here. These problems are analogous to our study problem in the sense that the study objects are similar and the objective is analogous in detecting and diagnosing the anomalies. Thus, successful traffic anomaly detection technologies in these fields can provide useful hints for the development of a general, effective failure detection technique.

In all, the literature review focuses on three analogous problems including traffic gridlock detection (in the study of communication networks), traffic incident detection (in the study of transportation networks), and network breakdown analysis (in the study of transportation networks). These are discussed below.

Traffic Gridlock Detection

The emergence of large-scale computer networks has incurred an increasing demand of telecommunications between computer networks. However, the possibility of traffic gridlocks poses a potential threat to the reliability of these communication networks. Challenged with this problem, computer scientists have initiated many research efforts in the area of effective detection and prevention of traffic gridlocks.

Since visualizations are virtually impossible in communication networks, quantitative methods have played a primary role in the surveillance of communication traffic. In practice, most communication networks collect passive measurements of traffic at routers and switches. These passive traffic volumes at key points comprise the basic input for traffic gridlock detection technologies. As a result, the gridlock detection studies identify the onset of traffic gridlocks by tracing traffic anomalies during the process of data analysis.

With the passive traffic flow available, different analysis approaches have been researched to realize effective detection. The primary ones include 1) sample statistics, 2) time-series analysis, and 3) wavelet analysis methods.

One example of sample statistics methods is due to Feather, et al. (1993), who showed in their research that network faults can be detected by analyzing the statistical deviations of network traffic from regularly observed behavior. In the class of time series analysis methods, Brutlag (2000) performed an example study in which he derived a series of gridlock detection thresholds based on the exponential smoothing and Holt-Winters forecasting techniques. These thresholds were then applied in a time series model which

can successfully detect aberrant network behaviors using them. Barford, et al. (2002), as an illustration of the wavelet analysis techniques, similarly developed a detection mechanism based on the methods of time series and wavelet analysis. His method relies on the information of flow levels and frequency characteristics.

In summary, most traffic anomaly detection techniques use the measure of traffic volumes as the basic indicator variable in their detection models. This is related to the limited data availability in communication networks. Nevertheless, the successful applications of these technologies have shown that the analysis of traffic flow quantities is adequate to distinguish the occurrence of traffic anomalies and detect the onset of traffic gridlocks.

Traffic Incident Detection

The second analogous problem, incident detection, represents an important study field in traffic engineering analysis. Traffic incidents result in immediate traffic flow disruptions, which are the primary causes of non-recurring delay in transportation networks. Effective detection of traffic incidents can improve traffic performance by prompt incident management to mitigate traffic disruption and reduce the likelihood of secondary crashes.

The development of incident detection techniques relies primarily on the available data from roadway surveillance systems. For now, traffic surveillance systems are comprised of a combination of roadway traffic sensors, highway patrols, CCTV (Closed Circuit TV), micro-radars, and acoustic sensors. Some other unconventional sensor technologies are beginning to find their ways into the systems, as well. As a result, the available traffic performance data for the input of incident detection take different formats including

vehicle trips (counts), vehicle speeds, traffic density, etc. These various traffic data comprise the basis for the development of Automated Incident Detection (AID) systems.

In all, the family of incident detection algorithms includes 1) pattern recognition methods, 2) traffic model methods, 3) statistics derivation methods, and 4) artificial intelligence methods (Weill, et al., 1998). They adopt different formats of traffic data and rely on a variety of analysis techniques.

The pattern recognition method recognizes traffic incidents as unusual traffic patterns that differ from normal conditions. For example, the widely used California Algorithms (Courage, et al., 1968) are designed to perform incident detection by comparing the occupancies of neighboring traffic count stations with pre-defined incident detection thresholds. The traffic model method employs the macroscopic flow models in traffic flow theory. As an illustration, the McMaster Algorithm (McMaster, 1991) makes use of a catastrophe theory to detect traffic incidents, which are denoted by sharp changes in traffic flows. The third method, statistical deviation method, is applied by comparing the predicted traffic interval data against historical records. The class of this method includes traditional statistical fitting, Bayesian inference, time series, and filtering algorithms, all of which have been explored in terms of traffic anomaly detection. Compared to the conventional methods, the method of artificial intelligence is relatively new. Nevertheless, some researchers have made progress in the field of incident detection by the use of artificial neural networks (e.g., Ritchie, et al., 1992).

An extension of the incident detection problem is the evaluation of various detection techniques. Popularly-used evaluation functions consist of detection rate, false alarm rate,

and detection time. In reality, however, evaluation data are scarce in the field. As a result, some researchers have employed simulation to theoretically evaluate the emerging incident detection algorithms. As an illustration, Lee, et al. (2002) initiated an investigation of incident situations through data mining in the PARAMICS (Parallel Simulation Model, Quadstone Inc.) simulation.

In all, a large class of incident detection techniques has been developed due to the possibility of different traffic data types and formats. Despite the choice of different detection variables, time series techniques still play a primary role in the effective and prompt detection of traffic incidents.

Traffic Breakdown Analysis

Traffic breakdown analysis is another analogous problem to this research. Its purpose is to analyze traffic anomalies in order to detect the onset of traffic breakdown in congestion studies. Traffic breakdown is a major contributor to roadway capacity loss. For example, Forbes & Hall (1990) found that once breakdown occurs, there is a 5-8% capacity loss due to an increase in queue discharge headway.

The scarce empirical information in this field makes traffic breakdown analysis difficult for practical engineering studies. Currently, traffic breakdown analysis is aimed at an early detection of traffic breakdown occurrence and a speedy dissemination of that information. This is also an important task in congestion management.

The detection of traffic breakdown relies on a successful recognition of real time traffic flow states. A three-phase theory is widely accepted among researchers. It classifies

traffic states into: free flow state, stop-and-go state, and synchronized flow state (e.g., Jost, 2002), which are analogous to the gaseous phase, liquid phase, and transition phase in a gas-liquid system, respectively.

In particular, Click, et al. (1997) developed a method that is able to predict traffic breakdown along freeways based on an analysis of the speed changes of vehicles over time. Zou (2003) performed a similar study when he developed a special time series on the changing rates of cross correlation between density dynamics and flow rate. The application results displayed that the proposed algorithm was able to better detect the onset of traffic breakdown.

In summary, most current traffic breakdown analysis techniques are based on a variety of basic traffic performance measures (such as speed, density and flow rate) and time series analysis methods. This is possibly to the wide data availability of such performance measures at the network level.

2.2 Simulation Failure Research

It might be due to the relatively short history of modern traffic simulations that the research on failure detection and analysis is scarce in this field. Nevertheless, the impacts of simulation failures on the validity of stochastic simulations are beginning to draw research attention from individual researchers.

Simulation Verification and Validation

The problem of simulation verification and validation has received increased attention as the result of the proliferation of traffic simulation models. It is considered an important basis for the effective and efficient use of traffic simulation in practice. However, till now, formal and consistent guidelines have not been developed regarding the application of stochastic simulation models.

Nevertheless, some researchers (e.g., Rakha et al., 1996, Rao and Owen, 1998, Milam, 2000) have conducted studies to derive a set of tentative guidelines from particular applications. Most researchers agree that conceptual validation, implementation verification, and operational validation should be the core parts of a high-level simulation verification and validation framework.

Besides individual studies, one large-scale, ongoing research initiative, NGSIM (Next Generation Simulation Model), was launched in 2000 to study the future development and applications of simulation models. In the NGSIM program, the FHWA (Federal Highway Administration), acting in the role of a major stakeholder of simulation practice, intended to manage public resources in a focused way as the “market facilitator” (NGSIM, 2003). The overall purpose is to influence and stimulate the wide use of traffic simulations. Among many crucial products of NGSIM program, a high-level verification and validation plan was developed for stochastic simulations. In this plan, a detailed verification and validation process was proposed to include five phases, namely planning, conceptual validation, implementation verification, operational validation, and reporting.

At the same time, the stochastic nature of traffic simulations has been addressed in some statistical approaches by individual researchers. Most of these efforts were included in

some advanced topics that study the large complexities of stochastic, large scale computer models. For example, in an effort to address potential errors and uncertainties in traffic simulations, Bayarri, et al. (2002) proposed a six-step validation framework based upon a Bayesian statistical methodology. These are 1) specifying the input/uncertainty map, 2) determining evaluation criteria, 3) data collection and design of experiments, 4) approximation of model outputs, 5) analyses of model outputs, and 6) feedback information. In the research by Sacks, et al. (2002), a set of five essential ingredients, namely context, data, uncertainty, feedback, and prediction, was abstracted from a statistically-based validation process. The study results verified that with careful calibration and tuning, traffic simulation can be an effective predictor of traffic performance in the field.

Simulation Failure Analysis

The literature review in the field of simulation validation and verification revealed that although uncertainty analysis has begun to be addressed, the detection and analysis of simulation failures have not been formally considered in the framework of traditional simulation analyses. For example, the Smartest Project (Algers, et al., 1998) performed an analysis to evaluate over thirty traffic simulators worldwide. In the summary of evaluation functions, the project recognized five model evaluation categories of efficiency, environmental impact, safety, comfort, and technical performance.

Nevertheless, individual researchers have begun to notice the phenomenon of simulation failures and estimate their impacts on simulation analysis. As an illustration, research on a Genetic Algorithm Signal Optimization Method (GASOM) by Park, et al, (2001)

considered the impacts of outlier observations in simulation evaluation and, accordingly, adopted the median instead of the mean to mitigate their impacts. Roupail, et al. (2002), in the study of variability-sensitive measures of effectiveness (MOE) in stochastic simulation, examined the tail probabilities resulting from unusual simulation runs that would bias the analyses. The research led to the proposal of using the measure of inter-quartile range (IQR) as the primary MOE to incorporate the impact of gridlock runs. In a parallel research, Sacks, et al. (2002) indicated the discrepancies of traffic gridlock occurrence between simulation and field observations. They pointed out that the presence of gridlock may be numerically indicated by low throughput and by large “run-to-run” variance, which can be further assisted by a close examination of animations to uncover the failure-leading circumstances.

In summary, the problem of failure detection and analysis has not received enough recognition in traditional simulation verification and validation techniques. Although recently simulation failures have been studied as an important phenomenon in stochastic simulation, there is still no effective guidelines to appropriately detect and address the occurrence of simulation failures.

2.3 Summary of Literature

The purpose of this research is to identify simulation failures through the detection of traffic anomalies in traffic simulation. The research is unique in the sense that, although the analysis of simulation failures should comprise a significant part in the framework of stochastic simulation verification and validation, little research has been performed along these lines. Since the surveillance of traffic behavior is one primary task in the field of

network management, this class of problems has been widely discussed in the study of some analogous problems. The common feature of these problems is the detection of traffic anomalies using quantitative methods. Therefore, the existing traffic anomaly detection techniques in these analogous problems provide an important technical background for the development of an effective and common failure detection and analysis procedure in this research.

The varying of input data availability results in different analysis algorithms in these fields. Among the analogous areas, the study of communication gridlock detection is based upon data of passive measures of network traffic (equivalent to traffic flow rates). It has been demonstrated that with appropriate analysis techniques, the study of changes in passive traffic alone is sufficient to detect network traffic anomalies. Although a simulation study does not have concerns with regard to the data availability, it is advisable to use the least amount of data to make any proposed failure detection method general and transferable across networks and simulators.

As for the analysis tools, it is a common practice to use the changes of indicator variables over time and/or space to recognize any unusual patterns in network traffic. Specifically, the practices in these analogous studies have shown that the method of time series analysis, which can trace the changes of sensitive variables over time, is able to accurately and promptly recognize the occurrence of network abnormalities.

In the field of traffic simulation, although much research has been invested in general-purpose simulation validation and verification, the phenomenon of simulation failures has received scarce attention. With the increased necessity of developing a formal and

comprehensive simulation verification and validation framework, the detection and analysis of simulation failures should not be limited to statistical methods only. In short, the literature points to the need for developing and evaluating robust techniques that will assist in detecting simulation model failures, which can be of great value to model developers and users alike.

CHAPTER 3: METHODOLOGY

3.1 Overview

A multi-layer approach to the problem of failure detection and analysis has been developed. It is founded on the use of key traffic performance measures that are tracked in time and space in the analysis of simulation. The approach comprises three layers: a time series inspection, a spatial analysis, and a causal analysis. The major tasks associated with each layer are depicted in Figure 3.1 below and are explained next.

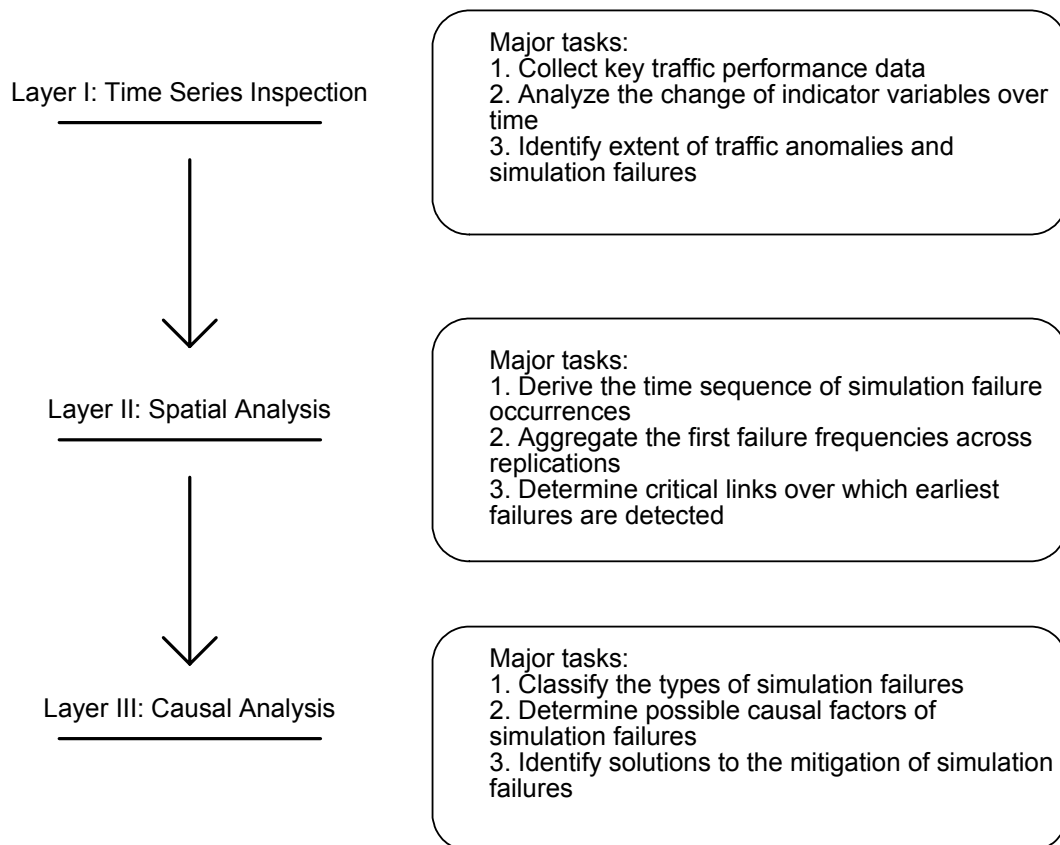


Figure 3.1 Multilayer Simulation Failure Analyses

The first layer pertaining to the time series inspection is intended to perform a series of

tasks including

- the acquisition of time series data,
- tracking changes of traffic performance data over time,
- detection of traffic anomalies, and
- judgment of simulation failure occurrence.

In order to perform the time series inspection, the indicator variables should be sensitive to the occurrence of simulation failures. With the prescribed detection thresholds (described later in this chapter), once an indicator variable exceeds a pre-specified value, a simulation failure “alarm” is set. Thus, the main function of the first layer is to execute a successful detection of simulation failures, while avoiding the mislabeling of temporary congestion as an actual failure.

The second layer pertaining to spatial analysis takes the detection results identified in the first layer to assess the spatial pattern of failure occurrence. It is noted that the occurrence of simulation failures is very likely to result in spillback onto many links in a given simulation replication. In order to locate the most critical links, these links are ranked according to their failure occurrence time, and only those ones having the earliest failure occurrence are recorded as first failing links. For network nodes (or intersections), in addition, a first failing node is labeled as such if any (one-way) link ending at that node are first failing. The frequency of failures for each link and node is then aggregated across replications. Finally, the links and nodes having the highest first failure frequencies are labeled as critical links and nodes in the initiation of simulation failures. Thus, the purpose of the second layer is to analyze the failure patterns and to identify

critical links and nodes by solving their first failure frequencies.

The third and highest layer is a causal analysis. It is intended to determine the possible contributing factors of simulation failures. This is based upon examining those critical links identified in the second layer. The concept is to use the spatial distribution of the first-failing links and nodes to judge what changes in model inputs or parameters are useful to mitigate unexpected occurrence of simulation failures. In general, simulation failures can be attributed to (a) input errors in the data stream, or (b) improper calibration of local parameters at the link-level, or (c) the selection of network-wide parameters that do not reflect the empirical data. Each type of failures can be mitigated by the use of appropriate user treatments. The causal analysis assists in making the choice of treatments.

The above three layers comprise a complete procedure of traffic simulation failure detection and analysis. Details on an integrated application of the method are described next in a simulation environment.

3.2 Data Preparation

Choice of Indicator Variable

The proposed simulation failure detection and analysis procedure is fundamentally based upon the analysis of time series data that are comprised of traffic performance interval data. In the process of choosing an effective indicator variable, two principal criteria should be considered: (a) the availability of the variable in standard simulation outputs, and (b) its sensitivity to the occurrence of failures. Based on these selection criteria, the

measure of the number of vehicle trips discharged from a link in a specified time interval (hereafter termed link trips out) is deemed to be an appropriate choice for this procedure.

There are normally many outputs available in a traffic simulation. Among the many candidate variables, the measure of link trips is seen as of particular relevance. It is one of the most elementary traffic measures of effectiveness, so that it is widely available in all known traffic simulation models. In addition, it is important to note that most traffic simulation models report traffic performance measures on a link based on only those vehicles that have already exited the link. In this research since the occurrence of link failures will obstruct vehicles from discharging at a “normal” rate, the values of most other traffic performance measures (such as speed or delay) will become unavailable or biased for failure analysis. For example, a link could report zero delay in a time interval if no vehicles are observed to discharge from it, while in reality those vehicles may be blocked from exiting the link and therefore are experiencing large delays that go unreported.

From the perspective of sensitivity, once simulation failures occur, most reported traffic performance measures will tend to be affected. Among them, the measure of link trips is able to promptly indicate the onset of a simulation failure, since it quickly drops to zero and persists at that level for the remainder of the simulation once a simulation failure occurs, as per the definition of a simulation failure. Under normal traffic states, by contrast, the measure of link trips typically follows a Poisson distribution and has a very small chance of reaching zero unless traffic demand is extremely slight in combination with a short observation interval.

Description of Detection Variables

Unrecoverable loss of link discharging capabilities is associated with zero link trips. But in some cases, the analysis of link trips alone may not be sufficient for the accurate identification of traffic status. For example, once a simulation failure occurs, unrecoverable traffic gridlocks will result in traffic spillbacks in a very short time, and links that are downstream of the problem area may experience demand starvation since they are no longer able to receive vehicles from the upstream links. In this case, although the number of link trips on these downstream links will drop and may exceed the prescribed thresholds, they are not actually suffering a capacity loss. Thus, false alarms could be reported by applying a naïve failure detection method. In order to avoid this possibility, two supplemental variables, namely vehicle trips in and change in link content, are included in order to construct a more robust set of failure detection criteria.

By definition, link trips denote the number of vehicles discharged *from* the subject link during a given time interval. This measure is termed as link vehicle trips-out (*LTO*) in this research. Another variable, link vehicle trips in (*LTI*) is, by contrast, defined as the number of vehicles discharged *onto* the subject link during the study time interval. The third variable, the change in link content (*CLC*) is defined as the change in the number of vehicles remaining *on* the subject link at the end of each time interval. These three variables jointly comprise the time series data used in the procedure of failure detection and analysis.

In the data collection stage, link trips-in and link trips-out across adjacent links are related to each other through an intermediate variable, movement trips-out (*MTO*),

observed at the upstream and downstream links, as illustrated in the Figure 3.2. This, of course, assumes that there are no sinks or sources between the entering and exiting movement flows.

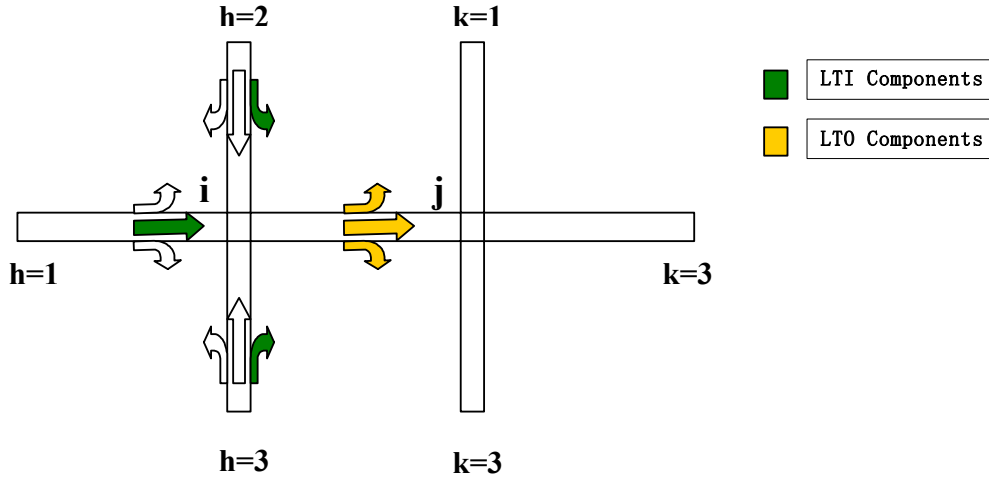


Figure 3.2 Relationships between LTI, LTO and MTO

As shown in Figure 3.2, both *LTI* and *LTO* on the link (i, j) can be aggregated over the corresponding *MTO*. That is, *LTI* can be calculated as the aggregation of the *MTO* fed onto the subject link, while *LTO* can be calculated as the aggregation of the *MTO* discharged from it. In practice, movement trips are often easy to obtain from simulation outputs. For a specific time interval r , thus, *LTO* and *LTI* on link (i, j) can be calculated as:

$$LTI_{(i,j)}^r = \sum_{h=1}^m MTO_{(h,i,j)}^r$$

$$LTO_{(i,j)}^r = \sum_{k=1}^n MTO_{(i,j,k)}^r$$

Where $LTI_{(i,j)}^r$ and $LTO_{(i,j)}^r$ denote the **LTI** and **LTO** on link (i, j) during time interval r , $MTO_{(h,i,j)}^r$ denotes the **MTO** on link (h, i) destined to node j , and $MTO_{(i,j,k)}^r$ denotes the **MTO** on link (i, j) destined to node k during r . The indices m and n denote the number of upstream and downstream links for link (i, j) , respectively, which contribute flow to or receive flow from the link. The formulas are of practical use since most simulators provide only values of link trips (**LTO**) and movement trips (**MTO**) in their simulation output.

If there are no capacity problems or simulation failures, all link vehicle trips on a network link should be serviced without significant delay. As a result, the number of vehicles discharged onto the subject link should approximate the number of vehicles exiting it. Thus, the variable **CLC**, which denotes the cumulative difference between **LTI** and **LTO**, can be used to signify traffic states on a study link. Given values of **LTI** and **LTO** at any time interval r , **CLC** is defined by the following equation:

$$CLC_{(i,j)}^r = \sum_{s=1}^r LTI_{(i,j)}^s - \sum_{s=1}^r LTO_{(i,j)}^s,$$

where $CLC_{(i,j)}^r$ stands for the **CLC** on link $i \Rightarrow j$ at the end of time period r , and $LTI_{(i,j)}^s$ and $LTO_{(i,j)}^s$ denote the **LTI** and **LTO** on link $i \Rightarrow j$ during time interval s .

If **CLC** fluctuates around a stable level, it denotes the presence of an equilibrium state on the subject link; on the other hand, if **CLC** monotonically increases above a certain threshold and does not drop back, it would indicate the presence of persistent queues on the subject link, which would in turn signify the occurrence of a simulation failure. In

fact, one attribute of a blocked link is that once it is saturated with vehicles, its *CLC* will approach and stay at a value consistent with the link storage capacity (more precisely, the link storage capacity minus the number of initial vehicles on the link).

In summary, three variables are used in the time series inspection. Among them, the indicator variable *LTO* counts discharging vehicles on the subject link, *LTI* counts entering vehicles onto the link, and the third variable *CLC* provides the change of number of vehicles occupying the link (assuming that the link starts from an under-capacity state at the beginning of the simulation). In the data collection process, the values of the variables *LTO* and *LTI* need to be tracked over time in each replication; *CLC* can then be derived from these intermediate variables.

In order to track the changes of the selected indicator variables, a simulation time period is divided into small, contiguous time intervals, and link performance data at each time interval are then requested during simulation. For example, if one hour simulation is divided into twelve five-minute intervals, a time series of twelve values on a performance measure can be obtained for every network link in every replication.

3.3 Layer 1: Time Series Inspection

Detection Function

For any network link that is in a normal (i.e., below capacity) state, the ratio between its cumulative statistics $\sum_{s=1}^r LTI_{(i,j)}^s$ and $\sum_{s=1}^r LTO_{(i,j)}^s$ will converge to *I* if the number of time intervals is chosen to be large enough. In such cases, *CLC* is expected to oscillate around 0 as *r* changes. By contrast, once a simulation failure occurs on a link, the value of *LTO*

will immediately decrease because of the sudden loss of its discharging capacity. While *LTI* is initially unaffected by spillback, the value of *CLC* on that link will monotonically increase until the subject link becomes full. At that time, *LTI* will drop to zero, and *CLC* will appear “stuck” at some positive number. A spillback will form and traffic on the upstream links will begin to be affected. Until (and unless) the initial vehicle blockages dissipate, incoming vehicles to the problem area will only exacerbate the problem.

Motivated by the above description, a failure detection function is defined as follows:

1. *LTO* decreases to 0 at the failure occurrence time, denoting that a complete link blockage (or a complete loss of link discharging capability) has occurred on the subject link,
2. *CLC* at the failure occurrence time is not 0, confirming that idle links (i.e. with very low demand) are not failure links, and
3. *LTO* remains 0 for all time periods later than the failure occurrence time, denoting that temporary capacity loss is not a failure.

Mathematically, for any eligible network link (i, j) , the following criteria are applied to detect whether any possible link blockage at time interval r :

- 1) $LTO_{(i,j)}^r = 0$,
- 2) $CLC_{(i,j)}^r > 0$, and
- 3) $LTO_{(i,j)}^t \leq LTO_{(i,j)}^r$ for any $t > r$

where $CLC_{(i,j)}^r$ and $LTO_{(i,j)}^r$ denote the **CLC** and **LTO** on the link i to j during time interval r , and $LTO_{(i,j)}^t$ denotes **LTO** on the link i to j during any following time interval t . Once a link meets all the above three criteria, a simulation failure on link (i, j) in time interval r is reported. A simulation replication will be recorded as a failure replication, if it contains one or more links exhibits a simulation failure at the end of simulation.

The above detection function can be modified by specifying a less stringent criterion δ for the lower boundary of **LTO** (say, $LTO \leq \delta$, $\delta \geq 0$). The modified function is used to track drops in discharge flows and to anticipate the occurrence of a full vehicle blockage on a link. Likewise, the alternative detection functions can be rewritten as follows:

- 1) $LTO_{(i,j)}^r \leq \delta$,
- 2) $CLC_{(i,j)}^r > 0$, and
- 3) $LTO_{(i,j)}^t \leq LTO_{(i,j)}^r$ for any $t > r$.

False Alarm Rate

The proposed failure detection functions can be evaluated in terms of a false alarm rate: the proportion of links that are wrongfully reported as experiencing unrecoverable vehicle blockage, while in actuality they are operating in a normal (unsaturated) traffic state.

The false alarm rate can be approximated from a theoretical derivation. The estimation is based upon the assumption that link counts in any give time interval follow a Poisson distribution (e.g., May, 1990), with both the mean and variance equivalent to the average interval flow rate. In most cases the expectation of interval flow rate is unknown in the

beginning of simulation. However, as long as the duration of time intervals is appropriately defined, it can be assumed that there is no traffic gridlock in the first time interval. Therefore, the average interval flow rate can be estimated from the first interval count LTO^1 . For any subsequent time interval r , thus, the probability mass function of LTO can be estimated as:

$$\Pr(LTO^r = x) = \frac{e^{-\hat{\lambda}} \hat{\lambda}^x}{x!}, \quad x = 0, 1, \dots; \quad \hat{\lambda} = LTO^1$$

For any given small value δ , the probability of observing an LTO^i value below δ can be calculated as:

$$\Pr(LTO^r \leq \delta) = \sum_{x=0}^{[\delta]} \frac{e^{-\hat{\lambda}} \hat{\lambda}^x}{x!}$$

where $[\delta]$ denotes the largest integer less than δ . In a simulation experiment with n replications and m distinct time intervals, we would have $n*m$ different values of LTO^r . Assume that each LTO^r is identically and independently distributed, the number of LTO^r with values less than s follows a negative binomial distribution, with the expected value being calculated as:

$$E = \Pr(LTO^r \leq s) * n * m = nm \sum_x \frac{e^{-\hat{\lambda}} \hat{\lambda}^x}{x!}, \quad x = 0, 1, \dots, [s]$$

The calculations can be illustrated by a numerical example. Assuming the number of replications $n=100$ and the number of time intervals $m=12$ and that there is no correlation between the probabilities of different links, we evaluate two probabilities: $\Pr(LTO_i = 0)$

and $\Pr(LTO_i \leq 0.1\hat{\lambda})$, where LTO^i are the link trips recorded in time interval one. The results are summarized in Table 3.1 for various values of $\hat{\lambda}$, representing the average vehicle count in the first time interval on any link.

Using LTO^i as the estimate of $\hat{\lambda}$ is based on the fact that most traffic simulators are unable to generate time interval “expectations of link flows” for each time interval. Alternatively, one could estimate it from the simulator input data stream directly.

$\hat{\lambda} = LTO^i$	$\Pr(LTO^i = 0)$	$\Pr(LTO^i \leq 0.1\hat{\lambda})$	$n * m$	$E(LTO^i = 0)$	$E(LTO^i \leq 0.1\hat{\lambda})$
5	0.007	0.007	1200	8.086	8.086
6	0.002	0.002	1200	2.975	2.975
7	0.001	0.001	1200	1.095	1.095
8	0	0	1200	0.403	0.403
9	0	0	1200	0.148	0.148
10	0	0	1200	0.055	0.033
15	3.10E-07	1.80E-06	1200	0.001	0.002
20	2.10E-09	3.80E-08	1200	0	0
30	9.40E-14	3.70E-12	1200	0	0

Table 3.1 Probability Values of LTO for Various First Interval Vehicle Counts

Table 3.1 shows the theoretical derivation of the probability of false alarms for any network link, when the number of analysis intervals (m) is 12 and the number of replications (n) is 100. Thus, we can conclude that for links that have an average count of 5 vehicles per interval, the number of false alarms is calculated to be about 8; when the count exceeds 10, this number drops to about 0.033, a fairly negligible value.

For illustration purpose, we consider a simulation network that is comprised of 20 links. The first five-minute count for 6 links are 6, 6, 9, 15, 15, and 15 vehicles, respectively, and all other links have a count value larger than 20. The number of false alarms for this

simulation can then be calculated by summing the product of the expected number of false alarms of a link, $E(LTO_i = 0)$, and the frequency of links at the same demand level, ***Freq***, as shown in Table 3.2. The expected number of overall false alarms is shown in the last column in the table.

LTO^1	$E(LTO^i = 0)$	<i>Freq</i>	$E(\# \text{ False Alarms })$
5	8.086	0	0.0
6	2.975	2	6.0
7	1.095	0	0.0
8	0.403	0	0.0
9	0.148	1	0.1
10	0.055	0	0.0
15	0.001	3	0.0
≥ 20	0	13	0
Total		20	6.1

Table 3.2 Example Calculation of the Expected Number of False Alarms

It is important to note that the above calculations consider only the resulting false alarm rate from the first detection criterion only. Therefore, the actual false alarm rate should be less than the above calculated values when the additional two criteria are satisfied as well.

The above computations have demonstrated that for a traffic link with a very low traffic demand, the false alarm rate could be high considering the number of replications and time intervals analyzed. To avoid this risk, only those links that have a traffic demand level above a minimal threshold should be considered in the application of the failure detection procedure. For example, if we set the threshold to an interval flow rate of eight vehicles, those links having an hourly flow rate of less than 96 vehicles per hour will be excluded from the analysis (assuming there are 12 analysis intervals).

Based on such considerations, only those links with meaningful flows are actually evaluated with the proposed failure detection function. Since these excluded links are unlikely to initiate a traffic blockage (these links are typically on the periphery of the network), this exclusion will not significantly affect the validity of the failure detection procedure.

Furthermore, the above description demonstrates that the choice of time interval length (or, equivalently, the number of time intervals in a simulation) will play an important role in the determination of the effectiveness of failure detection. In general, the duration of a detection time interval cannot be too small, since this may either cause a high false alarm rate, or require the omission of many links that do not satisfy the demand threshold. On the other hand, long interval durations will cause longer detection time for the identification of traffic simulation failures. Thus, the choice of the time interval duration often requires a compromise between detection accuracy and false alarm rate. Typically, the duration of time intervals will be multiples of the common signal cycle length in the study network so as to preserve the identity of the traffic performance expectations under fixed control and demand conditions.

When simulation failures are detected, the affected replications are typically excluded from the subsequent data analyses because interpretation of their results may be misleading. By doing so, the failure detection process helps maintain the validity of simulation analyses. Our further goal is to use the failure detection process to help uncover flaws present in the simulator (or its use) and, potentially, correct the flaws, as discussed in the next layers.

3.4 Layer 2: Spatial Analysis

The spatial analysis of simulation failures is based on the aggregation and examination of the earliest failures (first failures) for links and nodes across replications. Its product is a spatial distribution of *first failing links* and *first failing nodes* which will be used to judge critical locations in the network and to identify contributing factors to the detected failures.

A simulation failure will typically result in spillback over a large part of the network and, therefore, blockages at a number of locations. The most critical links are usually those that are more likely to fail earliest. Thus, for a given replication, those links having the earliest failure time are referred to as first failing links, and the associated downstream nodes are referred to as first failing nodes. Accordingly, those links and nodes having later failure occurrence are referred to as next failing links, and those having no failures are referred to as no-failing links and nodes, respectively. It should be noted that there may be multiple first-failing links and nodes occurring in a single run of the computer model.

If a traffic link or node is the earliest one experiencing a failure, its first failure frequency is recorded as 1 in a given replication, zero otherwise. Obviously, in a successful replication there are no first-failing links. At the end of simulation, the first failure frequencies are aggregated across replications to derive the total first failure frequencies for each link and each node in the subject network, as shown below.

$$FFF_{(i,j)} = \sum_{r=1}^n FFF_{(i,j)}^r$$

$$FFF_k = \sum_{r=1}^n FFF_k^r$$

where $FFF_{(i,j)}$ and FFF_k denote the total first failure frequencies on link (i,j) and at node k , and $FFF_{(i,j)}^r$ and FFF_k^r denote the first failure frequencies on link (i,j) and at node k in replication r , respectively.

The total first failure frequencies for each link and each node can be plotted on a network map to illustrate the spatial pattern of failure occurrence. The plot enables users to visually study the failure initiation pattern, and to subsequently perform a causal analysis based on the findings of critical locations.

3.5 Layer III: Causal Analysis

Exploratory Analysis

The spatial distribution of failures derived from the second layer provides the basis for conducting a causal analysis. An initial approach to the problem begins by answering two questions: 1) are the simulation failure frequencies low or high? and 2) are the first-failing links distributed equally across the network, or confined to a small area of the network?

If a simulation is found to produce a large number of simulation failures, that may be due to many contributing factors, such as simulator algorithm limitations, simulation coding errors, etc. Thus, further analyses are needed to make a judgment based upon the spatial

patterns of the simulation failures. On the other hand, if the probability of simulation failures is low, it implies that the number of simulation replications may be too small for conducting any further analysis of simulation failures. In this case, even though there is still a non-zero chance of failures, it is often hard to make judgments based on these limited observations. Under such conditions, an increased number of replications is required if an in-depth analysis is to be carried out.

From another perspective, if the first failing links are scattered all over the network, this may possibly denote that the contributing factors/parameters have a global effect on all traffic movements in the simulation. Conversely, if there are only few links that have an apparently higher frequency of failures than all others, it signifies that traffic gridlocks are confined to a particular area. Correspondingly, different types of treatments may need to be considered at the local or global level to reduce the failure frequencies.

Thus, the answers to the above two questions provide basic clues for the causal analysis of detected simulation failures, as summarized in Table 3.3.

Spatial Distribution Pattern of Simulation Failures	Frequency of Simulation Failures	
	Low	High
Local (few links)	Not of interest	Input coding errors, inadequate calibrations of local traffic parameters, or network capacity problems
Global (many links)	Possibly model algorithm errors, though more observations needed	Inadequate calibrations of global traffic parameters

Table 3.3 Exploratory Causal Analysis with Simulation Failure Occurrence Patterns

As the table shows, the contributions to simulation failures could be roughly estimated from the frequencies of failure occurrence and their spatial distribution patterns. Based on the failure category information, users can proceed to execute a detailed analysis within the resulting candidate fields. On the other hand, it should be noted that in reality when multiple factors exist, only the most significant ones will be evident in the determination of final failure occurrence patterns. In such cases, since the impacts of secondary factors are hidden, the proposed exploratory causal analysis can then be used to decide the most significant contributing factors in the current stage.

Detailed Analysis

As described in the first chapter, the contributing factors of simulation failures can be categorized into three areas: simulator-related, simulation-related, and network-related. Simulator-related and simulation-related factors are likely to yield unexpected simulation failures (though simulator-related factors are often irreducible), while network-related factors often result in expected failures (e.g., simulating projected traffic demands on a heavily loaded network). In addition, the contributing factors from the different categories are very likely to lead to different failure occurrence patterns.

❖ Simulator-Related Factors

The category of simulator-related factors refers mainly to errors or limitations in the traffic modeling algorithms of a simulator. From the perspective of end-users, it is of little interest to study the simulator-related factors since the model algorithms are hard-coded and remain mostly unchanged once the choice of a simulator is made. Meanwhile, some users may have some awareness of the simulator-related factors, since a literature

review before the simulation could disclose the various features of a choice simulator as well as its strengths and weaknesses.

Most simulation failures due to simulator-related factors are caused by the lack of proper modeling for a particular facility type (e.g., pedestrian crosswalk), or a special traffic behavioral situation (e.g., over-saturated condition). As a result, the occurrence of simulation failures will have a high correlation with facility type and/or traffic flow characteristics. Thus, if a correlation study shows that the simulation failure occurrence is related to a special transportation facility feature, or traffic flow characteristics, it is very probable that these failures are contributed by simulator-related factors.

❖ Simulation-Related Factors

Simulation-related factors mainly include inadequate, insufficient, or incorrect user modeling elements in the process of the simulation model construction. The development of a simulation model is comprised of multiple stages, such as data collection, input coding (mainly completed in the stage of model construction), and parameter calibration. Among them errors in data collection may cause bias in the initial input of simulation, which can be evaluated by the method of uncertainty assessment (e.g., Bayarri, 2004). Incorrect coding of model inputs can be rectified in a debugging process. The determination of proper calibration values, by contrast, is a very challenging process that may or may not be possible depending on the resources available to the project.

In most cases, errors in data collection and incorrect coding of input will result in a local occurrence of simulation failures. Poor choice of calibration parameters can result in either a local or a global failure occurrence depending on the scope of the erroneous

value. In other words, errors in the setting of a global traffic parameter may result in global-level failure occurrence, while errors in the setting of a local parameter will mostly result in local-level occurrence of simulation failures.

❖ Network-Related Factors

Network-related factors mainly refer to transportation capacity problems in the subject network. Simulation failures in this category mainly occur when a simulation model is used to study a future traffic scenario, where capacity problems could not be assessed by any other method.

Traffic congestion occurs at network locations that have the most critical capacity problems. Therefore, network capacity-related problems are very likely to result in failure occurrence at the local level. Further, the network areas where failures are noted are in most cases the cause (not the result) of the problem. In simulation studies, the identification of areas with capacity problems is often the major objective of the analysis.

In summary, the simulation failure causing factors and their resulting failure occurrence patterns are presented in Table 3.4.

Possible Cause			Likely results			Solution
Category	Contributing Factors	User Awareness Level	Failure Freq.	Failure Distribution Pattern	Occurrence Pattern	
Simulator-related	Simulation algorithm limitations	High/low	High/low	Global	Correlated with facility types or traffic flow characteristics	Change simulator/none (or API if applicable)
Simulation-related	Data collection	Low	Low	Local	Local peaking	Uncertainty data assessment
	Input coding	Medium	High/low	Local	Local peaking	Debugging
	Model parameters	Low	Low	Local/global	Local peaking or correlated with traffic flow	Model calibration
Network-related	Known capacity problems	High	High/low	Local	Local peaking	Traffic improvement plans
	Unknown capacity problems	Low	High/low	Local	Local peaking	Traffic improvement plans

Table 3.4 Summary of Detailed Simulation Failure Causal Analysis

The above table supports the notion that studies of failure occurrence patterns can provide an important basis for the causal analysis of simulation failures. In addition, this can always be supplemented by the user knowledge of when and where the analysis is carried out. For example, if failure detection is performed right after the construction of the simulation model, the detection of simulation failures will most probably serve the purpose of debugging the simulation coding errors. This analysis can be the first step in addressing a large gap in current practice in terms of simulation model calibration. However, any judgment on the network performance is tentative since the simulation model has not been fully calibrated and validated.

Alternatively, if the detection procedure of simulation failures is applied to a fully calibrated and validated model for a projected traffic scenario (either for a new traffic demand or with some proposed network changes), the occurrence of failures is most

likely to denote transportation capacity problems in the subject network. This is built on the common assumption that the simulation remains valid even after the network or traffic demand change.

Finally, observation of the vehicle animations is always a useful way for validating and supplementing the above described failure detection and analysis procedure. Since the failure replications have been identified at the stage of traffic anomaly detection, the observation of animation is neatly simplified with much fewer runs to focus on.

Failure Mitigation

As simulation failures may be attributed to different factors, the mitigation process varies accordingly. For network-related cases, the occurrence of failures is seen as expected, and the failure analysis results are useful for indicating capacity problems in an actual physical network. Users can assess various capacity improvement plans targeted at the problem areas. On the other hand, if simulation failures are found to be unexpected and due to simulator- or simulation-related factors, users should consider the necessary measures to minimize the occurrence of simulation failures. This process is referred to as failure mitigation.

The process of failure mitigation is based upon the detected simulation occurrence patterns. Since simulator-related causes cannot be changed or modified in typical simulation runs by end-users, the goal of failure mitigation is restricted to the study of simulation-related factors. Specifically, the intermediate objective is to identify these inadequate, inappropriate, or incorrect factors in the simulation modeling process.

At that point, failure mitigation should not be confused with a traditional model review, during which the process of simulation modeling is scrutinized for any possible errors. In general, since key elements (such as failure areas, etc.) have already been identified in the causal analysis of simulation failures, the failure mitigation process overrides a general-purpose model review.

If simulation failures are found to originate locally, tools in failure mitigation can include a review of corresponding coding, an uncertainty assessment of specific inputs, a pre-calibration of traffic behavioral parameters, or a traffic improvement plan if applicable. By contrast, if traffic failures occur globally on the network, a global treatment is often required. As end-users can seldom modify simulation algorithms, a calibration of global-level traffic parameters should be performed.

The assessment of traffic model parameters is a major challenge in microscopic traffic simulations. This is due to the complexity in simulating driver behavioral models. In most cases, a class of traffic behavioral parameters needs to be closely scrutinized. Even though sometimes the problem can be initially simplified by a correlation study, the process remains complicated when there are many parameters to consider, particularly when they have a common effect on some vehicle behavior models.

With such considerations in mind, sensitivity testing may be the only tool available to analyze the suspected traffic behavioral parameters and to determine their significance in causing simulation failures in a mathematical way. Since such a sensitivity test is multivariate with a large sampling space, statistical sampling is often required to perform the test strategically. Because every simulator has a different set of traffic behavioral

parameters, the design of a sensitivity test is simulator-specific. In consideration of this feature, additional details about the sensitivity tests will be described in the next chapter as they pertain to the CORSIM simulation model.

CHAPTER 4: METHODOLOGY IMPLEMENTATION IN CORSIM

The proposed methodology described in Chapter 3 was implemented for a number of case studies to verify its validity and effectiveness. A commonly used traffic simulator, CORSIM, served as the test-bed simulator. Since CORSIM is widely used in traffic engineering practice, the implementation of method in that environment should provide a useful tool for model developers and users alike.

4.1 CORSIM Simulator

Overview

The proposed failure detection and analysis method is applicable to any microscopic simulator as long as it can generate the required time series data. Among many available simulators in the United States and around the world, CORSIM is considered as the best choice due to its wide use, proven validity, low cost, inexpensive input data requirements, and a large choice of output performance measures.

The development of CORSIM (CORridor SIMulation Model) was rooted in the development of UTCS (Urban Traffic Control System) back in the 1970's. (TSIS Reference Book, 2003) After generations of functional expansion and upgrading, it has now become the core part of the Traffic Software Integrated System (TSIS) package, whose development was originally supported by the Federal Highway Administration (FHWA). The most recent version of CORSIM, version 5.1, was recently released in 2003 as part of TSIS 5.1.

CORSIM uses entry volumes at network source nodes as the basic form for traffic

demand input. It performs a stochastic assignment at every intersection according to the prescribed turning probabilities, which can be calculated from the turning movement counts in the field. Since these probabilities are taken to be independent of vehicle origins, vehicles from different sources will have a similar likelihood of being assigned to a specified downstream link. In view of this feature, the major objective of CORSIM is to reproduce link traffic performance (such as flow, speed, delay, etc), and not to be concerned about trip or path-based characteristics (for example, trip travel time) (Wan, 2002). A typical simulation process in CORSIM is illustrated in Figure 4.1 below.

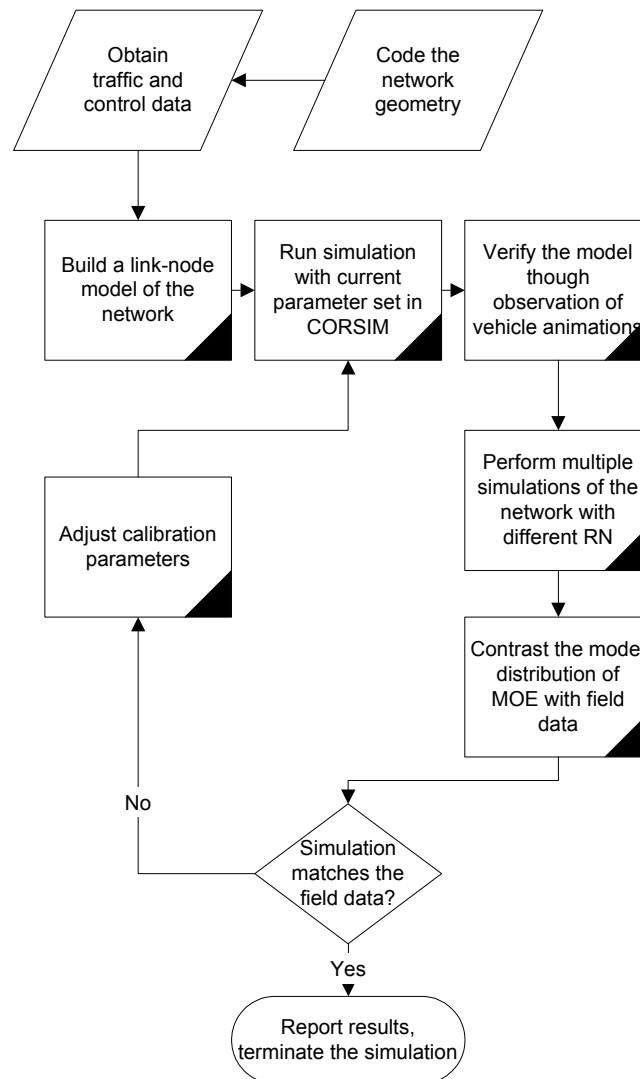


Figure 4.1 Simulation Process in CORSIM

Nationwide applications have demonstrated that after careful calibration, CORSIM is able to reproduce traffic performance at the study sites, and to provide users with quantitative measures for the purpose of assessing current and projected traffic scenarios (e.g., Owen et al., 2000). Nonetheless, its dependence on the stochastic assignment method, which is based solely on prescribed turning probabilities, does prevent CORSIM from carrying out an evaluation of traffic scenarios with significant network changes. For

example, significant geometric changes such as adding or dropping links, could result in a different traffic routing pattern and, therefore, different turning probabilities from those originally collected.

Regarding this research, CORSIM allows the simulation of time-dependent demand and network features, so that users can designate a number of time intervals over the entire simulation period, and specify time-varying inputs in each interval. Accordingly, users can also request intermediate traffic performance data for each time interval, which is required to generate the time series for the purpose of failure detection and analysis in this research.

In addition, representing the animation tool in the simulation package TSIS, the Graphical User Interface (GUI) of TRAFVU (TRAFfic Visualization Utility) allows for the verification of the proposed failure detection method by means of visual observations. Another noticeable feature of CORSIM is that users can directly access the animation files which are originally generated for use in TRAFVU. This certainly needs some computer programming efforts in order to effectively read useful information from binary files. From the failure analysis perspective, nevertheless, this provides the potential for tracking vehicle trajectory data, which might be used to quantitatively seek the “truth” of simulation failures.

Traffic Behavior Models in CORSIM

A successful application of CORSIM requires users to have some knowledge of the vehicle behavioral models, so that they become aware of the constraints and weaknesses of their simulation applications. Only when users have sufficient confidence in the basic

mechanism of a simulator can they use it to construct and calibrate simulation models in an effective way. The principal vehicle behavior models include two car-following models, a lane-changing model, two gap acceptance models, and a series of congestion behavior models.

❖ Car-Following Model

CORSIM contains two different car-following models for the freeway component (FRESIM) and surface network model (NETSIM). FRESIM uses the Pitt car-following model developed at the University of Pittsburg in 1993 (Crowther, 2001). In NETSIM, CORSIM uses an enhanced UTCS-1 car-following model, which is analogous to the Pipes model (May, 1990). The basic mechanism in the car following model in CORSIM is to always maintain a safe following distance between vehicles to avoid collisions under the most extreme deceleration maneuvers.

From this perspective, the cars following parameters are key measures that require calibration to ensure a realistic representation of traffic flow. The principal parameters in the car-following model include driver reaction time, start-up lost time, queue discharge headway, and free flow speed. While these parameters together determine the expected vehicle behavior in a certain traffic situation, for a specific vehicle, the car following sensitivity factor plays an important role from the perspective of modeling driver aggressiveness.

❖ Lane-Changing Model

The lane-changing model in CORSIM separates the entire process into two parts: the first

is the decision making process to simulate the attempt of a lane-change, and the second is the maneuvering process to complete the lane change. Thus, the lane changing model not only determines the number of lane-changes in a simulation, but also determines how safe and fast a lane-change maneuver can be carried out.

A complex set of parameters is used to describe lane-changing behavior. The most important ones include the driver reaction time, driver cooperation percentage, acceptable acceleration rate, and acceptable deceleration rate for the leading vehicles in the original lane and the following vehicles in the target lane.

❖ Gap Acceptance Model

Due to the fact that gap acceptance maneuvers are modeled differently for signalized and un-signalized intersections, the gap acceptance model in CORSIM is defined separately for both types. For signalized intersections, there are prescribed distributions of the critical gaps for right turn on red (RTOR) vehicles and for permissive left-turn vehicles. For un-signalized intersections, different critical gaps are defined separately for left-turn and right-turn vehicles, under the situations of avoiding near-side and far-side collisions, respectively. The parameters in the gap acceptance model are the distributional parameters for critical gaps. These are expressed in terms of distributions that depend on driver types.

❖ Congestion Behavior Model

CORSIM has a set of ad hoc behavioral parameters to describe special maneuvers in case of severe congestion. These models include a vehicle spillback model, a left-turn

“sneaker” model, a yellow/red light running model, and the like. The major control parameters include

- spillback probabilities which regulate the chance of a vehicle joining an existing downstream queue into the intersection,
- left-turn jumper/lagger probabilities which specify the occurrence of left-turn sneakers at the start and the end of a permitted green phase, respectively, and
- amber interval response which determines the chance of yellow/red light running.

In all, there are a series of driver behavioral parameters that must be considered to ensure proper and valid running of CORSIM simulation. It should be noted that these parameters impact the simulation at different levels. That is, some factors (such as vehicle queue discharge headway, start-up lost time, free flow speed, etc.) are link specific, while most others (such as spillback probabilities, critical gap distributions, etc.) have a common value for the entire network and, thus, apply to all network links. A listing of key driver behavioral parameters in CORSIM is summarized in Table 4.1.

#	Name	Rec Type	Function Category	Scope	Range	Unit
1	Mean value of start-up lost time	11	Car following model	Link specific	0-99	Tenths of Seconds
2	Mean queue discharge headway	11	Car following model	Link specific	14-99	Tenths of Seconds
3	Desired free-flow speed	11	Car following model	Link specific	0,10-65	Miles Per Hour
4	Duration of a lane-change maneuver	81	Lane change model	Global	1-8	Seconds
5	Mean time for a driver to react to a sudden deceleration of the lead vehicle	81	Lane change model	Global	1-30	Tenths of Seconds
6	Minimum deceleration for lane changing	81	Lane change model	Global	1-10	Feet per Second Squared
7	Difference in maximum and minimum acceptable deceleration for a mandatory lane change	81	Lane change model	Global	5-15	Feet per Second Squared
8	Difference in maximum and minimum acceptable deceleration for a discretionary lane change	81	Lane change model	Global	5-15	Feet per Second Squared
9	Deceleration rate of lead vehicle	81	Lane change model	Global	10-15	Feet per Second Squared
10	Deceleration rate of follower vehicle	81	Lane change model	Global	10-15	Feet per Second Squared
11	Driver type factor used to compute driver aggressiveness	81	Lane change model	Global	15-50	Not Applicable
12	Urgency threshold	81	Lane change model	Global	0-5	Tenths of a Second Squared per Foot
13	Safety factor X 10	81	Lane change model	Global	6-10	Tenths of Units
14	Percentage of drivers who cooperate with a lane-changer	81	Lane change model	Global	10-100	Percentage
15	Headway below which all drivers will attempt to change lanes	81	Lane change model	Global	1-30	Tenths of Seconds
16	Headway above which no drivers will attempt to change lanes	81	Lane change model	Global	30-100	Tenths of Seconds
17	Mean longitudinal distance over which drivers decide to perform one lane change	81	Lane change model	Global	50-2500	Feet
18	Probability of left-turn jumper	140	Congestion behavior	Global	0-100	Percentage
19	Left-turn maximum speed	140	Turn movement model	Global	0-44	Feet per Second
20	Right-turn maximum speed	140	Turn movement model	Global	0-26	Feet per Second
21	Probability of vehicle to join spill-back	141	Congestion behavior	Global	0-100	Percentage
22	Left-turn lagger probabilities	141	Congestion behavior	Global	0-100	Percentage
23	Near-side acceptable gap	142	Gap acceptance model	Global	15-75	Tenths of Seconds
24	Additional gap time for far-side street	143	Gap acceptance model	Global	10-75	Tenths of Seconds
25	Acceptable deceleration for amber interval response	144	Congestion behavior	Global	2-30	Feet per Second Squared
26	Acceptable gap for left-turn vehicles	145	Gap acceptance model	Global	10-100	Tenths of Seconds
27	Acceptable gap for right-turn vehicles	145	Gap acceptance model	Global	10-100	Tenths of Seconds
28	Free-flow speed percentage multipliers	147	Car following model & Lane change model	Global	0-1000	Percentage
29	Percentage multiplier for driver start-up lost time	149	Car following model	Global	0-1000	Percentage
30	Percentage multiplier for driver queue discharge headway	149	Car following model	Global	0-1000	Percentage

Table 4.1 Key Driver Behavioral Parameters in CORSIM

It is clear from the table that while some parameters may be directly estimated from field data, many others cannot. The CORSIM User Guide provides no guidance on how to calibrate these parameters that are difficult (sometimes impossible) to measure in the field. Given this limitation, the only recourse was to assess the sensitivity of these parameters to important traffic performance measures and to the likelihood of model failures.

4.2 Methodology Implementation in CORSIM

Simulation Failure Detection

CORSIM allows the division of a simulation period into multiple, shorter time intervals. For each time interval, users can specify time dependent geometry, traffic control, and traffic demand information. Accordingly, traffic performance measures for each intermediate time interval can be extracted from a CORSIM output file. Those are utilized to generate the time series data required for the implementation of the failure detection and analysis method.

CORSIM combines all simulation output into a single text file with the extension “.out”. To collect traffic performance measures at a specific time or location, users need to either continuously observe the simulation animation provided in TRAFVU, or extract the corresponding information in the output files. Since the time series inspection requires detailed output data at specific times and network locations, both of these methods are totally impractical for collecting and analyzing the time series data.

A computer code developed by the author is then utilized to extract, summarize, and

analyze the data from multiple CORSIM output files in an automated fashion. In consideration of the extended objectives of the failure detection and analysis methodology, the objectives of the computer code were to:

- collect time series data at the link and movement levels for each prescribed time interval and for each CORSIM replication,
- perform time series analyses to detect traffic anomalies according to the prescribed failure occurrence criteria, and
- summarize the occurrence sequence and derive the failure patterns over the spatial domain for the subsequent analyses.

The programming was originally performed using the REXX language (REXX User Guide, 1998). REXX is a programming language which is small in size and portable between operating systems and machines. One major advantage of REXX is that it has good capabilities in the manipulation of text strings, which is the major effort for text-in-text-out traffic simulations. Also, REXX allows for the execution of MS-DOS (Microsoft Disk Operating System) prompts in its own environment. Thus, it supports batch mode running of CORSIM as a subroutine in the program.

The code was later upgraded with a Visual Basic for Applications (VBA) environment, which is embedded in the Microsoft Office suite. One consideration for this upgrading is the relatively wide availability and use of VBA. The use of a more popular language can provide the proposed procedure with greater transferability. In addition, VBA has already been successfully applied in TSIS/CORSIM simulation, in the sense that there has been many application program interfaces (API) coded with VBA in the United States. For

example, Leonard (2004) at the Georgia Institute of Technology coded an analysis tool VBA at the simulation time interval and time step data levels. Thus, programming with VBA offers a practical value to for CORSIM users.

It should be noted that Leonard's coding work provided a basis for the tracking of vehicle trajectory data in CORSIM animation files. However, considering that tracking vehicle trajectory data requires much more programming and computation efforts, and that it is simulator specific, this research is limited to the analysis of traffic performance data at discrete time intervals only.

Figure 4.2 presents a flowchart describing the various steps involved in extracting the data needed for the simulation failure analysis.

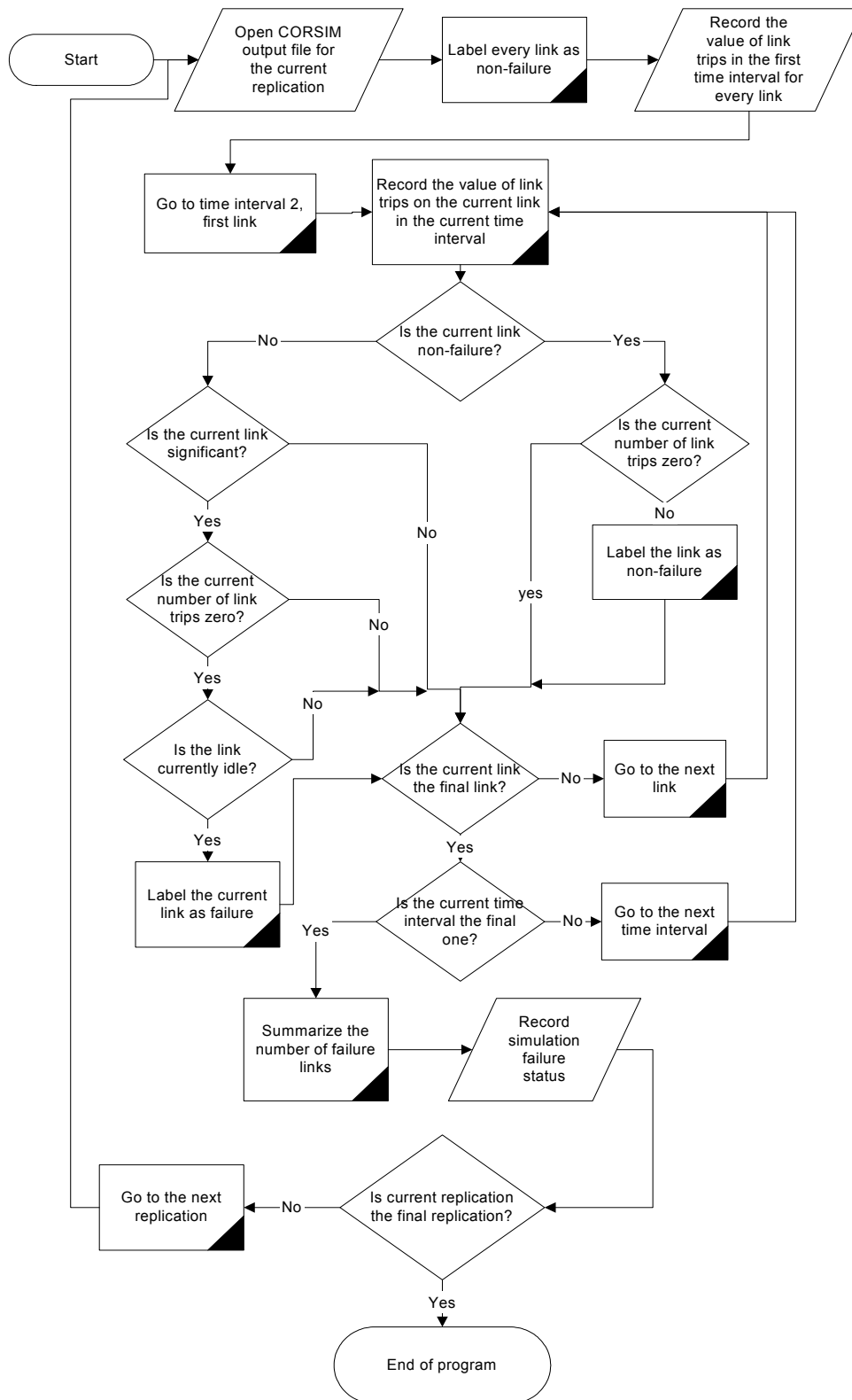


Figure 4.2 Flowchart of Simulation Failure Detection Process in CORSIM

Failure Mitigation with Sensitivity Test

Once the simulation failures have been successfully detected, their occurrence patterns can be analyzed to diagnose the contributing factors. The final goal is to seek possible solutions to mitigate them, as discussed in the previous chapter. With CORSIM as the test-bed simulator, the process can now be executed considering the features in CORSIM.

The failure patterns have been derived using a time series inspection and spatial analysis. The major challenge is then to determine the traffic behavioral parameters in a specific simulation contribute to the occurrence of failures. The tuning of traffic behavioral parameters is often difficult to perform, since the combined effect of many parameters are not only difficult to predetermine in the simulation, but also virtually impossible to measure in the field.

The adjustment of traffic parameters is often very difficult to handle since in most cases many traffic parameters need to be adjusted all at the same time. Thus, different approaches are applied to the measurable and non-measurable parameters to simplify the process. For those measurable parameters, it is recommended that they be calibrated with field data if that can be done at a reasonable cost. For non-measurable parameters, the only restriction is to ensure that they can generate rational traffic performance measures. Sensitivity testing is a common tool in the evaluation of the significance of unknown traffic behavioral parameters. The results of the sensitivity tests, thus, can be used in the development of mitigation measures for the simulation failures.

In traffic simulation, there is a complex set of traffic behavioral parameters to be adjusted in the model tuning as evident from Table 4.1. Considering that it is not practical to

scrutinize all traffic parameters, it is standard practice to examine only the most important ones. The choice of traffic parameters is made based on the analyst's experience about the simulator as well as the key attributes of the subject network. In light of the features of traffic behavioral models in CORSIM, the parameters recommended for the study of simulation failures include

- vehicle queue discharge headway (QDH),
- start-up lost time (SLT),
- spillback probability for the first vehicle and second in queue to join a spillback (SbPr1, SbPr2),
- left-turn jumper probability (LjPr),
- left-lagger probability (LlPr), and
- amber response acceptable decelerations for Driver Types one to 10 (ARD).

The key attributes of each parameter are listed in the Table 4.2.

#	NAME	Function Model	Sub-Function	Scope	CORSIM Range	Default	Proposed Range	Readily Measureable?
1	Mean queue discharge headway	Car following model	Queue discharging	Link specific	14-99	18	(1.4, 3.5)	Yes
2	Mean value of start-up lost time	Car following model	Queue discharging	Link specific	0-99	20	(0, 40)	Yes
3	Probability of vehicle to join spill-back	Congestion behavior	general	Global	0-100	(80, 40, 0, 0) for forming spill-back comprised of (1, 2, 3, 4) vehicles	(0,100)	No
4	Left-turn lagger probabilities	Congestion behavior	Left-turn only	Global	0-100	(50, 15, 0) for staying at the stop bar within (2, 4, 5) seconds	(0, 100)	No
5	Probability of left-turn jumper	Congestion behavior	Left-turn only	Global	0-100	38 for jumping across (1, 2, 3, 4, 5, 6, 7) oncoming lanes	(0, 100)	No
6	Acceptable deceleration for amber interval response	Congestion behavior	General	Global	2-30	(21, 18, 15, 12, 9, 7, 6, 5, 4, 4) for driver type 1 to 10	(4, 21)	No

Table 4.2 Selected Driver Behavior Parameters for Sensitivity Test

It should be noted that the first two parameters, mean queue discharge headway and mean

value of start-up lost time, are theoretically measurable in the field. However, since these two parameters often vary across links in the same network, it is virtually impractical to collect field values for all of them. Thus, these two parameters are included in the sensitivity test to identify their appropriate values. Again, since almost all real-world simulation work cannot consider all traffic parameters, the stated simplification can be deemed as a representative of real-world simulation applications.

4.3 Case Studies

The test of the proposed methodology consists of two parts, test of simulators and test of networks. In the test of simulators section, three different versions of CORSIM were applied to the same traffic network. The advantages and limitations of these versions are literally known. In the application test of this research, however, we were trying to evaluate the simulators empirically, specially, the study of their limitations related to the emergence of simulation failures. The results of the test of simulators are discussed in Chapter 5.

In the test of networks, we assumed that we have full awareness of the simulator capabilities. Therefore, any application results in this test will be attributed to the network modeling process and the networks themselves. Three case networks were studied to test the utility of the failure detection and analysis procedure from different perspectives.

The first and the second networks have identical network geometries, but different traffic demand and traffic control schemes. The study network is a sub-network of downtown Chicago, which is characterized by commuter traffic and high traffic demand.

The first case study verified the application of the proposed method as a pre-calibration procedure during the stage of simulation construction and calibration. The results for this study are presented in Chapter 6. In the second network we investigate the value of the method for the purpose of network diagnosis, with the assumption being that the model was already calibrated and validated. The results for the second study are discussed in Chapter 7.

The third network had considerably different features in geometry and traffic demand from the previous two networks. It was taken from the simulation analysis of the North Carolina State University (NCSU) campus area. Representative of a typical university road network, it is characterized by a peaked though varying traffic demand, mixed transportation modes, and low travel speeds throughout the network. The application of the method for this site was used to test the transferability of the proposed method across different networks. These results are presented in Chapter 8.

CHAPTER 5: FAILURE DETECTION ACROSS SIMULATORS

This chapter describes the application of the proposed failure detection and analysis methodology to the evaluation of simulators. As the proposed methodology is generic in nature and not simulator-specific, the initial application is completed by contrasting the performance of three recent versions of the CORSIM model on a common data set.

5.1 Simulator Description and Study Design

Simulator Description

As introduced in Chapter 4, CORSIM is a comprehensive microscopic traffic simulator that is capable of modeling and assessing a variety of traffic management strategies on different transportation facilities. As the “official” FHWA model, CORSIM has undergone a number of upgrades to improve its functionalities and to address problems that have been discovered in the course of its applications.

When this research started in 2000, CORSIM version 4.32 was used as the test-bed simulator for the study. Later in 2001 FHWA released CORSIM version 5.0 with some major modifications made to its modeling capabilities. In 2003 CORSIM version 5.1 was released that contained several significant changes in its traffic behavioral algorithms as well as some improvements to its user interface.

The failure detection and analysis procedure in this research is intended to be a general and transferable method across different simulators. Thus, the fact that two major upgrades of CORSIM occurred in the course of this research did not significantly

interrupt this research. Instead, it provided an opportunity to test the failure detection method across simulators.

While the most recent version (CORSIM 5.1) represents the most meaningful one to verify the user application value of the design method (as will be shown in the subsequent chapters), the available three versions contained some variations in their driver behavioral models. Thus, the applications of the proposed method in them can be viewed as a test of transferability across simulators. This is carried out by modeling an identical network (i.e. a standard data set) with the three versions.

Initially, in order to improve the understanding of the analysis results, the analyst conducted a review of the changes that have occurred across the three releases. It was found that both CORSIM versions 5.0 and 5.1 have some important changes in their functionalities and their driver behavior models. They are repetitively discussed below.

CORSIM 5.0 versus 4.32

In contrast to CORSIM 4.32, version 5.0 provides a major expansion in functionality. New capabilities include the simulation of freeway HOV operations (not relevant to this study which focuses on a signalized network), the calculation of control delay, and the modeling of vehicle-type-dependent turning percentages.

Also, CORSIM 5.0 had some enhancements in the driver behavior models and fixed some previously known bugs. According to the TSIS Website (<http://www.fhwa-tsis.com/>), key changes in driver behavior models in CORSIM 5.0 included:

- ❖ *Any configuration involving stop sign control can be modeled. Previously, some configurations involving stop sign control were not modeled correctly. Logic was also improved to model configurations involving both stop sign and yield sign control.*
- ❖ *The probability of joining spillback, entered on Record Type 141, now also applies to left turning vehicles. It previously applied to through vehicles only.*

These changes are expected to affect the failure occurrence pattern since they directly impact traffic operations under congested conditions.

CORSIM 5.1 versus 5.0

Release 5.1 of CORSIM offered additional capabilities in both ease of use and transportation modeling features. These include a new user interface, a new output data processor, and the support for an expanded network size.

Also, several known bugs were fixed and some reported errors in the driver behavior models corrected. According to the TSIS Website, key changes from 5.0 to 5.1 included:

- ❖ *The logic for determining if a vehicle would join spillback was changed. Previously there was no way to prevent a vehicle from becoming the first vehicle in spillback. Record Type 141 now defines the probability that a vehicle will BECOME the first, second, third or fourth or later vehicle in spillback instead of JOINING the first, second, third or fourth or later vehicle in spillback.*
- ❖ *Corrected a problem that allowed vehicles to accelerate at 12 ft/sec/sec when discharging from a link, even when the performance table limited the acceleration to a smaller value.*

- ❖ *Corrected an error that caused NETSIM vehicles to stop immediately when cooperating with a lane changer.*
- ❖ *Corrected errors that caused some NETSIM vehicles to jump all the way to the stop-bar when they became first in queue, regardless of how far they had to jump.*

It can be seen that several important changes have occurred in the driver behavior models. Regarding the spillback probabilities, it is important to note that the default values of the simulator have been adjusted as well as the definition change.

In general, appropriate driver behavior models are fundamental to the successful execution of micro-simulation models. Since the three versions of CORSIM have slightly different behavior models, they are expected to produce different results for the same input data set. The proposed failure detection and analysis procedure can then be applied to evaluate the impact of the driver model features of the three releases and, therefore assess the true value of the upgrades.

Study Design

Test-bed Network

In this test, the three different versions of CORSIM were run on a common dataset representing a surface street sub-network in the City of Chicago. The network is depicted in Figure 5.1. It connects a major freeway with the central business district (CBD) which is located on the right, bottom side of this map. The network contained 24 signalized intersections and 8 un-signalized intersections. The simulation models inputs came from field data that were gathered on Thursday, May 25, 2000, from 17:00 to 18:00 PM, a

typical weekday peak time. Medium to high traffic volumes of about 13,000 vehicles entered the study network during the time period, causing traffic congestion at a local level on some key links. However, and this is important to note, there were no observations of any sustained gridlock during the entire hour, although some temporary spillback occurred at various points in the network.

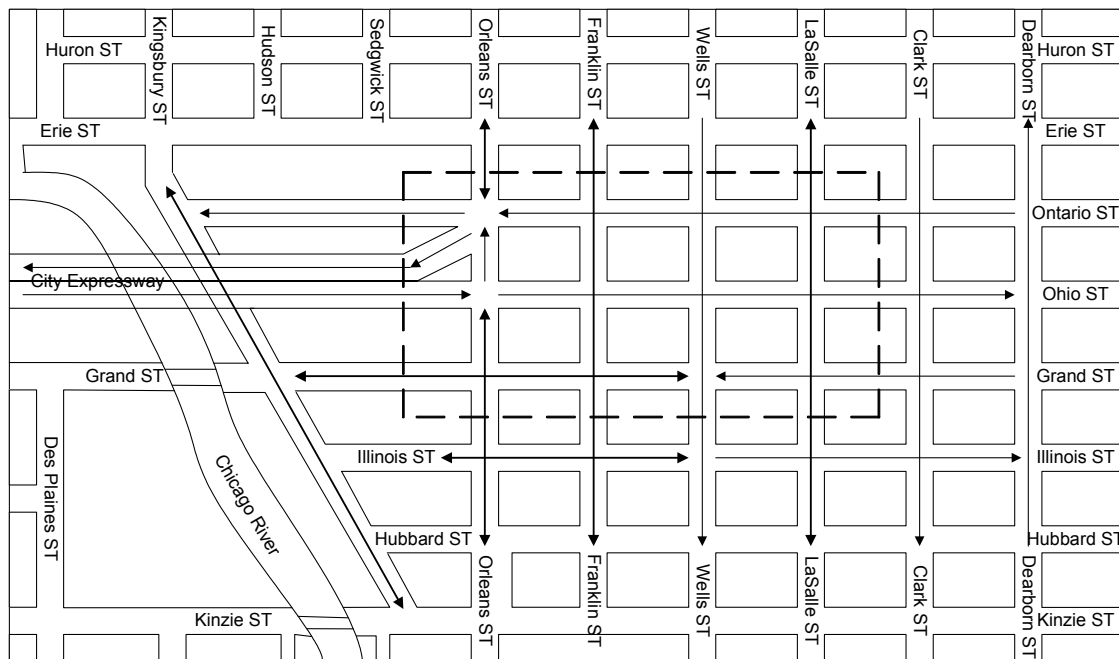


Figure 5.1 Test-bed Network in Chicago

It is important to accurately define what is meant by a “common” data set across the three CORSIM releases. Here, one needs to distinguish between 1) those inputs that come from the field and are necessary to run the code (e.g., traffic volumes, turning percentages, signal timing, network geometry among others), and 2) input values of the model parameters that specify vehicle and driver behavior under certain traffic situations. The first set is dependent on field data and indeed common across all replicate runs and simulator versions. The second, however, depends on driver behavior models of each

simulator, i.e., whether different simulators have the same types of parameters, and the default values of them are the same.

If simulators have different default values for the same parameters, one can still re-code the input model with a common set of default values. However, if a new parameter is introduced, or an existing parameter is re-defined (as in the case of the different definitions of spillback probability between versions 5.0 and 5.1 described above), it is sometimes impossible to truly make the case that the dataset is “common”. This limitation should be kept in mind as the results are analyzed.

Experiment Design

The purpose of this study is to evaluate the three simulators strictly from the perspective of simulation failure detection and analysis. Thus, the problem is simplified by accepting a common set of CORSIM default values for all unknown traffic parameters, while keeping all the field-based inputs identical across different simulators. The failure analysis focused on identifying network deficiencies is discussed in Chapters 7 through 8.

As noted above, CORSIM 5.1 has a different definition of spillback probabilities from the former two versions. In order to account for both changes in default values and parameter definitions, two sets of runs are possible for the version 5.1, one using the “former” default values of its predecessors, and the other using the “new” defaults. However, it is impossible for versions 4.32 and 5.1 to model CORSIM 5.1 defaults since one key parameter that has been assigned a new value in version 5.1 is unchangeable in the old versions. This gives rise to four studies over which a side-by-side comparison can be made on CORSIM 4.32/5.0 defaults, as shown in Table 5.1 below.

Simulator\Dataset	CORSIM 4.32/5.0 Defaults	CORSIM 5.1 Defaults
CORSIM 4.32	Case study in Section 5.2	Not considered
CORSIM 5.0	Case study in Section 5.3	Not considered
CORSIM 5.1	Case study in Section 5.4	Base case study in Chapter 6

Table 5.1 Study Design Regarding Three Recent CORSIM Releases

From the table we can see that in order to maintain a common dataset for the comparison purpose, CORSIM 4.32/5.0 default parameter values were coded for all the three releases. The evaluation of the three simulators was then performed based on them. For the last case of CORSIM 5.1 with the new defaults, it will serve as the base case for the evaluation of PM Chicago network, as to be discussed in Chapter 6.

Determining the number of Replications

The analyst constructed the simulation models with the field-collected input data and the CORSIM 4.32/5.0 default values for all traffic parameters. The detection time interval was set to be five minute. With other factors decided, the main consideration in this section is to estimate the replicate sample size that can produce statistically valid conclusions. Since the analysis object in this research is the occurrence of simulation failures, the particular concern is to obtain a precise estimate of the probabilities of failure replications. In order to do that, a pilot study was used.

A pilot study was firstly performed with CORSIM 4.32. The study used 30 replications as a first-cut experiment, which is a commonly used sample size in traffic simulation studies. The failure detection and analysis procedure was then applied, and it showed that 4

replications resulted in simulation failures. Thus, in this pilot study, the failure probability was 4/30, or 13%.

The occurrence of one or more simulation failures in a single run can be assumed to follow a Geometric distribution $G(p)$. With multiple replications, the occurrences of simulation failures follow a binomial distribution $Bi(n, p)$ with the parameter n denoting the number of replications, and p denoting the expected failure probability. Accordingly, the standard deviation of p can be estimated as

$$\hat{\sigma} = \sqrt{\frac{\hat{p}(1-\hat{p})}{n}}, \text{ where } \hat{p} \text{ denotes the sample failure probability.}$$

And, the $(1-\alpha)\%$ confidence interval for the estimation of failure probability p can be written as

$$\left(\hat{p} - z_{\frac{\alpha}{2}} \sqrt{\frac{\hat{p}(1-\hat{p})}{n}}, \hat{p} + z_{\frac{\alpha}{2}} \sqrt{\frac{\hat{p}(1-\hat{p})}{n}} \right)$$

Thus, the accuracy of the estimation, which can be reflected by the half-width of the above confidence interval, is a function of the sample size n and sample failure probability p .

With the pilot study above, if we use a sample size of 100 replications and the sample failure probability p is 0.13, the half-width of a 95% confidence interval ($\alpha = 0.05$) for the estimation of p is:

$$\text{Halfwidth} = z_{\frac{\alpha}{2}} \sqrt{\frac{\hat{p}(1-\hat{p})}{n}} = 1.96 \sqrt{\frac{0.13(1-0.13)}{100}} = 0.059$$

Likewise, for failure probabilities ranging from 0.1 to 0.9 and a fixed sample size of 100, we calculate the half-width values for their 95% confidence intervals, as shown in Figure 5.2.

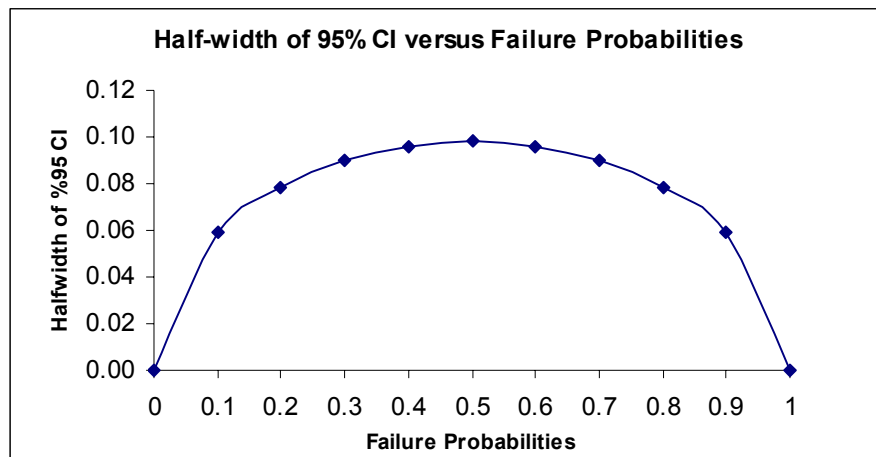


Figure 5.2 Half-width of 95% CI versus Failure Probabilities

It is shown in the figure above that the sample size of 100 replications produces 95th confidence intervals for (p) within an acceptable range of ± 0.1 . Thus, to maintain consistency, we use 100 replications as the common sample size in all the subsequent experiments in this research. The simulation results using CORSIM 4.32, 5.0, and 5.1 are discussed in Sections 5.2, 5.3, and 5.4, respectively.

5.2 CORSIM 4.32 Results

Failure Detection Results

The CORSIM 4.32 release was used to simulate the test network with 100 replications. In this study, system queue time (SQT) was taken as the main measure of overall traffic performance. CORSIM defines SQT as the aggregation of “delay calculated by taking

vehicles having acceleration rates less than 2 feet per second² and speed less than 9 feet per second”(CORSIM User’s Guide, 2003). Since queue time is defined as the aggregation of vehicle time in a slow-moving or stopped state, it is widely used to reflect the level of congestion in a transportation system. More importantly, this performance measure is not affected by the number of vehicles discharged from a link, which could otherwise bias the results when a link is partially or fully blocked.

The distribution of system queue time is shown in Figure 5.3. As the figure shows, most simulation replications are distributed to the left of the figure, though some ones (red ones) turn out to be outliers to them. The mean, median, and standard deviation are respectively 247, 196 and 154 vehicle hours.

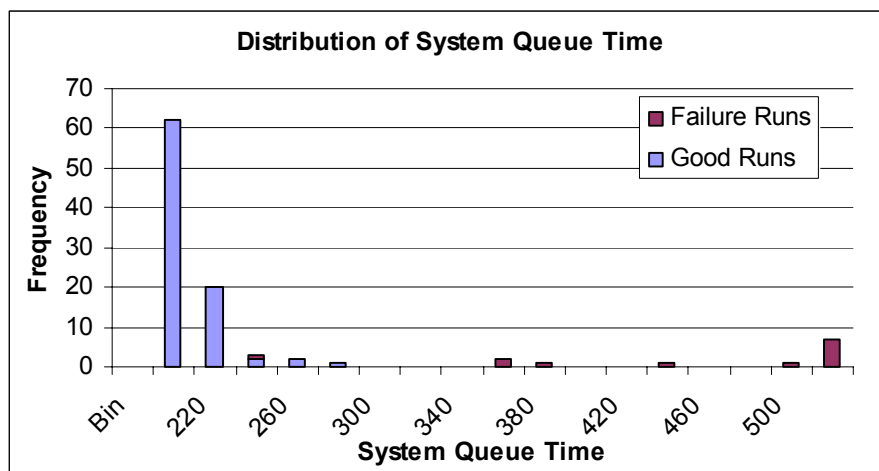


Figure 5.3 Distribution of System Queue Time in CORSIM 4.32 Simulation

The failure detection procedure was applied and 13 failure runs were differentiated from good ones, as marked by the red bars in Figure 5.3. The 95% confidence interval for the failure probability in this test was $13 \pm 6.6\%$, or (6.4%, 19.6%). It is shown that in CORSIM 4.32 simulation, there are a high consistency between outliers (replications

distributed distantly right to others) and failure runs (replications containing irrecoverable, unrealistic traffic blockages).

Spatial Analysis Results

The failure analysis procedure performed a spatial analysis on the first-failing intersections (nodes) and segments (links). The results are shown on Figure 5.4.

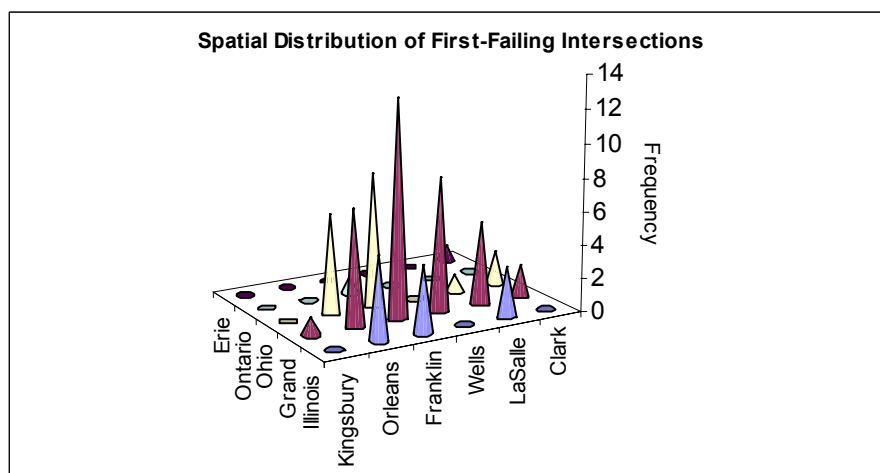


Figure 5.4 Distribution of First-Failing Intersections in CORSIM 4.32 Simulation

As the figure shows, it displays a local peaking pattern at the intersection Grand at Franklin. However, the Franklin Street is a two-lane two-way minor street that performs well in reality. Thus, we may conclude that the occurrence of simulation failures in that place would be caused by some abnormal factors in the simulation setting.

The animation check of the failure runs indicated that some left-turn vehicles on Franklin Street abnormally joined existing downstream queues at the end of their green time, blocked the intersection, and therefore disabled any conflicting flow at that intersection. The quick formation of spillback caused queues at neighboring intersections in that area.

Finally, a deadlock situation formed.

Obviously the vehicle blockage described above is inconsistent with the realistic driver behavior. This probability is governed jointly by the traffic parameters spillback probabilities and left-turn lagger probabilities. The above analysis indicated that the default values of these two parameters are too high, causing unrealistic driver aggressiveness in some vulnerable intersections and, therefore, irrecoverable simulation failures.

5.3 CORSIM 5.0 Results

Failure Detection Results

Likewise, CORSIM 5.0 was used to simulate the test network. Since the default parameter values are identical in both CORSIM 4.32 and 5.0, traffic parameters were taken as the model default values to maintain the same input dataset.

Similarly 100 replications were carried out in this test. As a result, the distribution of system queue time is shown in Figure 5.5. It is noted that the distribution of SQT has a very identical pattern to that in CORSIM 4.32 simulation (see Figure 5.3). Though, it has a slightly heavier tail on the right side. The mean, median, and standard deviation are 320, 202 and 231 vehicle hours, respectively.

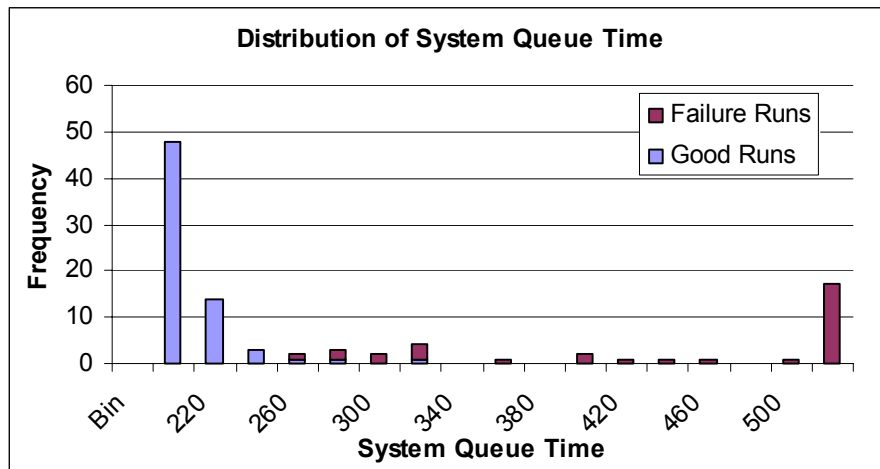


Figure 5.5 Distribution of System Queue Time in CORSIM 5.0 Simulation

The application results of the failure detection discovered 32 failure replications. The 95% confidence interval for the failure probability was then $32 \pm 9.1\%$, or (22.9%, 41.1%). As the above figure shows with red bars, almost all failure replications are distributed on the right tail of the SQT distribution, displaying a close association with the outlier replications.

Failure Analysis Results

The failure analysis procedure was then applied to the CORSIM 5.0 simulation. Part of the results, the spatial distribution of first-failing intersections on the network is shown in Figure 5.6 below. As the figure shows, most failures still initiate along Franklin Street, which is the same most vulnerable link to that in the CORSIM 4.32 simulation.

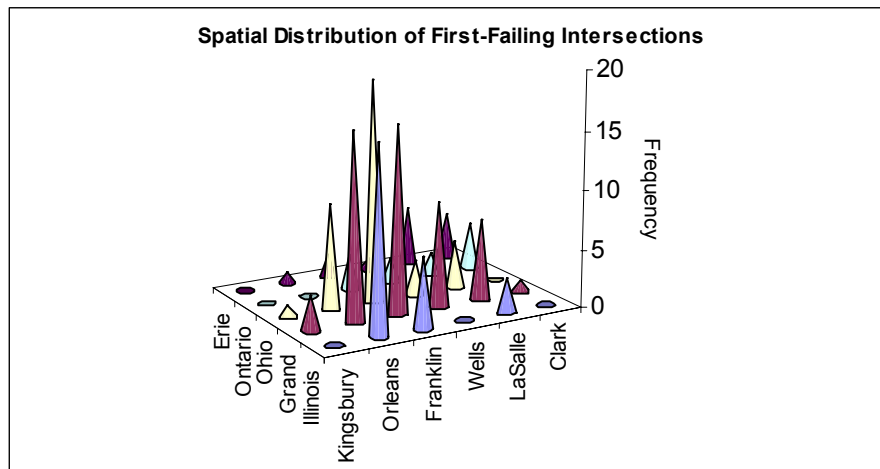


Figure 5.6 Distribution of First-Failing Intersections in CORSIM 5.0 Simulation

Visual observation of simulation animations was performed for those failure replications. Again, it was discovered that vehicles joining spillback tended to occupy the box area and therefore blocked the entire intersection. Hence, although the literature review showed that CORSIM 5.0 has improved the consistency between left-turn lagger probabilities and through spillback probabilities, the default values remain too high in the model to endanger the effective running of simulation.

5.4 CORSIM 5.1 Results

Failure Detection Results

Finally, CORSIM 5.1 was applied to the simulation of the test network. As noted earlier, since the definition and default values of spillback probabilities in CORSIM 5.1 has been changed from its predecessors, the parameters were therefore adjusted according to the default values in CORSIM 4.32 and 5.0 to ensure that a similar dataset was used for the comparison of the three releases. For other unchanged parameters, the model used default

values.

With 100 replication runs, the distribution of system queue time is shown in Figure 5.7. As the figure shows, the SQT is distributed evenly between 200 to 500 vehicle hours, while having a much heavier tail on the right (beyond 500 vehicle hours). The mean, median, and standard deviation are 575, 515 and 294 vehicle hours. Compared to the CORSIM 4.32 and 5.0 results, the system queue time distribution apparently shift to the right side of the figure, which denotes a higher value of SQT and a higher level of congestion in the network.

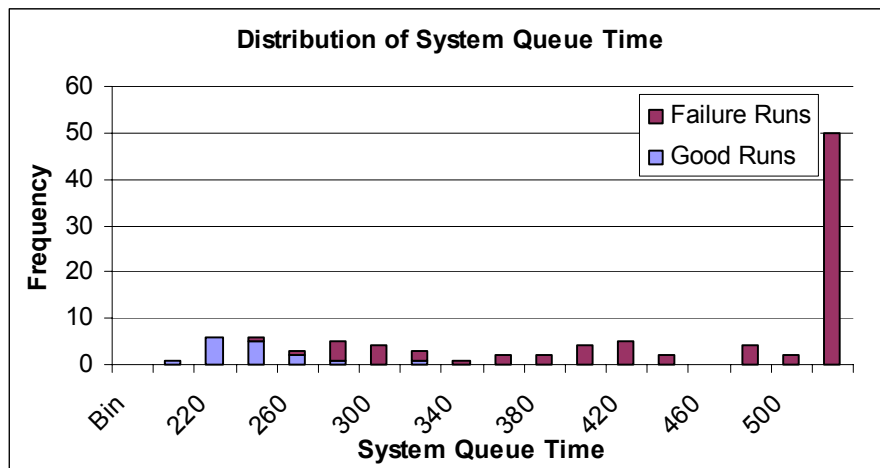


Figure 5.7 Distribution of System Queue Time in CORSIM 5.1 Simulation

The failure detection results indicated that most replications (84 among 100) were failure replications that contain at least one link which has unrecoverable vehicle blockage for at least one time interval (or, five minutes). The 95% confidence interval for the failure probability was calculated as $84 \pm 7.2\%$, or (76.8%, 91.2%). Thus, with the CORSIM 4.32/5.0 default setting (except spillback probabilities), CORSIM 5.1 displayed an unexpected high likelihood of simulation failures.

Spatial Analysis Results

The failure analysis procedure was again applied to the CORSIM 5.1 simulation. As a result, the spatial distribution of first-failing intersections is plotted in Figure 5.8. It is important to note that the critical intersection has shifted from Franklin Street in the previous studies to the Orleans Street, which is a corridor characterized by heavy northbound through and southbound left-turn traffic in the southern part (near side part in the figure).

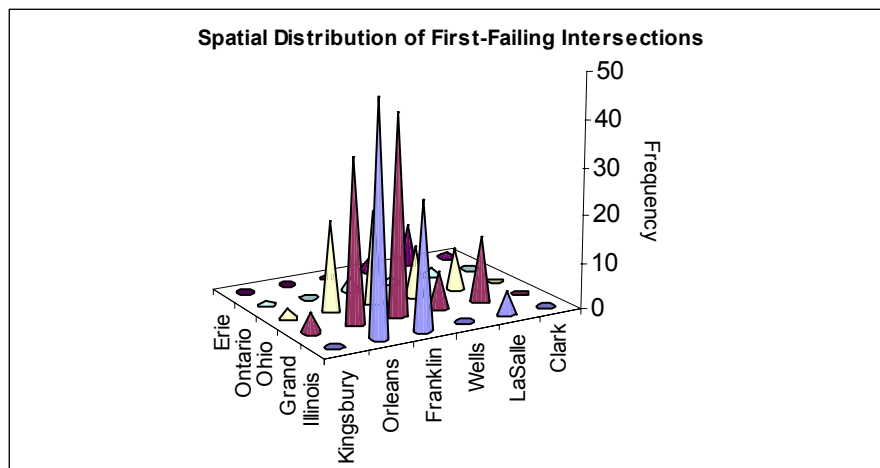


Figure 5.8 Distribution of First-Failing Intersections in CORSIM 5.1 Simulation

Visual scrutiny of animation files showed that in the problem area, the left-turn traffic tended to be obstructed by its heavy opposing through traffic. The obstructed vehicles filled the left-turn bay and blocked through vehicles on the street. The oncoming vehicles to the problem area caused queues in that approach and spillback to its upstream links. Finally, a deadlock situation formed. These observations proved that with the current model setting, the simulator has insufficient capabilities in simulating this situation.

5.5 Summary and Discussion

This chapter describes an application of the proposed simulation failure and detection method to the evaluation of simulators. This was conducted by applying three different releases of CORSIM to the same input dataset, and executing a side-by-side comparison of their performance. Since CORSIM 5.1 has a different definition and default value in one important parameter from its predecessors, the CORSIM 4.32/5.0 defaults were then coded for the three releases to form a consistent comparison.

In the study, CORSIM 4.32 and 5.0 generated close outputs in their traffic performance, although CORSIM 5.0 generated a slightly higher level of SQT and a higher chance of simulation failures. By contrast, CORSIM 5.1 displayed a much higher level of network congestion and a much higher probability of failure runs. Thus, for the test dataset, the upgrading from CORSIM 4.32 to 5.0 had no momentous impact on the network traffic performance, while the upgrading from CORSIM 5.0 to 5.1 had a significantly negative effect on both traffic performance and simulation failure probabilities.

The applications results of failure analysis indicated that different occurrence patterns in the three CORSIM releases. In versions 4.32 and 5.0, the problem area concentrates along a two-lane two-way minor street, while in version 5.1, it is shown that showed that the problem area is a major street that is characterized by a high percentage of left-turn traffic off the street and heavy opposing through traffic along the corridor.

The extremely high failure probability in CORSIM 5.1 raised concern about its validity. This is due to the fact that CORSIM 4.32/5.0 defaults were coded in the simulation. Actually, CORSIM 5.1 has adopted much lower default values as well as it changed the

definition of spillback probability probabilities. This new data set was used to constitute a base case study for the evaluation of the Chicago PM peak network in Chapter 6. It is shown that the new model generated a much lower level of congestion and reduced the failure probabilities by more than half (from 84% to 38%). These are discussed in the next chapter.

CHAPTER 6: EVALUATION OF CHICAGO PM PEAK NETWORK

The first network evaluation study applies the proposed failure detection and analysis method to the Chicago PM test network, using the simulator CORSIM 5.1 described in Chapter 5. The failure detection procedure was applied immediately after the stage of model construction using minimal input and simulator default values for all model parameters. This application serves as a pre-calibration effort to identify simulation failures associated with an un-calibrated model. Subsequently, a causal analysis was performed along with a sensitivity test to identify and evaluate the critical traffic behavioral parameters that contribute to failures. The final goal was to derive an improved simulation model that had a low probability of yielding simulation failures.

6.1 Network Description and Study Design

Network Description

The test network has already been introduced in Chapter 5. It is a surface street sub-network in the city of Chicago, Illinois. It is comprised of 56 surface street segments, two freeway segments, 24 signalized intersections, and eight un-signalized intersections. It represents a typical urban traffic environment. The simulation used input data obtained on Thursday, May 25, 2000, from 17:00 to 18:00 PM, a typical weekday peak period. Medium to high traffic volumes of about 13,000 vehicles entered the study network during the time period, causing traffic congestion at a local level on some key links. The link-node map of the study network is depicted in Figure 6.1.

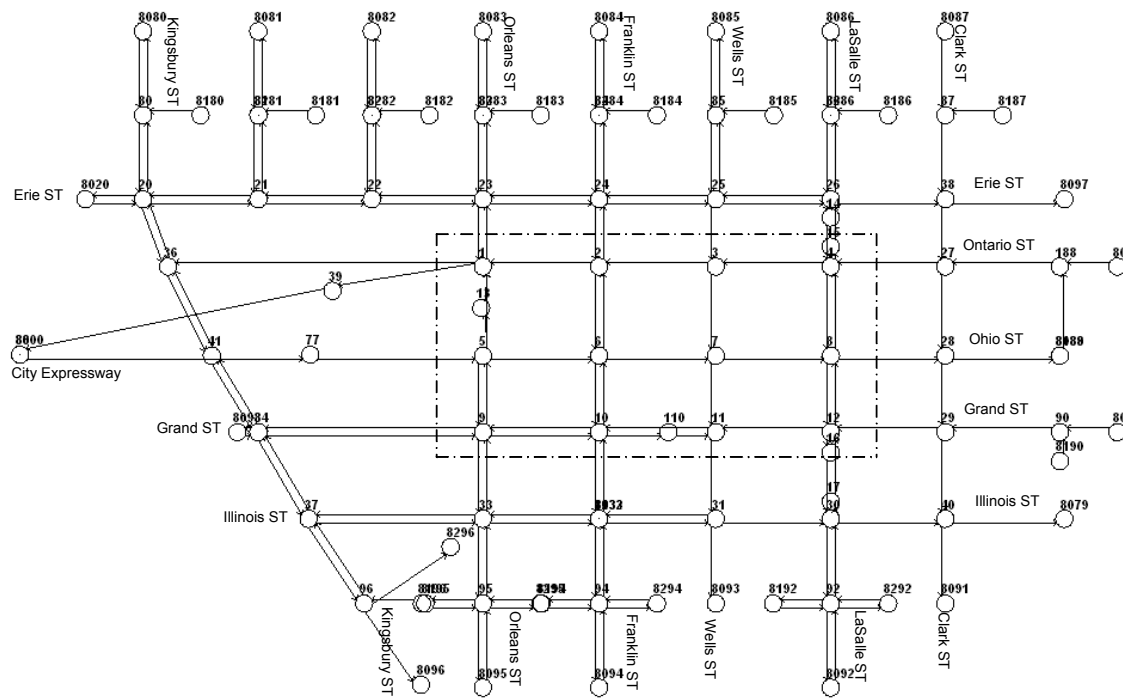


Figure 6.1 Link-Node Map of the Chicago Simulation Network

During the data collection stage, traffic counts for entry volumes and turning movements were obtained manually at many intersections and from video at central intersections (in the inner network defined by the dotted lines in Figure 6.1). Specification of the network geometry and traffic control was made from documents obtained from the Chicago Department of Transportation (CDOT) and verified through field observations. Details of the data collection efforts are discussed in Sacks, et al. (2002).

It was noted during the field observation that while the network was somewhat congested, there were no occurrences of traffic gridlocks during the entire hour. Thus, any simulation failures would not be representative of actual traffic conditions, but rather due to anomalies in the simulator and modeling process themselves.

A sample size of 100 replications was consistently used in the test (see Chapter 5). In order to generate the time series for failure detection and analysis, the one-hour time period was divided into 12 five minute (consecutive) time intervals, so that the time unit of failure studies was five minutes. Since traffic signals in this network operate on a common cycle length of 75 seconds, the simulation outputs in each time interval were aggregated over a period of four signal cycles. In an under-capacity situation, traffic performance for any time interval should be identically and independently distributed, assuming minimal spillback (from neighboring intersections) or leftover (from preceding cycles) queues.

For the base network simulation (described later in Section 6.2), each resulting output file from a single replication uses about 3 MB of space, and the simulation of 100 replications took about two hours (or about 36 seconds per run) in batch-mode on a personal computer (PC) with a Pentium IV 1.8 GHz processor. By contrast, an individual run in normal mode of CORSIM takes about two minutes to execute, and generates a set of animation files that are 100 MB each. Runs under the batch mode produced significant savings in both computer resource and computation time.

Study Design

The case study began with default settings for all traffic behavior parameters. This is a common practice to start a simulation, particularly when users have no previous knowledge of the subject network. Thus, in the initial stage of this study, CORSIM default values for all the traffic behavior parameters were temporarily accepted as being

representative of field conditions. The latest CORSIM release 5.1 is used in all experiments in this and all subsequent chapters.

In summary, the subject network was modeled with field-collected geometry, signal control, traffic demand, and turning probabilities, except that the traffic behavior parameters were set at their default values. This comprises a base network, the analysis of which serves to demonstrate the value of model calibration and can be viewed as a baseline to which subsequent refinement to the model can be compared. The detailed study results of the base network simulation are discussed in Section 6.2.

The immediate objective in the base network study was to mitigate the occurrence of simulation failures. Should they exist, and since many of the model parameters are unobservable in the field, sensitivity tests were performed on selected traffic behavior parameters. These tests help identify those critical factors and therefore improve the validity of the network. The failure mitigation effort through a sensitivity test is described in Section 6.3.

As the conclusion of the sensitivity tests, a set of “ideal” parameter values was identified and these values were then fed back into the simulator for another series of failure detection analysis. The modified model was then contrasted with the baseline network. This will be discussed in Section 6.4.

6.2 Base Network Study

In the base case study, it was expected that the analysis results could identify any coding errors in the process of model development, and to diagnose the current model to indicate

the particular need for further calibration. On the other hand, since the model had not been fully calibrated and validated, the analysis could not be used to make any firm conclusions regarding the network, other than the general capability of the model to represent the field observations (as described in Section 3.3).

Statistical Analysis

During the batch mode simulation running, the analysis procedure collected key network statistics each replication and stored the results into a separate text file. A statistical analysis was then performed to evaluate the distribution of simulation outputs of interest.

A histogram of system queue time (SQT) is shown in Figure 6.2, based on 100 runs of CORSIM simulation. In this figure, most replications exhibit a low level of congestion (i.e., low SQT). However, a few replications yield an unusually large system queue time. These replications result in a skewed distribution of SQT with a number of outliers (the threshold for outliers was determined to be 350 vehicle-hours based on a pilot study of the network and observation of several animation files) on the right tail.

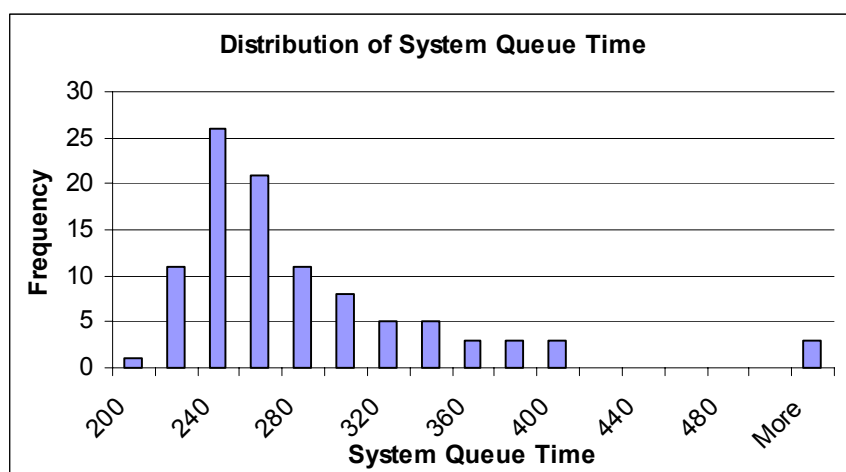


Figure 6.2 Distribution of SQT in the Base Case Simulation

The average system queue time was 274 vehicle hours, the median was 252, and the standard deviation was 88 vehicle hours. The large standard deviation indicated that these outlier replications may not be representative of the observed flow patterns. In order to ascertain whether an outlier run truly represented a simulation failure, the proposed failure detection procedure was applied to the base network.

Failure Detection Results

As stated in Section 3.2, a simulation replication will be deemed as a failure replication when the following three criteria are satisfied: 1) zero link flow on at least one major network link; 2) the detected zero-flow link(s) does not recover in the following simulation interval(s) of simulation; and 3) the detected zero-flow link(s) has vehicles queuing on it.

The simulation results in the base case study were analyzed using the proposed simulation failure detection procedure. The time series inspection and spatial analysis were carried out in the procedure. A partial output of the results is shown in Figure 6.3 below. The figure shows that the failure detection procedure directly reports the status of each replication, the number of links that have failed, and the first time interval in which a link failure has occurred (out of twelve simulation intervals) on the computer screen.

<i>Part II: Network flow detection results:</i>						
Currently analyzing replication number 1...	Replication Failure:	TRUE	# of Failure Links:	1	First Failure Time:	12
Currently analyzing replication number 2...	Replication Failure:	TRUE	# of Failure Links:	15	First Failure Time:	9
Currently analyzing replication number 3...	Replication Failure:	TRUE	# of Failure Links:	6	First Failure Time:	11
Currently analyzing replication number 4...	Replication Failure:	TRUE	# of Failure Links:	12	First Failure Time:	6
Currently analyzing replication number 5...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 6...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 7...	Replication Failure:	TRUE	# of Failure Links:	6	First Failure Time:	11
Currently analyzing replication number 8...	Replication Failure:	TRUE	# of Failure Links:	6	First Failure Time:	9
Currently analyzing replication number 9...	Replication Failure:	TRUE	# of Failure Links:	1	First Failure Time:	12
Currently analyzing replication number 10...	Replication Failure:	TRUE	# of Failure Links:	5	First Failure Time:	11
Currently analyzing replication number 11...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 12...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 13...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 14...	Replication Failure:	TRUE	# of Failure Links:	2	First Failure Time:	12
Currently analyzing replication number 15...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 16...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 17...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 18...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 19...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 20...	Replication Failure:	TRUE	# of Failure Links:	10	First Failure Time:	10
Currently analyzing replication number 21...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 22...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 23...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 24...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 25...	Replication Failure:	TRUE	# of Failure Links:	1	First Failure Time:	12
Currently analyzing replication number 26...	Replication Failure:	TRUE	# of Failure Links:	1	First Failure Time:	12
Currently analyzing replication number 27...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 28...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13
Currently analyzing replication number 29...	Replication Failure:	FALSE	# of Failure Links:	0	First Failure Time:	13

Figure 6.3 Snapshot of Failure Detection Output in the Base Case Study

The results indicated that among the 100 runs, thirty eight contained simulation failures, where one or more links failed to discharge any vehicles for at least one five-minute interval by the end of the simulation. These 38 replications were therefore judged to be invalid for the purpose of estimating traffic performance. The 95% confidence interval for this failure probability is $38 \pm 9.5\%$, or (28.5%, 47.5%). Considering the fact that no gridlock was observed in the field, the failure probability of around 30 to 50% appears to be too large.

For comparison purpose, the SQT distribution is re-plotted with failure and successful runs identified separately on the same graph. These are shown in Figure 6.4. An interesting and somewhat unexpected pattern emerges: while very large SQT are typically associated with failure, some simulation failures occurred even at moderate values of SQT. Consequently, the failure runs appear to spread over a wide range of SQT

from 220 to 500 vehicle hours. This pattern rebuts the validity of strictly excluding “outlier” runs from the simulation. For example, if one would eliminate replications in the highest 10% of SQT, only 6 of the 38 failure runs would be excluded. The proposed failure detection method thus appears to provide the best screening approach for the elimination of unreliable simulation replications.

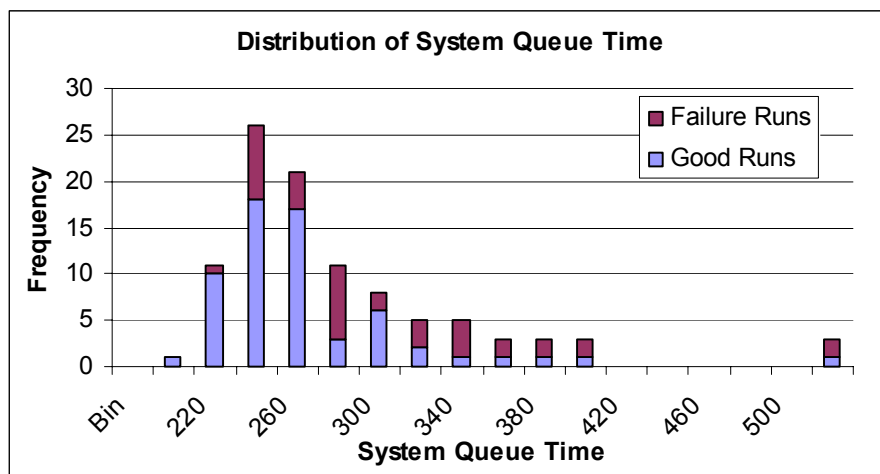


Figure 6.4 Classified Distribution of SQT in the Base Case Study

In summary, the proposed failure detection procedure has identified 38 out of 100 replications as failure runs. The high frequency of failure replications implies that there are still unaccounted factors in the current simulation. Since the base network uses default values for all its traffic behavior parameters, an examination of their impacts is warranted. Prior to that, however, there is a need to conduct a spatial analysis to identify the critical links on the network where simulation failures have initiated. This analysis is described next.

Spatial Analysis Results

A spatial analysis was performed for the base network simulation. The immediate goal was to derive the failure occurrence patterns and to ascertain whether the failure problems were systemic to the entire network, or focused on one or two intersections. The analysis was performed at a link level and a node level. The analysis was performed in parallel with the failure detection procedure.

A series of actions were performed to complete the spatial analysis of the most critical failure-initiating sites. First, the network links (or nodes) were ordered by their first (earliest) failure occurrence time (first time that $LTO^t=0$). Links with the smallest occurrence time were identified as **FFL** (first failing link). At the same time, if a link, says AB, failed in a given replication, then node B is also labeled as a **FFN** (first failing node). For a given link the frequency (in the 100 replications) in which that link appears as a **FFL** is calculated. Each link is associated with such a first failure frequency, **FFF**. Likewise, the **FFF** for each node is derived. Links and nodes with the highest **FFF** are identified as critical (here a threshold value needs to be specified to characterize what “highest” means).

A partial list of the most critical links and nodes (i.e., those resulting in more than 20 percent of all failures) is shown in Tables 6.1 and 6.2. From the tables it is shown that the intersection of Orleans at Grand (Node 9 in Figure 6.1) had the highest number of first failures (25 out of 38), and that most of the failures (19 out of 25) occurred on the southbound approach of the intersection.

First-Failing Link		Network Location	# First Failures	Percentage of Total Failures
A-Node	B-Node			
5	9	Southbound Orleans at Grand	19	50%
9	33	Southbound Orleans at Illinois	14	37%
34	9	Eastbound Grand at Orleans	13	34%
37	34	Northbound Kingsbury at Illinois	9	24%
41	34	Southbound Kingsbury at Illinois	8	21%

Table 6.1 Critical First-Failing Links in the Base Case Study

First-Failing Node	Network Location	# First Failures	Percentage of Total Failures
9	Orleans at Grand	25	66%
33	Orleans at Illinois	18	47%
34	Grand at Orleans	9	24%

Table 6.2 Critical First-Failing Nodes in the Base Case Study

Note that the sum of the number of first failures for all nodes exceeds the total number of failures. This is due to that sometimes multiple links (and therefore nodes) failed in the same time interval. In this case, a failure run reported more than once for the first failing link and node.

These first failing links and nodes were analyzed to investigate the contributing factors to the detected failure occurrence. Since a spatial analysis may identify multiple critical intersections and links at the same time, the spatial relationship between them needs to be studied to consider the spillback effects from one link to the next. In order to do that, we construct a 3-D plot of first failure frequencies of each node on the network map. Figure 6.5 illustrates the spatial analysis results for the baseline network. As the figure shows, the first-failing links appear to be concentrated on the western portion of the network, with the intersection of Orleans at Grand and Illinois (Nodes 9 and 33 in Figure 6.1) figuring prominently as critical intersections. This led us to speculate that a local

calibration of traffic behavior parameters on links connected to these nodes may reduce the occurrence of failures for the entire network.

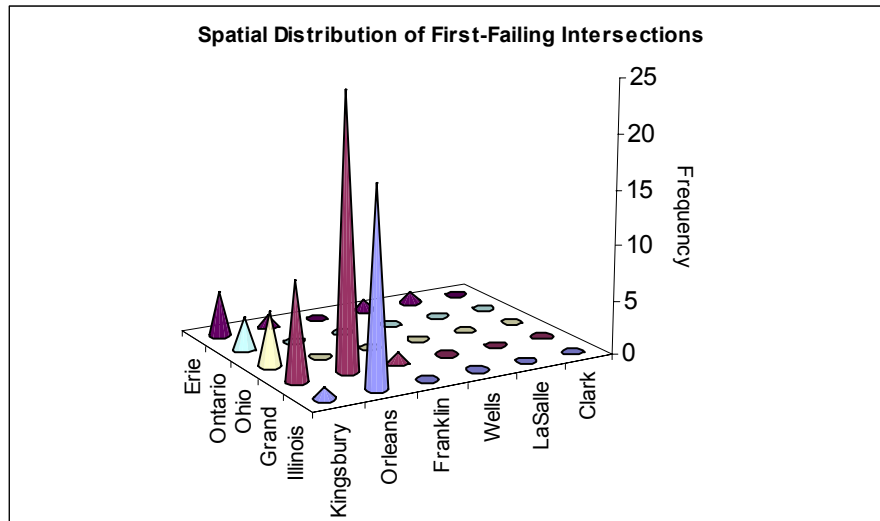


Figure 6.5 Spatial Distribution of First-Failing Nodes in the Base Case Study

Causal Analysis Results

The global pattern of simulation failures (as shown in Figure 6.5) exhibits local-peaking at the intersection of Orleans at Grand. Thus, this intersection was the focal point for further investigation into the contributing factors for those failures.

The entry approaches to the problem intersection were first studied. The spatial analysis results in Table 6.1 indicated that the southbound and eastbound approaches (Links 5=>9 and 34=>9) had large occurrence of failures. It is unlikely that traffic on the links in the opposite directions (i.e., 9=>5 and 9=>34) are contributing to those failures. Further, since the plot in Figure 6.5 shows that there were no failures at the intersection east of Orleans at Grand (i.e., Franklin at Grand), the most plausible cause of simulation failures

was blockage on the southbound downstream approach, which corresponds to the section of Orleans Street from Grand to Illinois (Link 9=>33 in Figure 6.1).

Once the problem area had been identified, further analysis was then necessary to judge the simulation dynamics leading to failures. We first checked the obvious. All the link input data associated with the section of Orleans from Grand to Illinois were checked and rechecked for possible coding errors, and none were found.

The analysis then turned to observation of the animation files, which was always the final and most reliable arbitrator for failure visualization. Only the 38 failure replications needed to be observed in the animation tool. To economize on the number of hours of observation, a random sample of the 38 failure replications was reviewed. These sample replications were rerun under normal (not batch) mode to generate the animation files. Consequently, visual observations showed that indeed the street section of Orleans from Grand to Illinois was actually the most common location where gridlock occurred. This confirms the conclusions in the above analysis.

Further investigation into the dynamics of the failure pointed to a capacity problem in the current model for the street section of Orleans from Grand to Illinois. With a permissive left-turn movement on this southbound approach, left-turn capacity was dependent on the flow of the opposing through traffic (northbound traffic on Orleans). During the evening peak, this opposing flow was significant, therefore yielding few adequate gaps for the southbound permitted left turns. These impeded left-turn vehicles then formed a queue in the left-turn bay which when filled, spilled back onto the through lanes, eventually blocking the link altogether. The spillback from this approach then propagated to

neighboring links, and finally resulted in the occurrence of a simulation failure.

From the above analysis, it is seen that the simulation failures originated in a single link (Link 9=>33 on the network map), and was related to the left-turn gap acceptance process and traffic spillback behavior under severe congestion. In reality, however, field observations indicated that the left turn was able to proceed through the intersection. This pointed to the need to investigate the relevant model parameters that may have erroneously contributed to the occurrence of simulation failures.

6.3 Sensitivity Test for Failure Mitigation

Test Design

The failure detection results in the base case study had indicated that the base case model generated an implausible value of nearly 40 percent failure runs. In addition, the failure analysis results showed that most of the network failures originated at the intersection of Orleans at Grand, and in particular due to the fact that the permissive SB left turn movement lacked adequate capacity. Thus, the analysis of mitigation factor began by looking into traffic parameters for the permissive left-turn vehicle behavioral models. In addition, since there was apparently spillback between intersections, which led to simulation failures in a short time, parameters regulating congestion behavior were also investigated.

The choice of test parameters considered three aspects. First, in CORSIM, left-turn behavior is governed jointly by several parameters including the left-turn critical gaps, the left-turn jumper probability, and the left-turn lagger probability. The length of left-

turn critical gaps was not considered since the animation showed that the key problems occurred at the beginning and the end of green time. Second, the key behavioral parameter regarding traffic congestion behavior is the vector of spillback probability. Finally, some of the most common calibration parameters for a signalized network such as queue discharge headway and start-up lost time, which are known to have a strong effect on approach capacity, were also included in the network tuning.

In all, seven specific traffic parameters were considered for a sensitivity study. These are:

- vehicle start-up lost time (SLT),
- vehicle queue discharge headway (QDH),
- probability that the first and second vehicles in queue will join a downstream traffic spillback (SbPr1, SbPr2),
- left-turn lagger probability for the first and second vehicles in queue (LlPr1, LlPr2), and
- left-turn jumper probability (LjPr).

Detailed definitions of these parameters are provided in Table 6.3.

Variable		Definition
Dependent Variables	FIPr	Probability of failures, equal to # FLs/100.
Independent Variables	QDH	Mean queue discharge headway, in tenths of seconds, denotes the mean time gap (headway) between vehicles discharging from a standing queue is entered.
	SLT	Mean value of start-up lost time, in tenths of seconds, is the delay experienced by the first vehicle in queue when responding to a phase change from red to green..
	SbPr1	The probability of a vehicle becoming the first vehicle in spillback
	SbPr2	The probability of a vehicle becoming the second vehicle in spillback
	LIPr1	The left-turn lagging probability if the left-turner is at the stop line within 2 seconds after the start of the NO GO interval
	LIPr2	The left-turn lagging probability if the left-turner is at the stop line within 4 seconds after the start of the NO GO interval
	LjPr	The probability of a lead left-turn vehicle jumping at the beginning of the green phase across the number of oncoming lanes

Table 6.3 Key Behavioral Parameters Chosen for Failure Mitigation Study

Some of the sensitivity parameters shown in Table 6.3 can vary from link-to-link (locally), or have a single, global default value for all network links (globally). Among them, start-up lost time and queue discharge headway are link-specific parameters, which can be adjusted either at a link level or at the network level, while the other five parameters are global parameters that can only be adjusted at the network level. Thus, a local parameter test was performed to test the two local parameters on the problem link (9=>33) that was identified in the failure analysis in Section 6.2, followed by a global-variation test of the other five parameters.

The Statistical Analysis System (SAS) software package (SAS Inc.) was used to perform a regression analysis of the simulation results. The dependent variable was chosen to be the percentage of replication failures, and the independent variables were chosen as the seven traffic parameters depicted in Table 6.3.

SLTxQDH Design

We first treat SLT and QDH at the problem link (Link 9=>33 on the network map) by fixing the other parameters at their default values. The default value for SLT is 2.0

seconds, and the allowable range is (0, 4.0). From a traffic engineering perspective, we chose these test values {1.4, 1.6, 1.8, 2.0, 2.2, 2.4} for the SLT in this study. Likewise, the default value for QDH is 1.8 seconds, the allowable range is (0, 3.5), and the values {1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2} were chosen as the test points.

CORSIM does not have any restrictions to reflect the correlation between SLT and QDH. However, from a traffic engineering perspective, these two parameters are typically related. Primarily, the queue discharge headway reflects the roadway capacity, which is mostly governed by the physical properties of that roadway; start up lost time reflects the driver reaction time to a signal, therefore it is mostly governed by driver response time and aggressiveness. However, as a common sense, a population of aggressive drivers will tend to have smaller values of SLT and shorter QDH, and vice versa.

In consideration of this correlation, those inconsistent pairs of possibilities for QDH and SLT are seen as impractical and excluded from the test. A rough criterion is set to be that the difference between QDH and SLT cannot exceed 0.6 seconds. As a result, 32 pairs of (SLT, QDH) are tested. The resulting two dimensional projection of the design is shown in Table 6.4.

QDH	SLT	QDH	SLT	QDH	SLT
1.4	1.6	1.4	1.6	1.4	1.6
1.6	1.7	1.6	1.7	1.6	1.7
1.8	1.8	1.8	1.8	1.8	1.8
2	1.9	2	1.9	2	1.9
2.2	2	2.2	2	2.2	2
2.4	2.1	2.4	2.1	2.4	2.1
	2.2		2.2		2.2

QDH	SLT	QDH	SLT	QDH	SLT
1.4	1.6	1.4	1.6	1.4	1.6
1.6	1.7	1.6	1.7	1.6	1.7
1.8	1.8	1.8	1.8	1.8	1.8
2	1.9	2	1.9	2	1.9
2.2	2	2.2	2	2.2	2
2.4	2.1	2.4	2.1	2.4	2.1
	2.2		2.2		2.2

Table 6.4 Two Dimensional Projection of the SLTxQDH Design

The effective pairs are marked by grey cells in Table 6.4. For each choice of SLT and QDH we used 100 replicate runs of CORSIM. The primary output in this test is the proportion of failures, denoted by FIProb. Based on 100 test runs of CORSIM, we derived the failure probabilities for the 32 sets of experiments. The results are labeled in the third column in Table 6.5. The shaded row denotes the case when default parameter values are used.

Test Parameters		FIProb Outputs	
QDH	SLT	Simulation	Regression
1.4	1.6	0.150	0.159
1.4	1.7	0.170	0.211
1.4	1.8	0.290	0.263
1.4	1.9	0.270	0.315
1.6	1.6	0.200	0.186
1.6	1.7	0.270	0.238
1.6	1.8	0.360	0.290
1.6	1.9	0.360	0.342
1.6	2.0	0.400	0.394
1.6	2.1	0.430	0.446
1.8	1.6	0.150	0.213
1.8	1.7	0.190	0.265
1.8	1.8	0.250	0.317
1.8	1.9	0.430	0.369
1.8	2.0	0.360	0.421
1.8	2.1	0.560	0.474
1.8	2.2	0.500	0.526
2.0	1.6	0.340	0.240
2.0	1.7	0.250	0.292
2.0	1.8	0.320	0.344
2.0	1.9	0.450	0.397
2.0	2.0	0.490	0.449
2.0	2.1	0.500	0.501
2.0	2.2	0.590	0.553
2.2	1.7	0.300	0.319
2.2	1.8	0.340	0.372
2.2	1.9	0.450	0.424
2.2	2.0	0.480	0.476
2.2	2.1	0.600	0.528
2.2	2.2	0.480	0.580
2.4	1.9	0.530	0.451
2.4	2.0	0.430	0.503
2.4	2.1	0.580	0.555
2.4	2.2	0.550	0.607

Table 6.5 Experimental and Regression Results in Local Parameter Studies

It is noted from this table that the resulting failure probabilities range from 15 percent to 60 percent. The wide range proves that the test variables, *QDH* and *SLT*, are significant in the occurrence of simulation failures.

A regression analysis on the above results was performed using the SAS program. The

model entered SLT, QDH, SLT², QDH², and SLT*QDH as the test variables, and used a stepwise regression to identify their significance and the coefficient estimates. The regression results are shown in Table 6.6.

Summary of Stepwise Selection							
Step	Variable Entered	Variable Removed	Number Vars In	Partial R-Square	Model R-Square	C (p)	F Value Pr > F
1	SLT		1	0.7604	0.7604	16.5537	101.54 <.0001
2	QDH		2	0.0846	0.8449	2.1220	16.91 0.0003

Resulting Model							
Variable	Parameter Estimate	Standard Error	Type III SS	F Value	Pr > F		
Intercept	-0.86570	0.09687	0.23709	79.87	<.0001		
QDH	0.13582	0.03303	0.05020	16.91	0.0003		
SLT	0.52136	0.05366	0.28026	94.41	<.0001		

Model				
Variable	Tolerance	R-Square	F Value	Pr > F
SltSq	0.002154	0.8490	0.81	0.3754
CrsPrd	0.004225	0.8490	0.81	0.3759

Table 6.6 SAS Analysis Results in the Local Parameter Test

As the table shows, both SLT and QDH are significant in the determination of failure probabilities. Among the two SLT shows a higher level of sensitivity.

Based on the derived coefficients in the regression analysis, a prediction function was derived to reflect the relationship between the failure probabilities and the variation of queue discharge headway and start-up lost time at the problem link.

$$FIProb = -0.86570 + 0.13582 * QDH + 0.52136 * SLT$$

The positive coefficients denote that smaller values of QDH and SLT reduce the chance of simulation failures in the base network simulation. However, these must also be consistent with traffic engineering principles. For example, a QDH of 1.4 seconds corresponds to a saturation flow rate of 2571 vehicles per hour, which would be very rare to observe at a signalized intersection on an urban street network. Although it is acceptable in simulation, the adoption of such low values often compromises the credibility of the simulation.

Finally, in consideration of the characteristic of the subject network, values of (1.7, 1.8) were used for QDH and SLT, respectively. These values are lower than the model defaults (1.8, 2.0), but still seen as acceptable from a traffic engineering perspective. This adjustment is consistent with the aggressive driver characteristics of a commuter traffic network in a large urban area. The solution also coincides with the field measurement at some key locations on the same network (Lin, 2004).

For this vector of parameter values, the prediction function yielded a failure probability of 0.304. This is a slight improvement from the failure probability with model defaults, which is 0.421 in regression and 0.360 in simulation test (Table 6.5 value, slightly different from 0.38 in the base case test). However, the failure probability is obviously still too high considering that no breakdown was observed in the field. Thus, the adjustment of SLT and QDH alone cannot fully account for the occurrence of unexpected simulation failures. Further analyses are then needed to test other candidate traffic behavioral parameters, as described in the next section.

Other Traffic Behavioral Parameters

The test of other traffic behavioral parameters utilized the results of the test of SLT and QDH. That is, it fixed the local values of SLT and QDH on the subject link while varying other candidate traffic behavioral parameters at the network level. The parameters considered in this test are (a) spillback probabilities for the first and second vehicles in queue (SbPr1, SbPr2), (b) the left-turn lagger probabilities for the first and second vehicles in queue (LlPr1, LlPr2), and (c) a left-turn jumper probability (LjPr).

CORSIM allows all of the test parameters to vary from 0 to 100 percent. And there is no specification to regulate the correlations between the parameters. However, from a traffic engineering perspective, one would expect some correlation between SbPr1 and SbPr2 and between LlPr1 and LlPr2. In this test we specified higher test ranges for SbPr1 and LlPr1 and lower test ranges of SbPr2 and LlPr2. As for the left-turn jumper probability, it was reported that the default value of 0.38 for LJ in CORSIM is already too high for realistic traffic situations (Rouphail, et al., 2003). Thus, we limited the range of LJ to [0, 0.38]. The decision of these ranges is mostly based upon expert knowledge about the network and the CORSIM simulator. No guidance exists in the CORSIM User Manual on how these parameters should be calibrated. The test values for the five parameters are 0.05 for SbPr1, 0.1 for SbPr2, LlPr1 and LlPr2, and 0.08 for LjPr. The resulting test parameter sets are shown in Table 6.7.

Parameter	Default	Test Range	Possible Values
SbPr1	0.80	[0.70, 0.90]	{0.70,0.75,0.80,0.85,0.90}
SbPr2	0.40	[0.20, 0.60]	{0.20,0.30,0.40,0.50,0.60}
LIPr1	0.50	[0.50, 0.90]	{0.50,0.60,0.70,0.80,0.90}
LIPr2	0.15	[0.05, 0.45]	{0.05,0.15,0.25,0.35,0.45}
LjPr	0.38	[0.00, 0.38]	{0.00,0.08,0.16,0.24,0.32,0.38}

Table 6.7 Design Values in the Test of Global Variation Parameters

As the table shows, there are many possibilities for each test parameter. Thus, the overall test space is too large for a full factorial design (3750 combinations per replication). To overcome this problem, a Latin Hypercube Sampling (LHS) design is used to economize on the number of runs needed. Latin-Hypercube Sampling design (e.g. Kollig & Keller, 2002) is a space filling design method that is used to spread the points as evenly as possible around the operating space. The output of LHS are sets of design points that, for an N point design, project onto N (typically equally spaced) different levels for each factor.

The design used was a 30 pt Latin Hypercube to generate the sample values for the five test variables. For each design settings, 100 replicate runs of CORSIM were made and the observed proportions of failures are recorded in Table 6.8.

Obs	Test Parameters					Output FlPr	
	SbPr1	SbPr2	LlPr1	LlPr2	LjPr	Simulation	Regression
1	0.70	0.40	0.80	0.45	0.32	0.07	0.12
2	0.75	0.50	0.50	0.45	0.00	0.46	0.39
3	0.90	0.20	0.90	0.05	0.32	0.37	0.37
4	0.85	0.60	0.70	0.45	0.38	0.43	0.39
5	0.75	0.30	0.70	0.15	0.16	0.23	0.25
6	0.70	0.30	0.50	0.25	0.32	0.09	0.09
7	0.70	0.50	0.80	0.15	0.38	0.14	0.12
8	0.80	0.20	0.80	0.25	0.08	0.34	0.34
9	0.75	0.60	0.60	0.25	0.16	0.39	0.34
10	0.70	0.20	0.70	0.35	0.24	0.09	0.10
11	0.75	0.20	0.80	0.25	0.08	0.27	0.26
12	0.90	0.40	0.90	0.05	0.00	0.54	0.60
13	0.75	0.40	0.90	0.25	0.24	0.16	0.24
14	0.80	0.50	0.70	0.05	0.16	0.37	0.39
15	0.90	0.60	0.80	0.35	0.16	0.60	0.58
16	0.85	0.30	0.50	0.15	0.24	0.36	0.36
17	0.80	0.20	0.60	0.45	0.00	0.28	0.38
18	0.80	0.40	0.60	0.35	0.38	0.15	0.24
19	0.85	0.20	0.60	0.15	0.38	0.24	0.26
20	0.70	0.30	0.70	0.05	0.08	0.25	0.21
21	0.85	0.30	0.50	0.35	0.00	0.58	0.49
22	0.90	0.40	0.80	0.15	0.00	0.64	0.60
23	0.90	0.60	0.60	0.45	0.32	0.44	0.49
24	0.80	0.60	0.90	0.35	0.08	0.40	0.46
25	0.80	0.50	0.60	0.05	0.24	0.35	0.35
26	0.90	0.50	0.50	0.35	0.24	0.45	0.50
27	0.85	0.50	0.90	0.25	0.38	0.42	0.35
28	0.75	0.40	0.70	0.05	0.32	0.36	0.20
29	0.70	0.60	0.50	0.15	0.08	0.24	0.31
30	0.85	0.30	0.90	0.45	0.16	0.47	0.40

Table 6.8 Experimental and Regression Results in the Global Parameter Test

A stepwise regression using SAS was performed on these data. It considered the five test parameters without including the interactions terms. The results are shown in Table 6.9.

Summary of Stepwise Selection

Step	Variable Entered	Variable Removed	Number Vars In	Partial R-Square	Model R-Square	C(p)	F Value	Pr > F
1	SbPr1		1	0.5944	0.5944	40.8296	41.04	<.0001
2	LjPr		2	0.1735	0.7679	14.2418	20.18	0.0001
3	SbPr2		3	0.0831	0.8511	2.5414	14.51	0.0008

Resulting Model

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-0.92949	0.13293	0.19239	48.89	<.0001
SbPr1	1.55668	0.16294	0.35918	91.28	<.0001
SbPr2	0.31202	0.08190	0.05712	14.51	0.0008
LjPr	-0.51523	0.08744	0.13663	34.72	<.0001

Variable	Tolerance	R-Square	F Value	Pr > F
LlPr1	0.969225	0.8512	0.02	0.8927
LlPr2	0.974496	0.8543	0.56	0.4607

Table 6.9 SAS Analysis Results in the Global Parameter Test

Among the five test parameters, SbPr1, SbPr2, and LJ are the only significant variables that have important impacts on the determination of failure probabilities. It was actually surprising to note that the left-turn lagger probability did not enter the final solution set. However, this can be partly explained by the fact that the actual values of LIPr are governed by the setting of SbPr.

With the coefficients from the above analysis, the resulting prediction function is summarized below.

$$FlProb = -0.92949 + 1.55668 * SbPr1 + 0.31202 * SbPr2 - 0.51523 * LjPr$$

Clearly higher values of spillback probability lead to a larger chance of failures. This is because a larger probability of joining spillback increases the choice of vehicle lock-up in the intersection area. On the other hand, a larger left-turn jumper probability can help increase the capacity of a left turn movement, thus helps to ease the problem in this network. Thus, their boundary values should be used to mitigate the occurrence of unexpected failures. It should be noted, however, lower values of spillback probabilities may decrease the number of vehicles discharging from a link. As for left-turn jumpers, the adoption of an unrealistically high value would be inconsistent with observed driver behavior. Thus, caution should be paid in the final selection of these values.

A final solution set (1.7, 1.8, 0.70, 0.20, 0.38) for the test parameters (QDH, SLT, SbPr1, SbPr2, LjPr) was selected. The regression analysis predicted 3% chance of simulation failures under that scenario, which is a great improvement compared to the default value set of (1.8, 2.0, 0.80, 0.40, 0.38) which generated 38% failures in the base case study. Thus, the failure rate is much reduced but not totally eliminated with the adjustment of the selected parameters alone. Simulation results for the tuned method are discussed in the next section.

6.4 Tuned Case Study

The sensitivity test results had shown that by adjusting some key traffic parameters, the probability of failures could decrease substantially. Thus, the adjusted traffic parameter set was substituted in the case network study to generate an “after” case study, which is referred to as the tuned Chicago PM network.

The parameters adjustments included 1) a change in queue discharge headway from 1.8

seconds to 1.7 seconds at the problem link, 2) a change in the start-up lost time from 2.0 seconds to 1.8 seconds at the problem link, and 3) a reduction in the probability for the first and second vehicles in queue to join a downstream spillback from 80% and 40% percent to 70% and 20%, respectively. The first two adjustments are consistent with traffic engineering principles since commuter traffic in large metropolitan areas may exhibit a high level of aggressiveness in peak traffic conditions. The third change is only meaningful from the CORSIM perspective in the sense that these variables are very hard to calibrate in the field.

The model with adjusted parameters was simulated 100 times. The application of the failure detection procedure indicated that only eight replications still had simulation failures, an 80% drop from the baseline model results of 38 failure runs. Based on the sample, the 95% confidence interval for the failure probability is $8 \pm 5.3\%$, or from 2.7% to 13.3%. The results of the system queue time distribution are plotted in Figure 6.6.

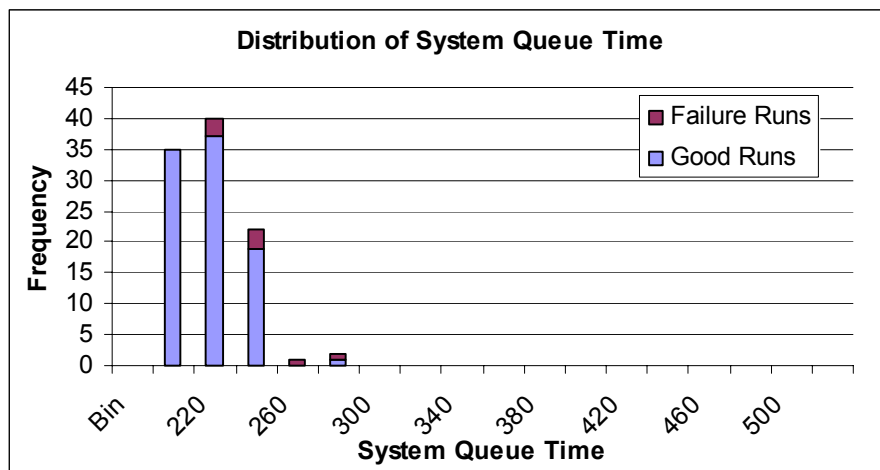


Figure 6.6 Distribution of SQT in Simulation with Adjusted Parameters

It is shown that compared to the distribution of SQT in the baseline network study (as

shown in Figure 6.1), the right tail of SQT is now almost completely removed. In terms of basic statistics, the average system queue time for the “good” runs (denoted by blue bars) is now 208 vehicle hours, a 19% decrease from that in the base case simulation. The median is 207 vehicle hours. The standard deviation is 19 vehicle hours, which is only around one fifth that in the base case0.

Once again, the detected failure replications were analyzed to identify the critical locations and the possible contributing factors to simulation failures. The analysis results are shown in Tables 6.10 and 6.11. It is noted that although the failure probability has dropped from 38 percent to eight percent, the spatial pattern of their occurrence is virtually identical to the base case. That is, the intersection of Orleans at Grand (Node 9) still plays a key role in the initiation of failures, and the problems still concentrated on the northbound and eastbound approaches.

First-Failing Link		Network Location	# First Failures	Percentage of Total Failures
A-Node	B-Nnode			
5	9	Southbound Orleans at Grand	4	50%
34	9	Eastbound Grand at Orleans	4	50%
9	33	Southbound Orleans at Illinois	2	25%
37	33	Eastbound Kingsbury at Orleans	2	25%

Table 6.10 Critical First-Failing Links in the Tuned Case Study

First-Failing Node	Network Location	# First Failures	Percentage of Total Failures
9	Orleans at Grand	6	75%
33	Orleans at Illinois	3	38%

Table 6.11 Critical First-Failing Nodes in the Tuned Case Study

Figure 6.5 shows the spatial pattern of the first failure frequencies for every intersection on the tuned network. By the same reasoning as the base study, we could conclude that

the section of Orleans Street from Grand to Illinois (Link 9=>33) is still the major contributor to the much reduced simulation failures.

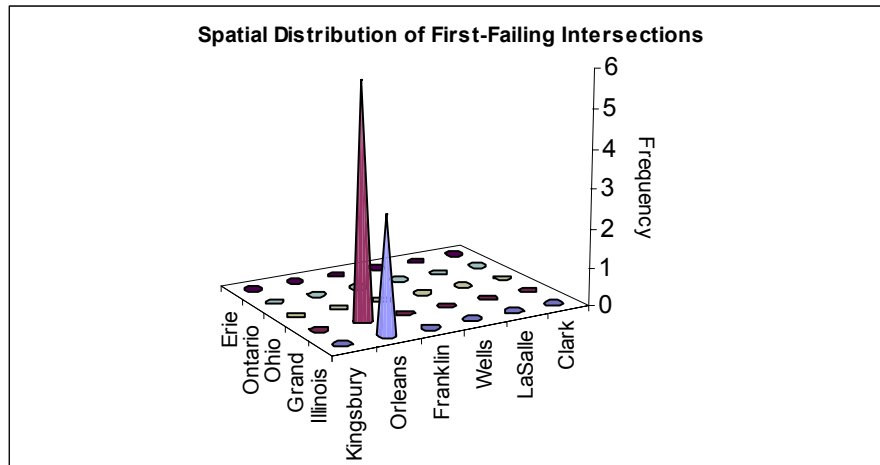


Figure 6.7 Spatial Distribution of FFF on the Tuned Network

The similarity in failure patterns in the base and tuned networks was not surprising since it was reasonable that the contributing factors to simulation failures comprise a series of factors. Although some of them had already been addressed by adjusting traffic behavioral parameters, these adjustments could not completely eradicate the occurrence of simulation failures.

6.5 Summary

The case study of Chicago PM peak network began with the use default values for all traffic behavior parameters. As expected for an un-tuned network, the failure detection results yielded a 38% failure probability, which formed sharp contrast with the observation of no breakdown in the field. Therefore, it was concluded that the modeling process needed to be improved by tuning some key traffic behavior parameters.

The analysis of simulation failures identified critical network sites in the initiation of simulation failures. By attributing the detected simulation failures to a permissive-left-turn movement in a major corridor, it designated several critical traffic parameters for a sensitivity analysis to mitigate the current high probability of simulation failures.

Using a combination of simplified regression models, an adjusted set of traffic behavioral parameters was conceived for this network. The regression analysis predicted that there would be a significant reduction in simulation failures when an adjusted set of parameters was used. The later verification test confirmed the mitigation effect on failure probabilities (38% to 8%), by feeding the solution parameters back into the baseline network.

The failure analysis on the tuned network shows a similar failure occurrence pattern as the base network analysis. The results indicated that although some contributing factors have been already adjusted, the simulation failures cannot be totally eradicated by solely adjusting the selected traffic parameters. This verified that the high probability of simulation failures is very likely to be due to a combination of simulator- and simulation-related factors.

CHAPTER 7: EVALUATION OF CHICAGO AM PEAK NETWORK

This case study is intended to demonstrate the effect of the propose failure detection and analysis method by applying it to the same traffic network under different demand and control conditions. It is focused on the analysis of the AM peak hour for the Chicago network described in Chapters 5 and 6.

7.1 Network Description and Study Design

Network Description

The AM Chicago network is geometrically identical to the PM network. However, the demand distribution over the network has been altered, as depicted in Figure 7.1.

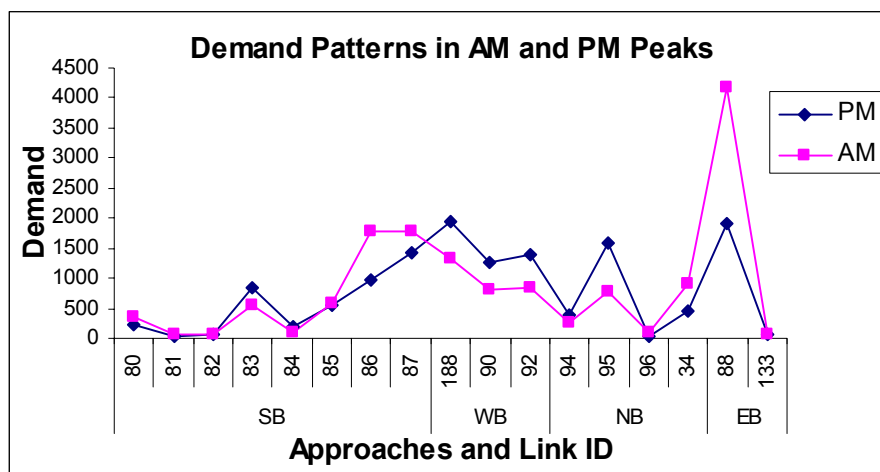


Figure 7.1 Illustration of Demand Changes between AM and PM Periods

It is noted from the above figure that compared to PM, the AM network had more vehicles traveling southbound and eastbound, and fewer vehicles traveling northbound

and westbound. This corresponds to a higher inflow from outside the central business district (CBD), which is located on the south-eastern portion of the network.

In order to adapt to the changing traffic patterns, a different traffic signal control scheme was implemented in the AM peak. Changes in the signal plan were implemented to service the higher AM southbound and eastbound movements. Thus, the AM network described in this chapter is reconstructed based on the PM network, with a modified traffic input demand pattern and a new signal plan.

Case Study Design

Similar to the PM network simulation, the simulation of the AM Chicago network started with an un-tuned network with default traffic behavioral parameters. This initial network served as the base case network for the AM studies. The simulation detection procedure was applied for the diagnosis of simulation failures.

Even though the data indicate that the AM and PM networks had very different traffic demand patterns, it is reasonable to expect that both networks serve the same driver population. Thus, the driver behavioral parameters should be fairly consistent between the two networks. A set of selected traffic parameters has been developed from the PM network studies. These parameter values should be applicable to the AM network, as well. Thus, the base model was reconstructed with the solution parameter set derived from the PM studies in Chapter 6, resulting in a tuned network. The application was intended to assess whether the parameters developed for the PM analysis can be transferable and indeed improve model performance when applied to the AM peak.

It was observed both from the simulation and the field data that the AM network was operating under capacity. This lessens the chance of observing a significant number of simulation failures. To demonstrate the effectiveness of the method, demand volumes were artificially increased via a growth factor, so as to induce simulation failures. When a meaningful sample of failures was obtained for the un-tuned model, the failure detection procedure was re-applied and its validity re-checked.

The analysis for the base demand model is described in Section 7.2 and 7.3, while that pertaining to the increased demands is described in Section 7.4 and 7.5.

7.2 Base Case Study

Similarly, the simulation of the AM Chicago network began with an un-tuned network with default traffic parameters in CORSIM. Since the AM network was geometrically identical to the PM's, the modeling process was completed by modifying the PM network with a new traffic demand pattern and associated signal control plans.

The model was simulated with 100 replications, and the summary statistics for each replication were collected for use in the statistical analysis. The system queue time (SQT) was similarly chosen as the representative traffic MOE. A plot of the system queue time distribution is shown by the solid blue bars in Figure 7.2. The figure shows the distribution is peaked to the left and has a thin right tail. Thus, most replications had a SQT distributed in a narrow band. The average system queue is 182 vehicle hours, the median is 181 vehicle hours, and the standard deviation is 9 vehicle hours.

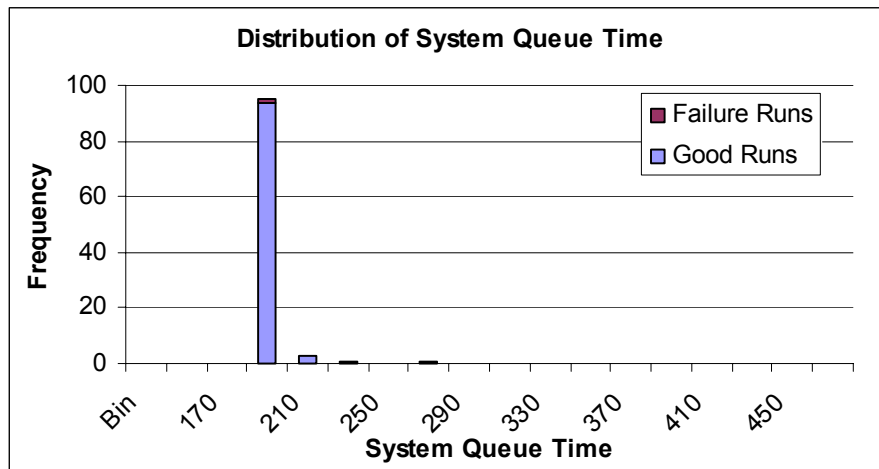


Figure 7.2 Distribution of SQT in the Base Case Simulation

The failure detection procedure was applied to diagnose the validity of each replication. The detection results, as depicted in the above figure by the red bars for failure runs, indicated that only three replications resulted in simulation failures, with two of them distributed on the right tail of the entire distribution (see Figure 7.2). Based on this sample, the 95% confidence interval for the failure probability is $3 \pm 3.3\%$, or (0, 6.3%). The exclusion of these three failure replications made the simulation outputs even more homogeneous between replications. The average system queue time for those good runs only is 180 vehicle hours, and the standard deviation is only 4 vehicle hours.

For the three failure replications, the failure occurrence patterns were analyzed with the proposed spatial analysis procedure. These links and nodes having the earliest failure occurrence are summarized in the following Tables 7.1 and 7.2. The tabular results show that Link 25=>26, which correspond to the section of Erie Street from Wells to LaSalle, experiences capacity problems and lead to simulation failures. However, as the number of

simulation failure observations was small, the current analysis does not yield an adequate sample size from which to derive solid conclusions.

First-Failing Link		Network Location	# First Failures	Percentage of Total Failures
A-Node	B-Node			
85	25	Southbound Wells at Erie	2	67%
25	26	Eastbound Erie at LaSalle	2	67%
2	6	Southbound Franklin at Ohio	1	33%
6	10	Southbound Franklin at Grand	1	33%
32	10	Northbound Franklin at Grand	1	33%
24	25	Eastbound Erie at Wells	1	33%
10	32	Southbound Franklin at Illinois	1	33%
37	33	Eastbound Kingsbury at Orleans	1	33%
24	84	Northbound Frankin Exit	1	33%

Table 7.1 Critical First-Failing Links in the Base Case Study

First-Failing Node	Network Location	# First Failures	Percentage of Total Failures
25	Erie at Wells	2	67%
26	Erie at LaSalle	2	67%
6	Franklin at Ohio	1	33%
10	Franklin at Grand	1	33%
32	Franklin at Illinois	1	33%
33	Orleans at Illinois	1	33%
84	Franklin at Huron	1	33%

Table 7.2 Critical First-Failing Nodes in the Base Case Study

The spatial pattern of failures is plotted in the following Figure 7.2. It exhibits a scattered pattern on the network. This is partly due to the small number of failure observations, which are inadequate to identify the critical sites. Nevertheless, since the Erie, Franklin, and Illinois Streets were all minor streets on the network and susceptible to traffic spillback, the failure occurrence on these links could be possibly due to traffic spillback from upstream links.

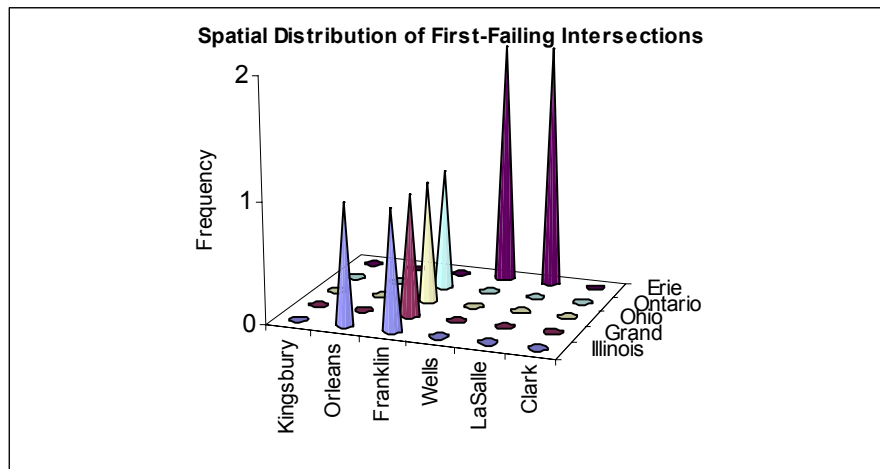


Figure 7.3 Spatial Distribution of the First Failure Frequencies in the Base Case Study

7.3 Tuned Case Study

In the AM period, the majority of traffic was headed south and east to the Chicago CBD; while in the PM a larger portion of traffic was traveling north and west to the expressway away from the CBD (see Figure 7.1). Thus, it was reasonable to assume that both the AM and PM networks serve the same driver population, and that the driver behavioral parameters in CORSIM should be consistent in both peaks.

Subsequently, the base case network was tuned by applying the pre-calibrated driver behavioral parameters from the PM study (see Section 6.4). Specifically, the vehicle mean queue discharge headway was set at 1.7 seconds, the start-up lost time was set at 1.8 seconds, and the spillback probabilities were set at 70% and 20% for the first and second vehicles in queue, respectively.

This tuned model was simulated with 100 replications, and summary statistics for each replication were obtained to perform a statistical analysis. As the selected representative MOE, the distribution of system queue time is plotted in Figure 7.4. The mean, median, and stand deviation of SQT are respectively 173, 173, and 4 vehicle hours.

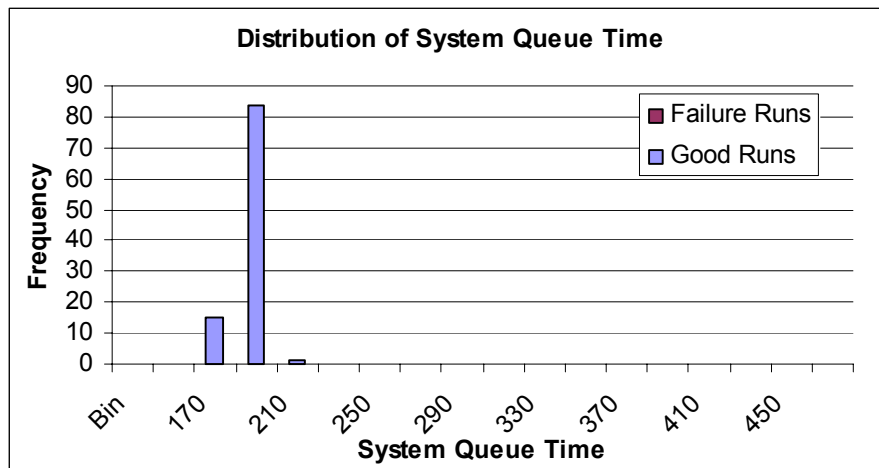


Figure 7.4 Distribution of SQT in the Tuned Case Simulation

The proposed failure detection method was applied to the simulation. It was not surprising to find that even with the same detection method and pre-calibrated thresholds, no failure replications were detected. Thus, the pre-calibrated traffic parameters eliminated all (albeit small number of) simulation failures in the AM simulation network.

The analysis of the input data indicated that the total entry volumes to the AM network were around 14,000 vehicles, while those for the PM were around 13,500 vehicles for PM. Thus, even with a slightly higher level of total demand, the AM network simulation demonstrated a much smaller probability of simulation failures than the PM network.

This observation can be explained by a more even distribution of traffic demand during the AM network. The subject network has only two major corridors for northbound traffic, both of which were two-way streets. By contrast, there were two one-way corridors and two two-way streets for southbound traffic. Since the traffic demand in the AM is characterized by a larger proportion of southbound traffic, it was more easily handled by the prevailing network configuration.

7.4 Test Case Study

Development of Test Case

The previous base case and tuned case studies had shown that the AM network was operating under capacity at the current traffic demand levels. In order to analyze the effect of the high demand-to-capacity ratios on simulation failures, a demand ratio test was performed by applying a uniform demand growth factor for all entering traffic. The intent was to (a) determine the point at which the network breaks down and to (b) obtain a larger sample size of simulation failures over which the detection procedure can be tested. It should be noted that this test assumes unchanged route selection and driver behavior in highly congested conditions. Thus, the turning probabilities and traffic behavioral parameter values in the tests were taken to be identical to the pre-tuned values.

The demand growth factor was applied at intervals of 5%. The test results are illustrated in the following Figure 7.5. It is shown in this figure that with a network demand ratio of 1.05, there are no simulation failures in both base and tuned case studies; when the demand ratio increases to 1.10, 20% of replications are reported as simulation failures in the base case, while no failures are found in the tuned case study. When the demand ratio

increased to 1.15, 85% of the base case runs and 40% of the tuned case runs are found to have simulation failures. When the demand ratio reaches beyond 1.2, all replications for both cases are found to be failure runs.

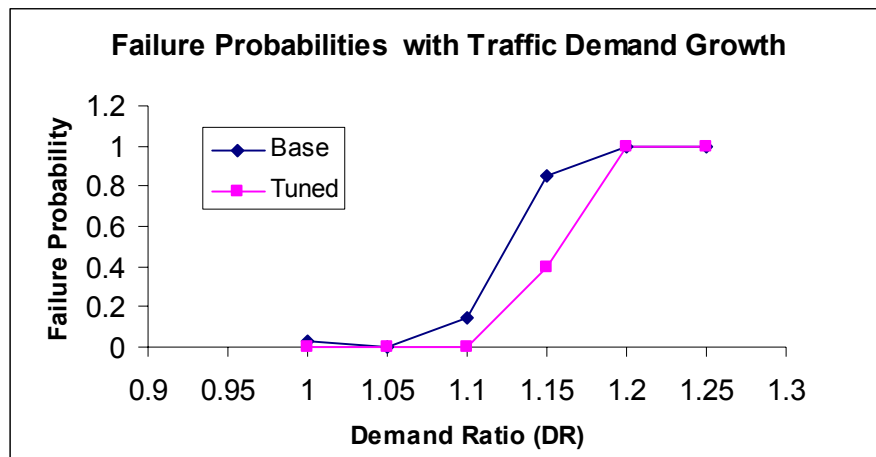


Figure 7.5 Effect of Traffic Demand Growth on Simulation Failures

(DR=1 indicates base demand)

Thus, the demand ratio of 1.15 (which yielded around 40% of failure replications in the tuned case study and 85% failure replications in the base case study) denotes a marginal demand level for potential network breakdown. This ratio was used to construct the test case study. The test case was intended to perform network analysis from a traffic engineering perspective.

Simulation Analysis Results

The test case network was simulated with an expanded sample size of 100 replications, and the simulation outputs were analyzed again using the proposed failure detection and analysis. It was found that 43 replications resulted in failures. The 95% confidence

interval of it is $43 \pm 9.7\%$, or (33.3%, 52.7%). The distribution of system queue time is plotted in Figure 7.6 below, with good runs denoted by blue bars and failure replications by red bars. The mean, median and standard deviation are 343, 299 and 104 vehicle hours, respectively. Obviously the test case has a much increased level of SQT, which reflects the impact of the increased traffic demand on the network.

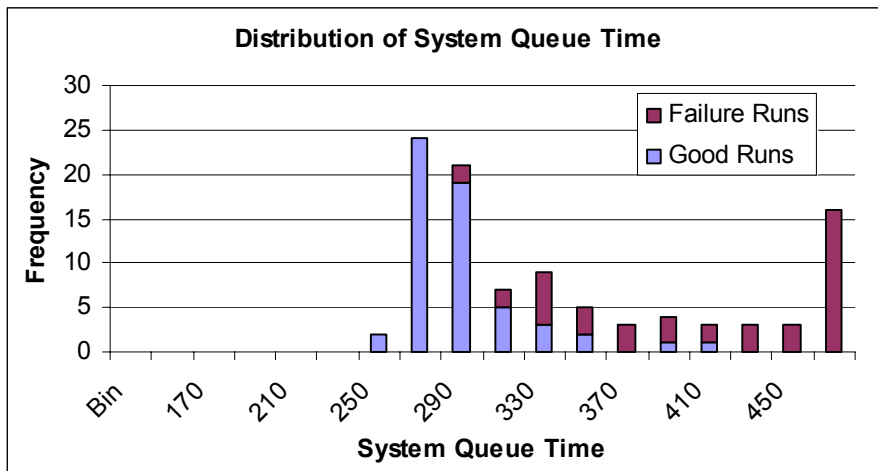


Figure 7.6 Distribution of SQT in the Test Case Simulation

The detected failure replications were analyzed using the proposed analysis procedure. The identified critical first-failure links and nodes are summarized in Tables 7.3 and 7.4, respectively.

First-Failing Link		Network Location	# First Failures	Percentage of Total Failures
A-Node	B-Nnode			
24	25	Eastbound Erie at Wells	22	51%
25	26	Eastbound Erie at LaSalle	22	51%
22	23	Eastbound Erie at Orleans	16	37%
2	24	Northbound Franklin at Erie	16	37%
23	24	Eastbound Erie at Franklin	15	35%
85	25	Southbound Wells at Erie	15	35%
6	2	Northbound Franklin at Ontario	14	33%
10	6	Northbound Franklin at Ohio	12	28%
84	24	Southbound Franklin at Erie	9	21%

Table 7.3 Critical First Failing Links in the Test Case Study

First-Failing Node	Network Location	# First Failures	Percentage of Total Failures
25	Erie at Wells	24	56%
26	Erie at LaSalle	22	51%
24	Erie at Franklin	19	44%
23	Erie at Orleans	16	37%
2	Franklin at Ontario	14	33%
6	Franklin at Ohio	13	30%
10	Franklin at Grank	11	26%

Table 7.4 Critical First Failing Nodes in the Test Case Study

It was found that the simulation failures tended to originate along one minor street on the network, which is Erie Street (comprised of Nodes 23, 24, 25, 26, and 38 in the study area), a two-lane two-way facility. The street has stop sign controls at the intersections of Erie at Franklin (Node 24), Erie at Wells (Node 25), and Erie at Clark (Node 38). Since stop sign controlled intersections have lower capacity when the priority flows are heavy (which is the case for this analysis), it is plausible that this minor street will experience capacity problems with a uniformly increased demand ratio.

To study the relationship between the key intersections, the spatial distribution of first-failure intersections is plotted in the following Figure 7.7. It is shown in the plot that the intersection at Wells and Erie (Node 25) has the highest failure frequency, followed by its neighboring intersections LaSalle at Erie (Node 26) and Franklin at Erie (Node 24), which together form a local peak pattern of failure occurrence. Thus, the most critical location appears to be the intersection of Erie at Wells.

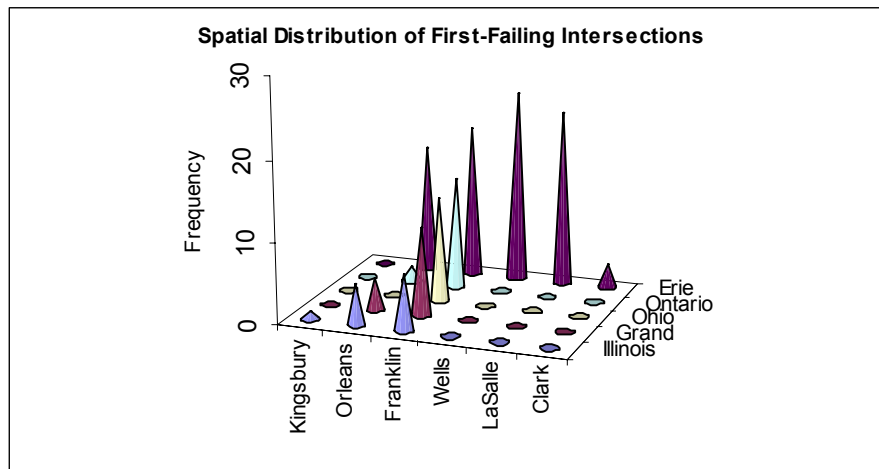


Figure 7.7 Spatial Distribution of the First Failure Frequencies in the Test Case Study

The graphical plot shows that among the three downstream links of the problem intersection (Node 25), the intersection LaSalle at Erie (Node 26) is the destination node that exhibited more simulation failures. Thus, the failure causing location appears to be the section of Erie Street from Wells to LaSalle (Link 25=>26).

Further analyses were performed by viewing the animation files of the detected failure replications. A sample of failure replications was rerun with a normal running mode to generate animation files. Visual observations of these animation files verified the above conclusions regarding the judgment on the decision of critical locations.

The analysis indicated that traffic congestion on the link of Erie from LaSalle to Clark (Link 26=>38 on the network map) initiated simulation failures by causing traffic spillback to the upstream intersection of Erie at LaSalle. Specifically, the problem link was controlled by a stop sign in the field, with the traffic priority given to traffic on Clark Street. When the traffic demand increased, vehicles on Erie formed long waiting queue while yielding to traffic on Clark Street and blocked the access to the problem link. This

blockage formed traffic spillback to the upstream node (26) and upstream links (86=>26, 25=>26, and 4=>26). Among the three upstream links, the Erie Street from Wells to LaSalle (Link 25=>26) was the most vulnerable one in consideration of that it is a two-lane two-way minor street with a fair level of traffic demand. Finally, incoming traffic demand accumulated at the problem link, blocked nearby areas, and formed unrecoverable gridlock in the simulation.

7.5 Supplemental Traffic Improvement Analysis

The above study results have shown that the critical link on the AM network was along Erie Street from LaSalle to Wells, which is vulnerable to the traffic spillback from the stop-sign controlled downstream intersection, Erie at Clark. To address this problem, traffic improvement plans (TIP) can be proposed along two directions: one is to improve the capacity of Erie Street to increase its resistance against traffic spillback, and the other is to improve the performance of the intersection Erie at Clark so as to reduce the chance of traffic spillback.

Among other options, optimizing traffic control at the key intersection is an inexpensive treatment to improve its performance. Thus, we propose a yield control at the problem intersection to replace the original stop sign. The impact of this change is evaluated using the proposed failure detection and analysis procedure, and the case is labeled TIP.

Similarly as previous studies, the TIP case network was simulated with 100 CORSIM replicate runs. The system queue time distribution is plotted in Figure 7.8. The mean, median, and standard deviation are respectively 334, 290, and 124 vehicle hours. The

figures shows that the SQT in the TIP case study has displayed almost the same pattern to that of the test network (see Figure 7.6).

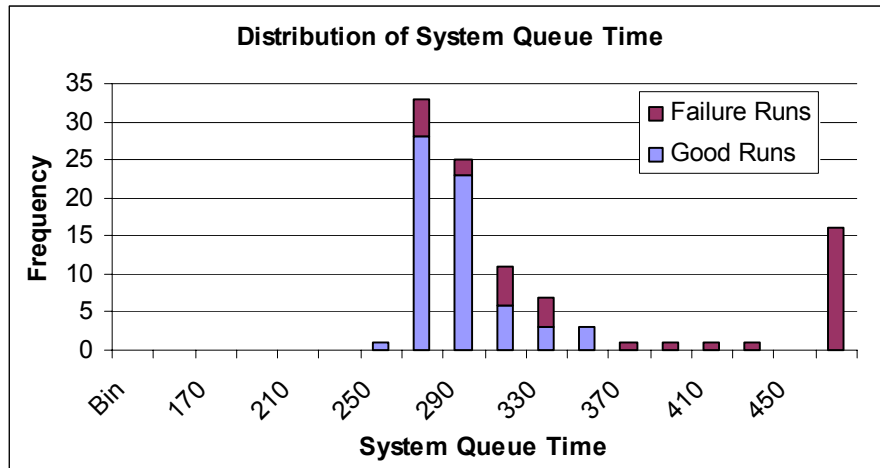


Figure 7.8 Distribution of System Queue Time in the TIP Case Study

The failure detection procedure revealed that 36 among 100 replicate runs were actually failure runs (marked by the red bars in Figure 7.8). Compared to the original network, the sample failure probability has slightly dropped from 43% to 36%. The 95% confidence interval is $36 \pm 9.4\%$, or (26.6%, 47.4%), a little lower than that in the original network.

The failure analysis procedure identified the first-failing sites in the origination of simulation failures. The critical links and intersections are shown in Tables 7.5 and 7.6, respectively.

First-Failing Link		Network Location	# First Failures	Percentage of Total Failures
A-Node	B-Nnode			
25	26	Eastbound Erie at LaSalle	23	64%
24	25	Eastbound Erie at Wells	19	53%
85	25	Southbound Wells at Erie	18	50%

Table 7.5 Critical First Failing Links in the TIP Case Study

First-Failing Node	Network Location	# First Failures	Percentage of Total Failures
26	Erie at LaSalle	23	64%
25	Erie at Wells	20	56%
24	Erie at Franklin	10	28%

Table 7.6 Critical First Failing Links in the TIP Case Study

It is shown in the above tables that the problem intersection is Erie at LaSalle (Node 26), and the problem approach is the eastbound approach of it (25=>26). This is similar to the results in the original network. Further, the spatial distribution of the first-failing intersections is plotted in Figure 7.9.

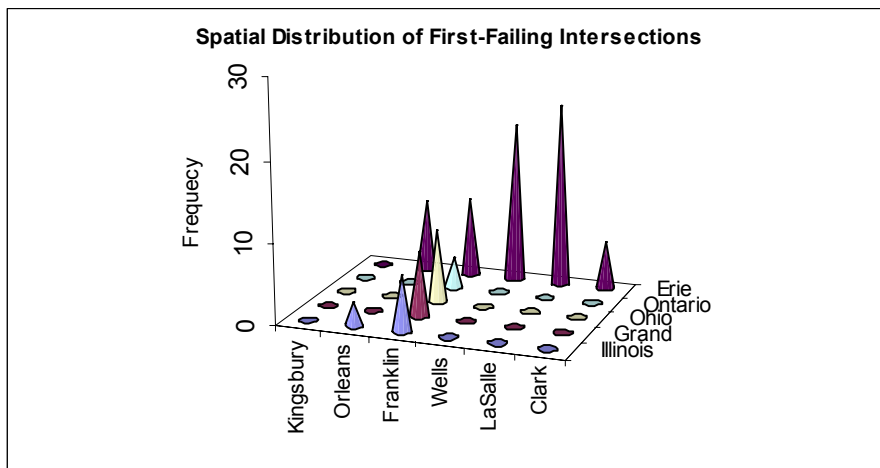


Figure 7.9 Spatial Distribution of the First Failure Frequencies in the TIP Case Study

The spatial pattern in the above figure has almost the same peak at the intersections Erie at Wells and Erie at LaSalle. Also, the supplemental animation observation of these failure runs indicated that the problem still persists in the intersection Erie at Clark, causing traffic spillback to the problem area.

The above analysis indicated that the change of traffic control at the key intersection did not significantly solve the existing problem and reduce the number of simulation failures. Thus, additional traffic improvement plans should be considered to improve the traffic performance on the study network.

7.6 Summary

In the PM network simulation, an un-tuned network was first simulated as the base case study. The failure detection results showed that there was a fairly small chance (3%) of simulation failures occurrence. Although the failure occurrence patterns did show a local tendency of failure origination, the small number of observations did not allow the analyst to make any significant conclusions regarding the simulation process and the subject network.

Since AM and PM were observed to service the same driver population, the pre-calibration results in PM study was used to construct a tuned case model. It was shown that in this tuned network simulation, no failures occurred. This improvement shows that the pre-calibration product from the PM studies was similarly effective in the AM.

A demand ratio test demonstrated that the ratio of 1.15 was likely to result in a marginal traffic breakdown for the tuned traffic network. New demand at this ratio formed a test case study which was intended to investigate the capacity features of the subject network. It was shown that if the traffic assignment pattern was unchanged, the minor street on the north portion of the network was very vulnerable to traffic spillback caused by a stop controlled intersection.

A traffic improvement plan was proposed to change the traffic control at the problem intersection from stop to yield. However, the simulation results indicated that at this capacity level, the proposed adjustment of traffic control alone was not sufficient to solve the existing problem.

It is noted that since the simulation of AM was assumed in a different stage from PM, the failure detection and analysis procedure demonstrated different utilities. In the PM study, the analysis procedure mainly served as a pre-calibration procedure and the detection results were utilized to improve the simulation modeling process. By contrast, in the AM studies, the major purpose was used to analyze the subject network from a traffic engineering perspective, and the final goal was to predict and overcome capacity constraining areas on the study network.

CHAPTER 8: EVALUATION OF NCSU CAMPUS NETWORK

The North Carolina State University (NCSU) Campus is the third network application of the proposed failure detection and analysis procedure. As a typical university transportation environment, the NCSU network has special features in its geometric and traffic demand patterns that are very different from an urban traffic network simulated in the previous chapters. Despite the differences, the proposed failure detection and analysis methodology is as applicable to this network as to the Chicago networks.

8.1 Case Study Description

Network Description

The NCSU network is depicted in Figure 8.1. The network includes 82 major surface street segments and 43 at-grade intersections. Among them 18 intersections are controlled by traffic signals; the rest are controlled by traffic signs and an urban compact roundabout at the east entrance to the campus. The study time period was from 16:30 PM to 18:00 PM on a school day. Around 15,000 vehicles were input from 33 different network entries during the study time period. The campus network was known to experience severe traffic congestion at some critical sites during the peak.

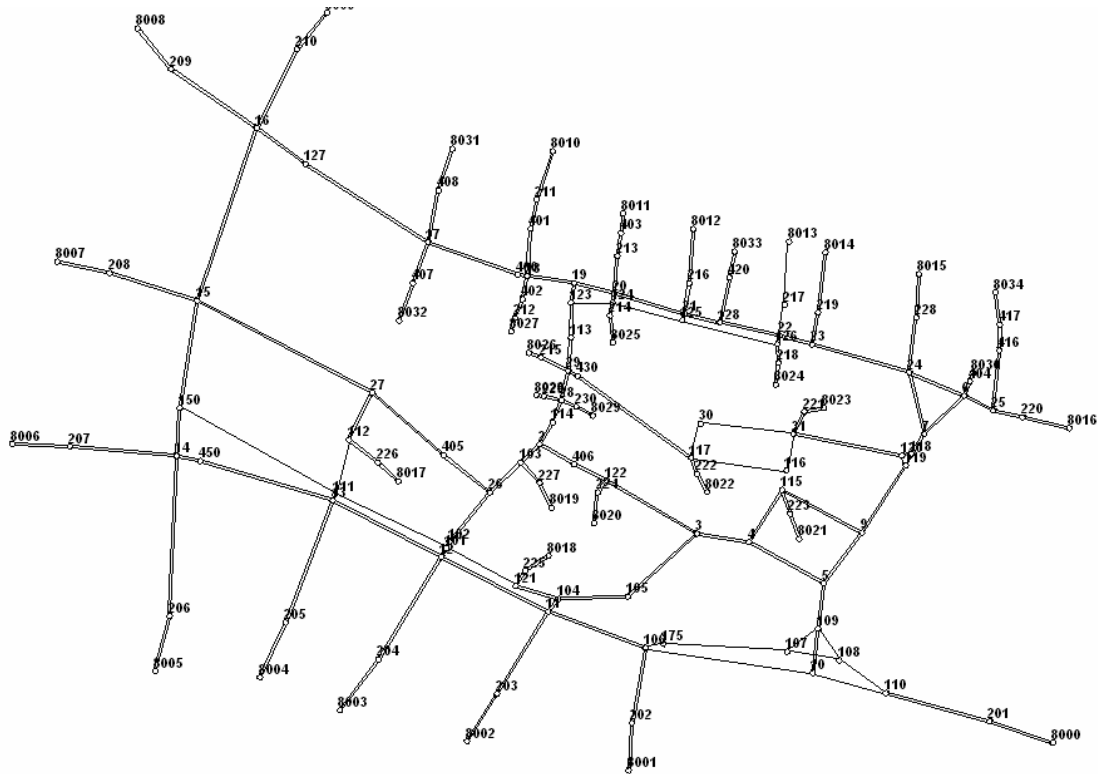


Figure 8.1 Link-Node Map of the NCSU Campus Network

The NCSU network represents a typical university transportation environment. It is characterized by low speed limits enforced by speed humps and the like installed at critical sites, shared paths with transit and non-motorized traffic, and roadside parking. As for traffic control, un-signalized intersections predominate in this network. These features were therefore considered in the CORSIM environment.

While CORSIM can simulate low speeds, it cannot model traffic calming devices (e.g., humps) which then need to be treated by other ways, such as a reduced free flow speed. CORSIM is capable of modeling high volume transit service (buses in particular). However, currently it cannot directly model roadside parking, but perhaps only its effect, on link capacities.

Simulation of pedestrians is a known difficulty for CORSIM (e.g., the Smartest, 1997). While CORSIM can approximate the impacts of pedestrians on conflicting vehicle movements at a signalized intersection, it is unable to simulate details of pedestrian behavior at, for example, sidewalks and crosswalks. This posed difficulty in the modeling of this network because the study period was a peak time for both vehicles and pedestrians. In view of this, dummy intersections sometimes were then coded to account for reduced capacity and increased vehicle delay at the crosswalk sites.

CORSIM is able to simulate conventional un-signalized intersections with a stop or yield sign. However, it has limited capabilities in simulating roundabouts. In the modeling process, the roundabout on the study network was approximated by a group of consecutive curved links and a series of un-signalized T-intersections.

Case Study Design

The NCSU Department of Transportation (NCSU DOT) began developing the campus network simulation in August, 2003. The project included two parts, a transportation planning model and a traffic operation model (Covington, 2003). In the blueprint of the project, the study objectives were to estimate the future travel demand and to identify critical transportation problems. Particularly, it was expected that a CORSIM model could 1) simulate current traffic conditions and find out critical transportation problems, and 2) apply forecasted travel demand from a TransCAD (Transportation Planning Software, Caliper inc.) model, and 3) provide an operational analysis for the prospective relocation of the engineering school in 2006. Our research focuses on the first objective only.

In the CORSIM model development stage, the network geometry was determined by traffic engineers using a GPS device. Part of traffic counts were directly obtained from the North Carolina Department of Transportation (NCDOT), the City of Raleigh Department of Transportation (RDOT), and others were manually collected by NCSU traffic engineers and transportation students. An incomplete model calibration was performed on critical gap parameters in order to match the observed queue length in simulation with the field. This partially-calibrated model was referred to as an initial network to begin our studies in Section 8.2.

The simulation of the initial network was analyzed using the proposed simulation failure detection and analysis procedure. The initial purpose was to debug the current simulation and to provide a more robust model for further analysis. With the identification of some errors in the initial network, the network was reconstructed using the information. This formed the base case network, as described in Section 8.3.

The initial network also benefited from a review by a panel of simulation experts. They provided critiques about the choice of free flow speeds on the network. These comments were again reviewed by the author. As a result, a more consistent set of free flow speeds were applied to the base case network, which constituted an adjusted network in Section 8.4.

The failure detection and analysis procedure indicated that all the above three networks generated an extremely high number of failure replications. Thus, a tuning study was performed on key traffic parameters. It was found that a high circulating speed in the roundabout could ease the problem and reduce the chance of simulation failures.

The analysis of the tuned network in Section 8.5 indicated that simulation failures were eased though still existing at a stop-sign controlled intersection. The problem was finally attributed to the inadequate ability of CORSIM to simulate un-signalized intersections.

8.2 Initial Network Study

The study began with an initial case network. This network was seen as incomplete in the sense that the modeler claimed it as a partially calibrated model, and implied the necessity for further tuning and improvement. The failure detection and analysis procedure was then applied to the network to diagnose the revised model.

One notable feature in the study is that the entire simulation period in this initial network was divided into six fifteen-minute intervals. This is a common unit in traffic engineering analyses (e.g., data collection, output analysis, HCM analysis, etc.). The use of a longer detection unit would possibly yield a lower chance of false alarms (Type I error), but a higher chance of missing failures (Type II error). In order to maintain consistency, the simulation period was redefined as 18 five-minute intervals.

One hundred replications were executed. System queue time was again chosen as the representative MOE. The distribution of system queue time in this study is plotted in Figure 8.2. As the figure shows, the system queue time distribution has a very long right tail. The mean, median, and standard deviation of SQT are 1441, 1490 and 520 vehicle hours, respectively.

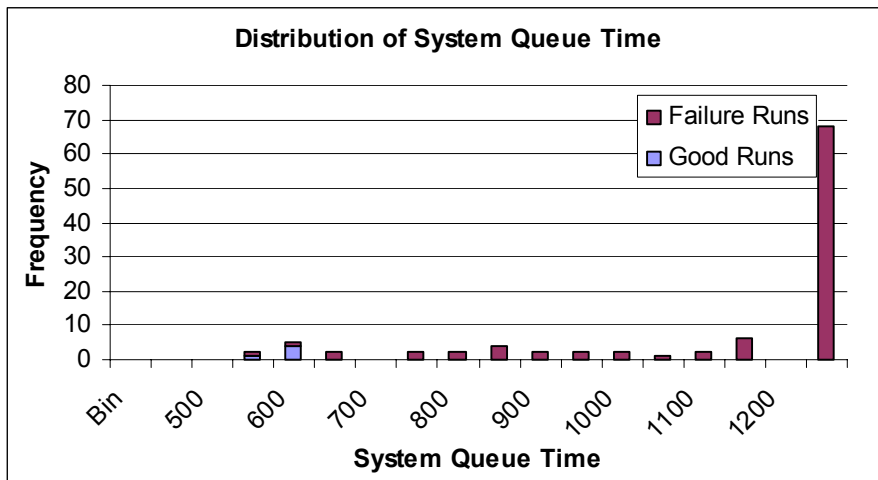


Figure 8.2 Distribution of SQT in the Initial Case Simulation

The failure detection procedure identified 95 failure runs (shown above by the red bars). The 95% confident interval of this resulting failure probability is $95 \pm 4.3\%$, or (90.7%, 99.3%). This was an unexpectedly large number, particularly in light of the long detection time unit in this study. Almost all the right-tail replications are failure runs that contain serious traffic blockage (evidenced by disabled link discharging capacities) for at least 5 minutes by the end of simulation. The detection results highlighted the need to diagnose the current simulation model from the perspective simulation failure detection and analysis.

Since there was a high probability of failure replications, two supplemental response variables, the Number of Final Failure Links (FFL) and the Duration of Failure Time (FT), were added to analyze the degree of failures. For any given replication, The Number of Final Failure Links count the actual number of failure links in the last time interval, while the Duration of Failure Time count the time duration from the first failure interval to the end of simulation. For the initial case study, the average FFL of the 95

failure replications was 63 links, and the average FT was 43 minutes. Both values denoted a high degree of simulation failures occurred in those failure runs.

The failure analysis procedure identified critical links in the simulation. As shown in Tables 8.1 and 8.2, there is a long list of first-failing links and nodes. This is because the long detection interval allows for a great possibility of traffic spillback, so that many locations can be blocked in the same time interval. Nonetheless, the results demonstrate that the most critical site is the roundabout area comprised of Nodes 118, 119, and 120. Table 8.2 shows that among the top five critical nodes, three of them (119, 120, and 118) are the component nodes of the roundabout, and the other two (7 and 9) are its neighboring nodes.

First-Failing Link		Network Location	# First Failures	Percentage of Total Failures
A-Node	B-Node			
9	119	Northbound Pullen at Stinson	85	89%
31	120	Eastbound Stinson at Pullen	84	88%
120	119	Pullen at Stinson Roundabout	83	87%
7	118	Southbound Pullen at Stinson	82	86%
119	118	Pullen at Stinson Roundabout	82	86%
118	120	Pullen at Stinson Roundabout	81	85%
24	7	Eastbound Primrose at Pullen	73	77%
6	7	Southbound Pullen at Primrose	64	67%
5	9	Northbound Pullen at Dunn	58	61%
115	9	Eastbound Dunn at Pullen	53	56%
4	5	Eastbound Cates at Pullen	30	32%

Table 8.1 Critical First-Failing links in the Initial Case Study

First-Failing Node	Network Location	# First Failures	Percentage of Total Failures
119	Pullen at Stinson Roudabout	87	92%
120	Pullen at Stinson Roudabout	85	89%
118	Pullen at Stinson Roudabout	83	87%
7	Pullen at Primrose	73	77%
9	Pullen at Dunn	64	67%
5	Pullen at Cates	35	37%

Table 8.2 Critical First-Failing Nodes in the Initial Case Study

A spatial distribution of the first failing intersections is plotted in Figure 8.3. The brown bar on the right side of the map denotes the location of the problem roundabout.

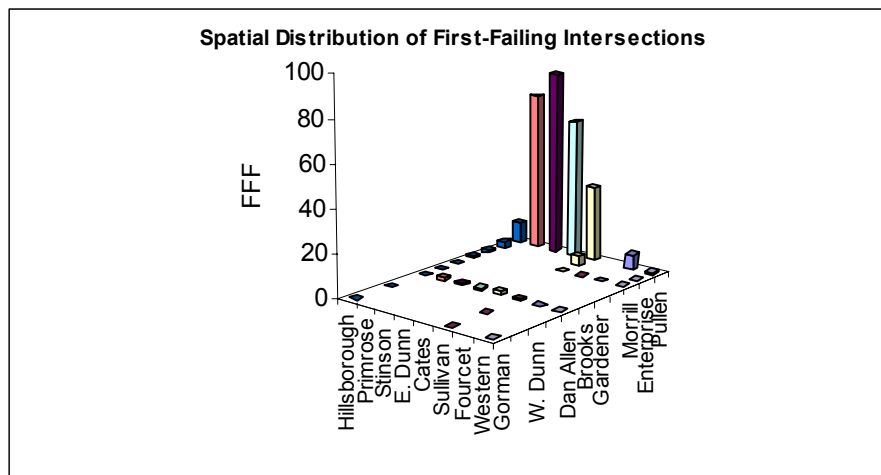


Figure 8.3 Spatial Distribution of the First Failure Frequencies in the Initial Case Study

The analysis was intended to diagnose the current model and guide attempts for further improvements. Once the analysis indicated problems at the roundabout area, the coding of the roundabout was scrutinized. A review of the current coding found that a yield sign at the southbound approach of the roundabout was missing. Also, the animation files showed that the roundabout was poorly approximated by a triangle, and the lane width of the circulating lane was 12 feet.

Another problem noticed was the lane utilization. It was observed that some vehicles utilized wrong lanes in the animation files. Thus, the coding of lane utilization was checked. It was found that although the lane utilization in the first time interval was specified correctly, the following time intervals lacked any specification. Thus, after the first 15 minutes, there were actually no restrictions on the lane usage in the model.

As a correction, the traffic control features at the roundabout were first rectified. The component links were recoded with curved links with an increased lane width of 18 feet. Further, the lane utilization specifications in the first time interval were applied to the entire simulation period. These changes led to a new base network.

To permit failure detection at a more refined level, the simulation time period was re-divided into 18 five-minute time intervals, so that the failure detection unit in the base network study was five minutes. This new detection unit was used for all the thereafter studies in this chapter.

8.3 Base Case Study

The base case network was simulated with 100 replications and the failure detection process was applied thereafter. The resulting system queue time distribution is plotted in Figure 8.4. The mean, median and standard deviation of SQT are 1536, 1450 and 299 vehicle hours, respectively.

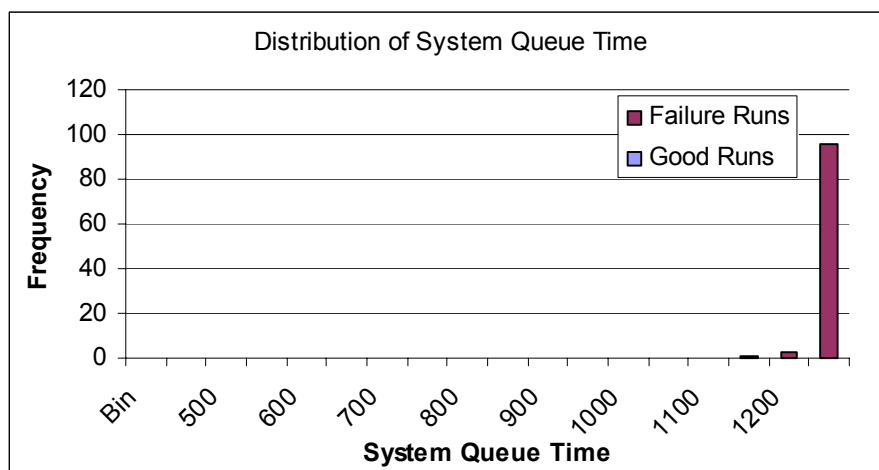


Figure 8.4 Distribution of SQT in the Base Case Simulation

It was surprising to note that again all replications displayed an extremely high SQT and were diagnosed to be failure replications by the proposed failure analysis procedure. This was associated with the debugging changes made to the base network. In the initial model, the lack of lane utilization specifications and traffic control at one approach of the roundabout exaggerated the overall link capacity. The correction of these errors, therefore, resulted in a higher level of traffic congestion.

As for the degree of failure, the average FFL of was 27 links, and the average FT was 24 minutes. They were apparently improved from those in the initial case study.

The failure analysis procedure identified the critical first failing sites in this corrected base model. As shown in Tables 8.3 and 8.4, the failure originating areas seem to have shifted from the roundabout area to other locations, which confirmed the positive effects of the changes made in the coding of the roundabout.

First-Failing Link		Network Location	# First Failures	Percentage of Total Failures
A-Node	B-Nnode			
215	29	Westbound Yarborough at Dan Allen	41	41%
430	29	Dan Allen Deck Exit to Dan Allen	32	32%
227	103	Pay Lot Exit to Dan Allen	28	28%
117	430	Westbound Yarborough at Brooks	23	23%
202	106	Northbound Nazareth at Western	20	20%

Table 8.3 Critical First-Failing Links in the Base Case Study

First-Failing Node	Network Location	# First Failures	Percentage of Total Failures
29	Dan Allen Deck Exit to Dan Allen	51	51%
103	Pay Lot Exit to Dan Allen	28	28%
430	Yarborough at Brooks	23	23%
106	Nazareth At Western	20	20%

Table 8.4 Critical First-Failing Nodes in the Base Case Study

The spatial distribution of the First Failure Frequencies (*FFF*) is plotted in Figure 8.5. As the figure shows, the failures are now concentrated at the intersection of Dan Allen parking deck at Dan Allen Road (the dark red bar). The intersection is located on a major corridor west of the campus. It is known to experience severe congestion (stop-and-go traffic) during the PM peak.

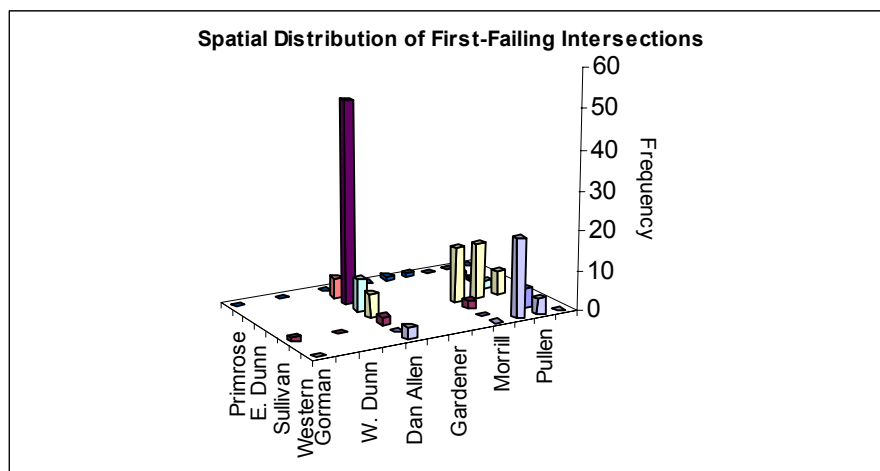


Figure 8.5 Spatial Distribution of the First Failure Frequencies in the Base Case Study

Field observations indicate that although Dan Allen Road is in a “stop and go” situation, forced yielding behavior can be observed in the field. Specifically, traffic from the minor streets (Dan Allen Deck Exit and Yarborough Street) is often allowed to intersection by cooperating drivers on the major street, so that there is no complete blockage on the minor streets in reality. Thus, there is a discrepancy between the simulation and the field behavior. The problem could be mitigated by changing the setting of free flow speeds, as discussed in the next section.

8.4 Adjusted Case Study

The initial network was reviewed by traffic simulation experts from HNTB consultants (HNTB North Carolina, 2004). They were concerned about the inconsistency of the free flow speeds between the simulation and the field. In the initial CORSIM model, the free flow speeds on the campus area were too high in most places compared to the field data. We reviewed these comments and agreed that the free-flow speeds should be recoded to match simulation settings with field observations. This alteration was made on the base network. The results comprised an adjusted network.

The setting of free flow speeds in the adjusted network included:

- Western Boulevard: 45 MPH, now consistent with the field posted speed
- Gorman Street: 35 MPH, now consistent with the field posted speed
- Hillsborough Street: 25 MPH along campus area (from Dan Allen to Pullen) while 35 MPH along non-campus area, now lower than the field posted speed
- Pullen, Dan Allen (except otherwise described), Morrill, and Sullivan Street: 25 MPH, now consistent the field posted speed
- Parking lot (deck): 10 MPH, Pedestrian walk (Sections of Dan Allen): 10 MPH, now consistent with the field posed speed
- Other university roads: 15 MPH, now consistent with the field posed speed

The adjusted network was simulated with 100 replications. The system queue time is plotted in Figure 8.6. The mean, median, and standard deviation are 981, 924 and 211 vehicle hours, respectively. It is noted that compared to the base network, lower system

queue time is achieved due to the altering of free flow speeds.

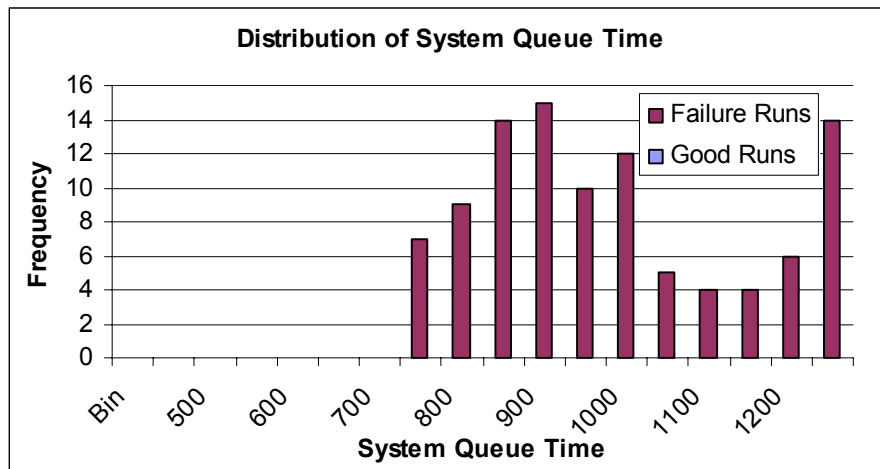


Figure 8.6 Distribution of SQT in the Adjusted Network Simulation

The failure detection procedure was again applied to the simulation. It indicated that there were one hundred percent failures. The average FFL was 37 links, and the average FT was 33 minutes. Compared to the base case network, the use of lower free flow speeds had a negative impact on the occurrence of simulation failures. In all, altering of free flow speeds above was not sufficient to reduce the failure probabilities and to generate any successful runs.

The failure analysis procedure identified the first-failing sites. As shown in Tables 8.5 and 8.6, the failure originating area shifted to include the intersection of Cates at Pullen (Node 5 on the network map), which is controlled by a stop sign on Cates Street.

First-Failing Link		Network Location	# First Failures	Percentage of Total Failures
A-Node	B-Node			
4	5	Eastbound Cates at Pullen	46	46%
115	4	Collisium Deck to Cates	45	45%
3	4	Eastbound Cates to Collisium Deck	33	33%
122	3	Eastbound Cates at Morrill	24	24%

Table 8.5 Critical First-Failing Links in the Adjusted Case Study

First-Failing Node	Network Location	# First Failures	Percentage of Total Failures
4	Floyd/Collisium Deck to Cates	53	53%
5	Cates at Pullen	46	46%
3	Cates at Morrill	29	29%

Table 8.6 Critical First-Failing Nodes in the Adjusted Case Study

The spatial distribution of the failure leading frequencies is plotted below in Figure 8.8. It is shown that the failure origination distribution has an apparent local peak. Though the intersection Pullen at Coliseum Deck at Cates (Node 4) has the highest number of first failure frequencies, the intersection of Cates at Pullen is most likely to be the failure causing site in initiating traffic blockages and spillbacks. Overall, the change of free flow speeds in the adjusted network had mitigated the previously identified problem on Dan Allen Drive (see purple bar in Figure 8.7).

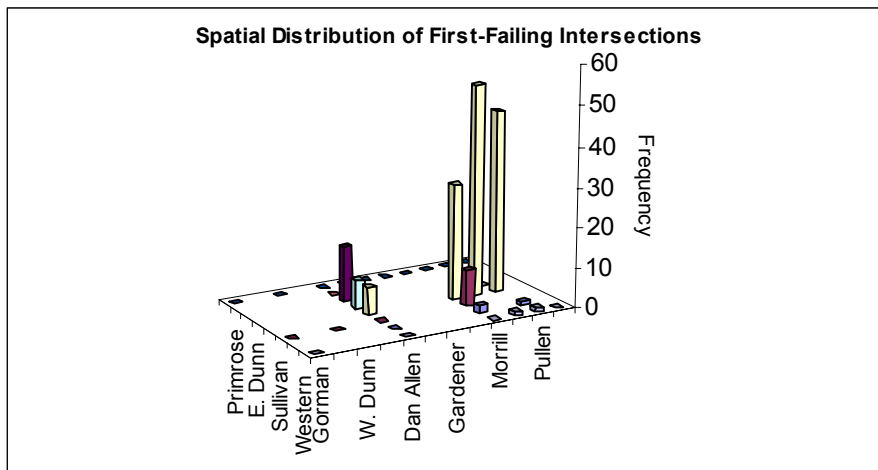


Figure 8.7 Spatial Distribution of the First Failure Frequencies in the Adjusted Case Study

Animations showed that the intersection Cates at Pullen, with a stop sign control, experienced capacity problems for left-turning vehicles from the minor street, thus causing spillback to block the upstream intersections. Field observations verified this

proposition. However, the 100% failure chance obviously amplified the problem. Thus, further tests were needed to improve the model by other tuning efforts.

Since the adjusted network still contained one hundred percent of simulation failures, further tuning studies were performed on selected traffic behavior parameters. The purpose was to mitigate the occurrence of failures and to generate successful runs in simulation. This is discussed in the next section.

8.5 Tuned Case Study

Parameter Test

Although the adjusted network did not provide any successful runs, the failure analysis demonstrated that with a more consistent setting of free flow speeds on the network, the locations of critical intersections matched field observations. Thus, it was used as the start point for further tuning of the model. The major purpose of tuning was to evaluate the sensitivity of selected traffic parameters and to achieve a lower level of failure probabilities.

Previous analysis indicated that the adjusted network had capacity problems in a stop sign controlled intersection. In order to address the problem related to the heavy left turn demand on the minor street, specific traffic parameters were included in the tuning test to seek solution to this problem.

In summary, the consideration traffic parameters included two groups. One was a collection of global traffic parameters that can impact the link capacities in the simulation, particularly the left-turn capacities. The other was some local control parameters, which

have potential to improve the situation at the problem intersection.

For the first group, previous studies indicated that 1) start-up lost time (SLT), 2) queue discharge headway (QDH), and 3) spillback probabilities (SbPr) are critical traffic parameters for an urban traffic network. For this campus network with many sign controlled intersections, the analyst also presumed that 4) critical gap values (CritGp) that govern gap acceptance behavior at un-signalized intersections should be reassessed.

As for the second group, previous studies indicated that the intersection of Cates at Pullen was the critical site. The intersection was evaluated from the perspective of the capacity on the minor street. The evaluation was carried out from two perspectives. One was to increase the performance of minor street traffic, which has already been taken into consideration above in the test of critical gaps. The other was to promote a smooth traffic flow on the major street, Pullen Street. The animation showed that the Pullen Street was somehow hindered by the low efficiency of the roundabout downstream of the problem intersection. Thus, additional test parameters were chosen that included 5) the free flow circulating speeds (FFCS) and 6) the lane width of the roundabout (LW), and 7) the free flow speeds (FFS) near the problem intersection on Pullen Street.

Every test case was simulated with 30 replicate runs. The results are shown below.

❖ Effects of SLT, QDH and SbPr

The tests of SLT, QDH, and SbPr were carried out simultaneously. Previous studies indicated that low values of SLT, QDH, and SbPr could result in smaller failure probabilities. Thus, we tested two set of parameters, and contrasted the resulting failure

probabilities with the start point network. The results are shown below in Figure 8.8.

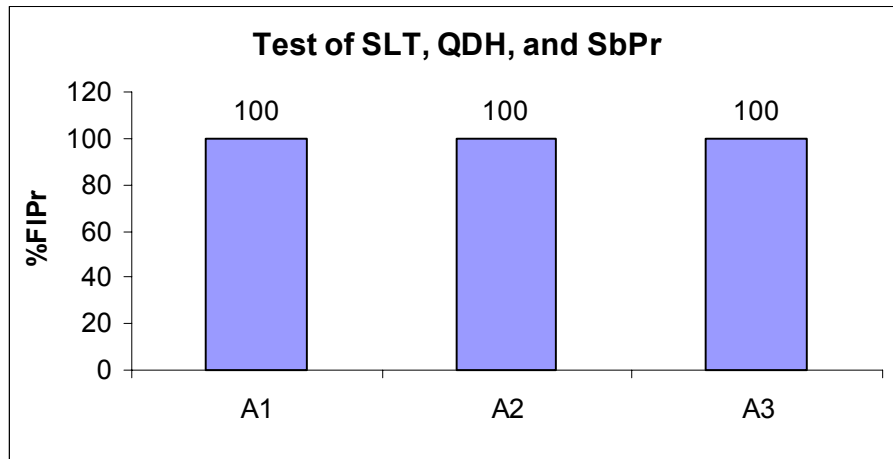


Figure 8.8 Effects of SLT, QDH, and SbPr Test

In the figure, cases A1, A2, and A3 have (SLT, QDH, SbPr1, SbPr2) with values (2.0, 1.8, 80%, 40%), (1.8, 1.7, 70%, 20%) and (1.6, 1.4, 70%, 20%), where A1 denotes the start point network (or, the tuned case network in Section 8.4). The figure shows that the changes in SLT, QDH, and SbPr did not reduce the chance of simulation failures.

❖ Effects of Critical Gaps

Since the test network is characterized by having a large number of un-signalized intersections, a test was performed on the values of critical gaps at un-signalized intersections. By default, the distributions of critical gap values for near-side and far-side crossings are (56, 50, 46, 42, 39, 37, 34, 30, 26, 20) and (12, 21, 26, 31, 35, 39, 42, 46, 49, 51) in units of tenth of a second for driver types 1 to 10, respectively. The allowable ranges for them are (15, 75) and (10, 75), respectively. Thus, we designed three set of values for test, and the results are shown in Figure 8.9.

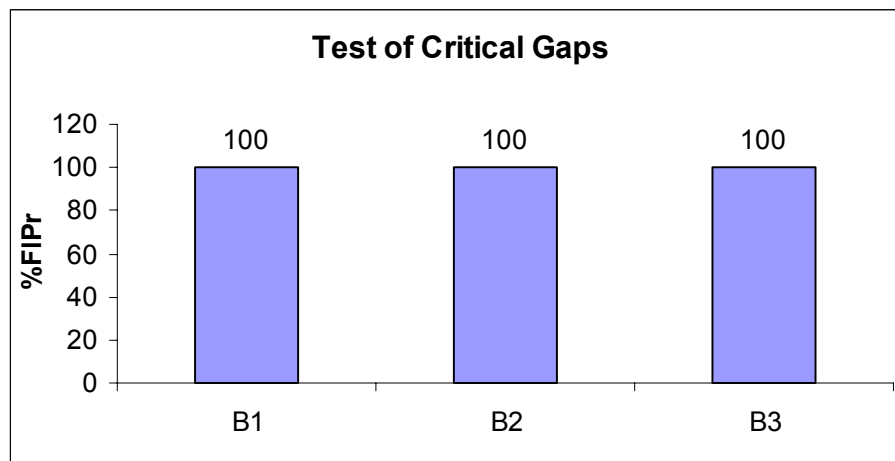


Figure 8.9 Effects of Critical Gap Test

In the above figure, the critical gaps in network B1 are inherited from the initial tuning by the original modeler, and their values are (44, 44, 40, 40, 37, 35, 34, 30, 26, 20) and (10, 20, 26, 31, 35, 39, 42, 46, 49, 51) for the near side and far side critical gaps. This setting was kept in the start point network as well as all other previous studies. Two other possibilities including B2 with (35, 30, 30, 30, 30, 30, 30, 30, 26, 20) and (10, 20, 26, 31, 35, 35, 35, 35, 35, 35) for the near side and far side critical gaps, and B3 with (15, 15, 15, 15, 15, 15, 15, 15, 15, 15) and (10, 10, 10, 10, 10, 10, 10, 10, 10, 10), were tested. From this figure we can see that the change of critical gaps did not reduce the chance of failure probabilities, either.

❖ Effects of Roundabout Circulating Speed

Simulation animation showed that the roundabout along Pullen Street was the key intersection that apparently constrained the transportation capacity on that street. Thus, a test was performed on the free flow circulating speeds at the roundabout. The results are shown in Figure 8.10 below.

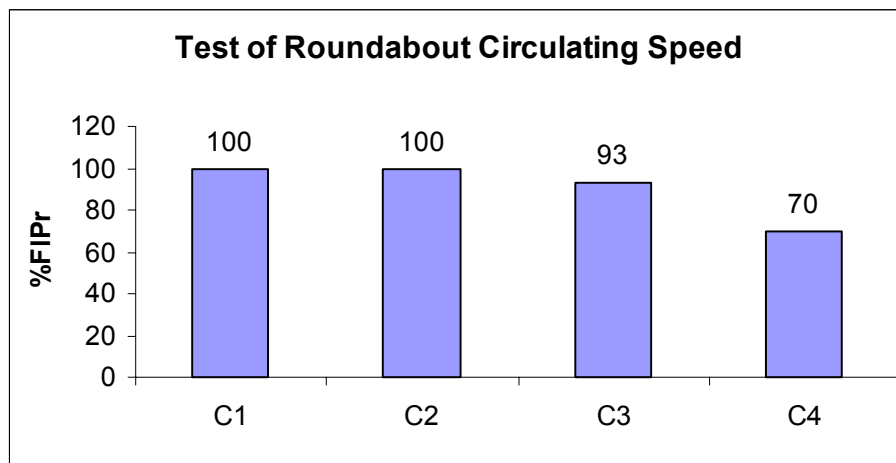


Figure 8.10 Effects of Roundabout Circulating Speed Test

In the figure, networks C1, C2, C3, and C4 have roundabout circulating speeds of 10, 15, 20, and 25 mph, respectively. The selection of a high circulating speed is not meaningful in traffic engineering since it is in conflict with the field speed. However, as the simulation of roundabout is a known difficulty in CORSIM, the test of a high circulating speed can be seen as a means to mitigate the poor approximation of roundabout operation in CORSIM.

As the figure shows, the use of a high circulating speed can actually reduce the chance of simulation failures from 100% at 10 and 15 mph to 93% at 20 mph, and to 70% at 25 mph. These results implied that the approximation of roundabouts in CORSIM may produce more reasonable values when an unrealistic high circulating speed is adopted.

Thus, the adjustment of circulating speed was accepted, and network C4 was used as a new start point for the successive tuning studies.

❖ Effects of Roundabout Lane Width

The next test was performed on the lane width of the roundabout. Its effect has rarely been mentioned in previous CORSIM studies. However, due to the fact that there is a fair amount of bus traffic in reality at the roundabout area, the selection of a larger lane width is meaningful from the perspective of traffic engineering principles. Three cases were tested, and the results are shown in Figure 8.11.

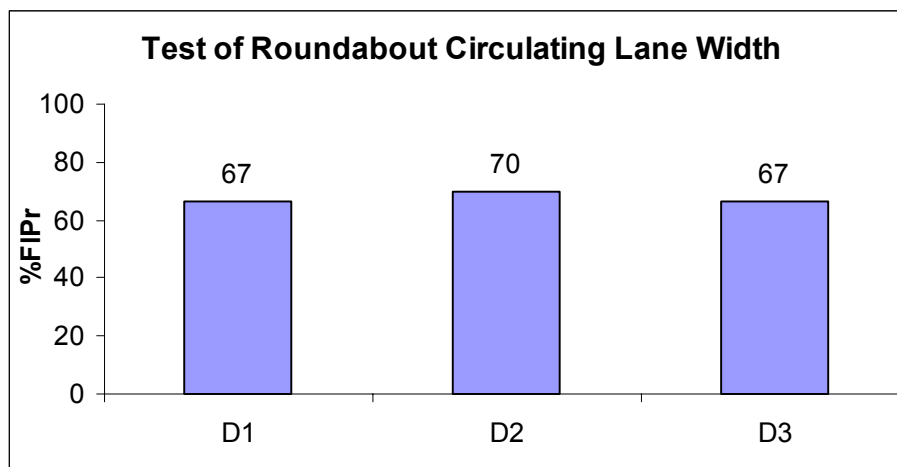


Figure 8.11 Effects of Roundabout Circulating Lane Width Test

In Figure 8.11, networks D1, D2, and D3 have roundabout circulating lane widths of 12, 15, and 18 feet, respectively. Among them, D2 represented the value inherited from the previous studies (the new start point network). The figure shows that the sensitivity of the failure probability to lane width is low. Therefore, the roundabout circulating lane width of 15 feet was preserved in the next iteration.

❖ Effects of Pullen Free Flow Speed

The above two studies focused on the roundabout on Pullen Street, and it was found that a high circulating speed could reduce the chance of simulation failures in this simulation.

Further, we were interested to determine if a change of free flow speeds in other areas along the key street could further reduce the failure probabilities. A trial test was then performed by changing free flow speeds for the upstream and downstream links of the problem intersection (Cates at Pullen). The test results are shown in Figure 8.12.

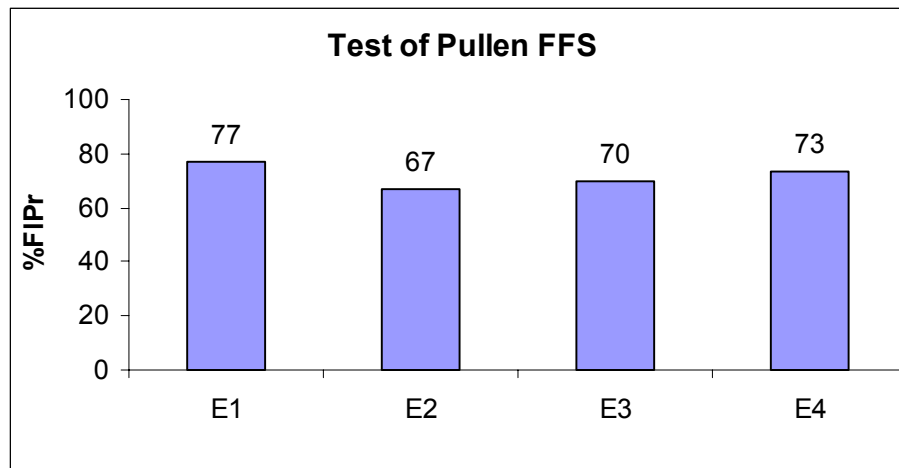


Figure 8.12 Effects of Pullen Free Flow Speed Test

In Figure 8.12, test networks E1, E2, E3, and E4 have free flow speeds of 15, 20, 25, and 30 for the links upstream and downstream of the problem intersection, where E3 denotes the new start point network. However, there is no apparent tendency (i.e., no statistically significant change) between the four cases. Thus, the free flow speed of 25 mph was preserved.

In summary, five tests were executed to test seven different traffic parameters in the NCSU network simulation. The results indicated that the selection of a high roundabout circulating speed was the only effective countermeasure that can significantly reduce the failure probabilities. As a result, a test was constructed using this high circulating speed to reevaluate the network. This comprised the tuned network.

Tuned Network Study Results

The tuned network was simulated with 100 replications. Like all the previous studies, we analyze the network results from two aspects, system queue time representing a conventional perspective and first failure frequency representing a failure detection and analysis perspective.

The distribution of system queue time is plotted in Figure 8.13 below, where failure runs are denoted by the red bars and good runs by the blue bars. The mean, median and standard deviation of SQT are 682, 613 and 252 vehicle hours, respectively. In the figure, the system queue time is apparently distributed to the left of that in the adjusted case study (see Figure 8.6), with the only change made to the roundabout circulating speed.

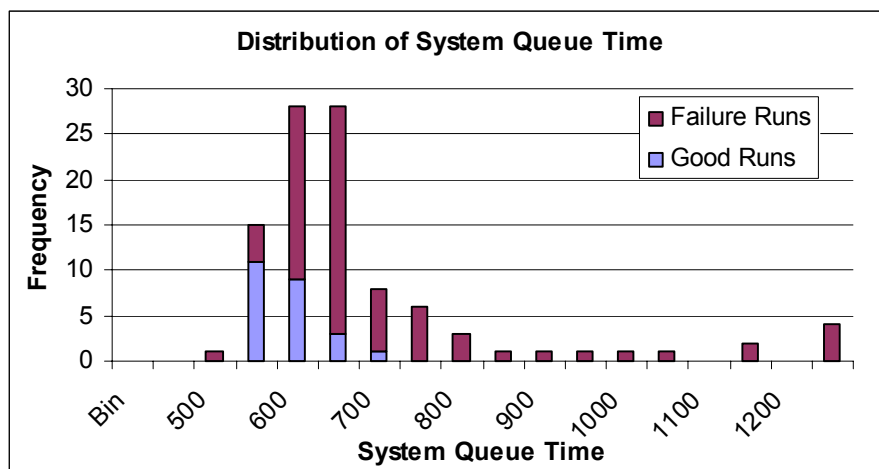


Figure 8.13 Distribution of System Queue Time in the Tuned Case Study

In total 76 failure runs are reported, which denotes a slightly higher failure probability than that in the pilot study (70%) in the parameter test part which only included 30 replications. Based on this sample study, the 95% confidence interval of the failure

probability is $76 \pm 8.4\%$, or (67.6%, 84.4%). As for the number of final failure links and the duration of failure time, the FFL was 14, and the FT was 15 minutes. Both of them were significantly improved from the previous cases. Thus, the use of an unusually high roundabout circulating speed can effectively promote the successful execution of the NCSU campus simulation.

The failure analysis procedure indicated that the problem persisted in the same area, at the intersection of Cates at Pullen (shown in Tables 8.7 and 8.8). Since this finding matched the field observations, the results indicated that the tuned network was similarly valid from the perspective of traffic engineering analysis.

First-Failing Link		Network Location	# First Failures	Percentage of Total Failures
A-Node	B-Node			
4	5	Eastbound Cates at Pullen	39	51%
115	4	Collisium Deck to Cates	29	38%
3	4	Eastbound Cates to Collisium Deck	25	33%
122	3	Eastbound Cates at Morrill	20	26%
105	3	Northbound Cates at Morrill	13	17%

Table 8.7 Critical First-Failing Links in the Tuned Case Study

First-Failing Node	Network Location	# First Failures	Percentage of Total Failures
5	Cates at Pullen	39	51%
4	Floyd/Collisium Deck to Cates	39	51%
3	Cates at Morrill	25	33%

Table 8.8 Critical First-Failing Intersections in the Tuned Case Study

The spatial distribution of first-failing intersections is plotted in Figure 8.14. It shows an apparent local peak at the intersection Cates at Pullen, with the eastbound approach being the critical site for failure occurrence.

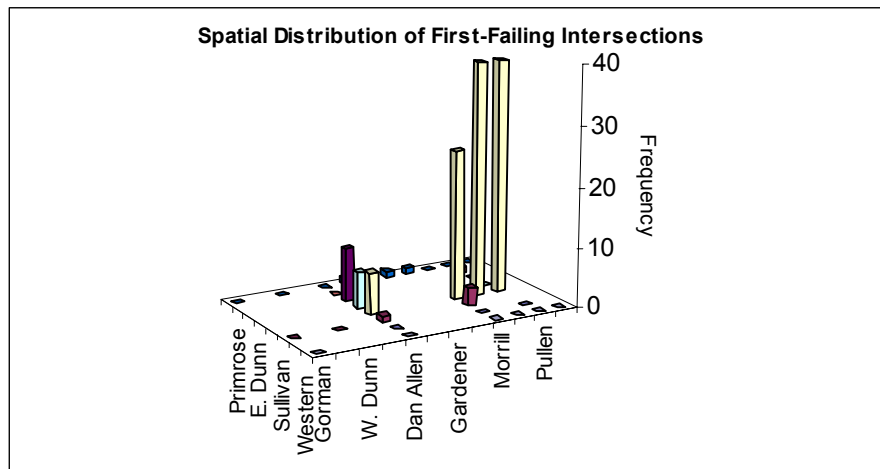


Figure 8.14 Spatial Distribution of the First-Failing Intersections in the Tuned Network Study

The tuned network simulation contained 23% good runs. Hence, the failure probability was still too high compared to reality. Since the tuned network had the most plausible set of parameter values, this high failure probability can be attributed to simulator-related factors (the poor ability of CORSIM in modeling un-signalized intersection operations) and network-related factors (insufficient capacity of the problem intersection).

8.5 Summary

The NCSU campus network was simulated as the third case study for the evaluation of failure occurrence. Since the network has quite different geometric and traffic demand features from a typical urban network, the simulation was intended to test the transferability of the proposed failure detection and analysis method.

The application of the proposed failure detection procedure showed that with a five-minute detection interval, around 95% of the runs resulted in simulation failures. The failure analysis procedure shows a local peaking failure pattern centered at the Pullen-

Stinson roundabout, which directed us to find out some coding errors in the problem area.

The debugging of errors in the initial model formed a base case network. The simulation of it yielded a surprising 100% chance of simulation failures with the failure detection time unit of 5 minute. This was explained by the negative effect on transportation capacities of the debugging changes. The failure analysis procedure indicated that the problem area shifted from the roundabout to a distant corridor.

An adjusted network was constructed by modifying the free flow speeds in the base case network. The principle of speed changes was to match the simulation setting with empirical values from the field observations. The failure detection of the adjusted network again revealed a 100% failure probability. However, further network analysis verified the positive impact of these changes. Specifically, an apparent improvement in the network statistics (i.e. lower SQT) implied that the tuning of free flow speeds was effective in reducing the level of congestion on the network. Also, an in-depth failure analysis indicated that the critical area for failure origination was now at a stop-controlled intersection with a known heavy left-turn volume, which finding matched field observations of the congestion pattern on the network.

The adjusted network served as the start point for a parametric study. Seven different parameters were studied. It was found that coding a high free flow circulating speed at the roundabout is effective in reducing the failure probabilities. Thus, a tuned network was developed using this high circulating speed.

The simulation of tuned network yielded 76% simulation failures, which remained too high compared to reality. This was finally attributed to the apparent inability of CORSIM

in modeling un-signalized intersections and the inadequate capacity at the problem intersection.

Overall, the application of the proposed failure detection method highlights its value in identifying the problem areas for simulation debugging and model calibration. The successful application verified the transferability of the proposed method between different networks, even though the final results in terms of failure reduction were rather disappointing.

CHAPTER 9: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The likelihood of simulation failures poses a significant obstacle to the effective implementation of stochastic traffic simulation models. In this research, an extensive analytic procedure has been devised to detect, diagnose and offer solutions to mitigate the simulation failure problem in a mostly quantitative and automated fashion. The procedure is intended to be simulator-independent, although its application in this thesis is confined to the CORSIM model. This chapter provides a summary of the important findings derived from the research (section 9.1), highlights the major conclusions (section 9.2) and sets recommendations for future work in this and related areas (section 9.3).

9.1 Summary of Results

Results described herein pertain to (a) the assessment of simulators' performance on a common data set, and (b) experiments on three real-world transportation networks in Chicago and Raleigh.

➤ Evaluation of Simulators

The proposed simulation failure detection method was first applied for the purpose of contrasting the performance of three recent releases of the CORSIM model (4.3.2, 5.1 and 5.2) using a common data set. System queue time (SQT) was the chosen performance measure. To ensure consistency between inputs, all simulations were based on the same field traffic data and using CORSIM 4.3.2 or 5.0 default traffic parameter values (there was an important change in defaults traffic parameters in version 5.1). The results are summarized in Table 9.1 below, and are based on 100 replications of a common data set.

Network	Features	SQT (Vehicle Hours)			Failure Detection Results	
		Mean	Median	STDEV	Sample FIPr	95% CI of FIPr
CORSIM 4.32	Default parameter values	247.77	195.65	153.68	13.00	(6.41, 19.59)
CORSIM 5.0	Default parameter values (same as 4.32, except forced correlation between LLG and SbPr)	319.77	202.12	230.59	32.00	(22.86, 41.14)
CORSIM 5.1	Parameter values were reset according to 4.32/5.0 (different from 5.1)	574.99	514.81	294.07	84.00	(76.81, 91.19)

Table 9.1 Summary Results in the Evaluation of Simulators

As the table indicates, CORSIM 5.0 generates a slightly higher level of SQT and a higher probability of simulation failures than CORSIM 4.3.2, with CORSIM 5.1 producing a much higher level of congestion and failure runs than the former two releases. This demonstrates that with each upgrade, the simulator was generating more conservative estimate of system performance.

From the failure analysis perspective, the only difference between the three models is the set of driver behavioral model parameters, and not any network related features.

Specifically, in CORSIM 5.0, two previously uncorrelated behavioral parameters namely the spillback probabilities and left turn lagger probabilities were treated differently in this release. This change resulted in a higher probability of left turn lagers, therefore leading to more vehicle lock-up situations. In CORSIM 5.1, that phenomenon was further evaluated, and partially addressed by adjusting the default values of spillback probabilities. However, in this contrasting study, the parameters were reset according to CORSIM 4.32/5.0 defaults. Therefore, it appears that the changes in other driver behavioral algorithms in CORSIM 5.1 had a negative impact on the mitigation of simulation failures.

➤ Evaluation of Chicago PM Peak Network

The proposed failure detection and analysis method was then applied to evaluate the simulation of a test-bed network. Extensive data collection took place on that network in the year 2000, and there were no observations of gridlock at anytime. This evaluation was conducted in a before (Base, or un-tuned model) and after (tuned model) settings. The tuned parameters were estimated from the failure analysis of the un-tuned network. Similar to the previous section, Table 9.2 summarizes the findings of the simulation performance for the Base and Tuned cases. Again, the results are based on 100 replications of CORSIM 5.1 in all cases.

Network	Features	SQT (Vehicle Hours)			Failure Detection Results	
		Mean	Median	STDEV	Sample FIPr	95% CI of FIPr
Base Case	Default parameter values, including (1.8, 2.0, 80%, 40%) for (SLT, QDH, SbPr1, SbPr2)	274.49	252.47	87.77	38.00	(28.49, 47.51)
Tuned Case	(1.7, 1.8, 70%, 20%) for (SLT, QDH, SbPr1, SbPr2)	207.76	207.22	18.62	8.00	(2.68, 13.32)

Table 9.2 Summary Results in the Evaluation of Chicago PM Peak Network

The results in the above table show that a better choice of traffic behavioral parameters can significantly reduce the reported congestion level and likelihood of simulation failures. The large values of failure probabilities reported in the Before Case are due to inadequate parameter calibration, as the field data showed no propensity for vehicle lock-up. Still, even with the tuned network, the analyst was only able to remove some of, but not all of the failure runs.

➤ Evaluation of the Chicago AM Peak Network

The Chicago AM peak network has identical geometry as the PM's, but with different traffic demand patterns and traffic controls. Based on the observation that both networks service the same driver population, the calibration parameters derived in the PM studies

were applied to that network. Again, field data collected for this network indicated no occurrence of gridlock or lock up during the observation period. Four case studies were developed. The first two considered the observed field demand pattern, while the last two focused on a future traffic scenario in which entry demand levels were uniformly increased by 15%, in order to induce congestion and increase failure probability. The simulation and failure detection results are summarized in Table 9.3 below.

Network	Features	SQT (Vehicle Hours)			Failure Detection Results	
		Mean	Median	STDEV	Sample FIPr	95% CI of FIPr
Base Case	Default parameter values, including (1.8, 2.0, 80%, 40%) for (SLT, QDH, SbPr1, SbPr2)	182.44	181.49	9.09	3.00	(0.00, 6.34)
Tuned Case	(1.7, 1.8, 70%, 20%) for (SLT, QDH, SbPr1, SbPr2)	173.29	173.02	3.77	0.00	(0.00, 0.00)
Test Case	A uniform demand increase of 15%	342.85	298.85	103.52	43.00	(33.20, 52.70)
TIP Case	Change of stop control to yield control at problem intersection	334.36	279.06	124.30	36.00	(26.59, 45.41)

Table 9.3 Summary Results in the Evaluation of Chicago AM Peak Network

It is shown in the above table that under current demand levels, the likelihood of failure predicted by the model was consistent with the field observations, regardless of whether the Base or Tuned model parameters are used. However, the application of the adjusted driver parameters did eliminate all failures runs, although that reduction is somewhat trivial (from 3% to 0%). Regarding the projected demand scenarios, the spatial analysis indicated that the network tended to consistently fail along a minor street due to spillback generated at a stop-controlled intersection. In order to alleviate that problem, yield control was substituted at that intersection in the hopes of reducing the critical gap, and consequently queuing at that location. As the results in Table 9.3 indicate, this provides minimal relief, and no statistically significant decrease in failure occurrence.

It is important to note that in the latter two case studies, it was assumed that the simulation model has been finely tuned, and that the effect of simulator version on system performance known. Thus, the main consideration for these studies was to associate any detected failures with network capacity problems. While the quick solution that was tested did not perform adequately, the spatial analysis was able to pinpoint the problem intersection which should be the focus of any future traffic improvements that are deemed necessary to handle the increased traffic demand.

➤ Evaluation of the NCSU Campus Network

The third network simulated in CORSIM is that of the NCSU campus. Obviously, that network has very different geometric features and traffic demand patterns from the previous two cases. The purpose of this study was to assess the transferability of the proposed simulation failure detection and analysis method across networks. In total, four sets of simulation, each consisting of 100 replications were conducted. The results for these case studies are summarized in Table 9.4 below. It should be noted that there was no formal calibration of the model parameters based on field measurements in this study. To offer additional insights into the failure patterns, two additional columns are added. The FFL represents the average number of network links that fail first (out of a total of 253 network links). The column labeled FT represents the time from simulation start to the first failure, based on a simulation time of 60 minutes.

Network	Features	SQT (Vehicle Hours)			Failure Detection Results			
		Mean	Median	STDEV	Sample FIPr	95% CI of FIPr	FFL	FT
Initial Case	Ad-hoc calibration of model parameters, with arbitrary free flow speeds and minor tuning on critical gap distributions	1440.86	1489.57	520.01	95.00	(90.73, 99.27)	63	43
Base Case	Debugging efforts: change of roundabout coding, specification of lane utilization	1466.47	1388.18	247.04	100.00	(100.00, 100.00)	27	24
Adjusted Case	Change of free flow speed according to network observations	981.49	923.67	210.96	100.00	(100.00, 100.00)	37	33
Tuned Case	Adoption of an unusually high roundabout circulating speed	682.29	613.22	252.27	76.00	(67.63, 84.37)	14	15

Table 9.4 Summary Results in the Evaluation of NCSU Campus Network

It is evident from the results indicated in Table 9.4 that CORSIM was not able to successfully model the performance of this network. Regardless of what treatment was applied, the failure occurrences were very significant, ranging from 76 to 100%. However, the number of links affected and the first failure time varied according to treatment. There were many factors that contributed to simulation failures; chief among them was an inadequate representation of traffic operations at un-signalized intersections, which were very prevalent on this particular network. This problem was also evident in the analysis of the Chicago AM peak network, and points to the need for re-assessing the gap acceptance algorithms in CORSIM. In addition, there were observed capacity problems at a key intersection (at Pullen and Cates), and of course a lack of field calibration of many driver behavioral parameters.

Overall, the findings of this research confirm the utility of the proposed simulation failure detection and analysis procedure as a means to assess the utility of simulators and to highlight network related problems that are sometimes user-induced or due to the characteristics of the network environment itself. Over the long run, this scheme will be of value to both software developers and end-users of the model in producing a reliable

simulation model without the need to expend endless hours debugging for possible input and/or parameter value errors.

9.2 Findings and Conclusions

Key Findings

The series of findings derived from this research effort are discussed in terms of the stated research objectives specified in Chapter 1 of this document.

Objective 1: Developing and verifying a failure detection method for simulation models

The proposed failure detection method was based on an inspection of time series for key variables that are able to detect traffic anomalies. This was done by tracing key traffic performance on important network links over the time domain. Specifically, in this research the indicator variables chosen were the number of entering and exiting link vehicle trips as well as link occupancy.

The method was applied to real world case studies to verify its utility. The applications reported failure occurrence in each replication as well as its occurrence time and spatial distribution. The test results demonstrated that the proposed failure detection method was an effective and efficient way to identify the occurrence of simulation failures.

Objective 2: Identifying the role of simulation failures in the larger framework of simulation verification and validation

It is important to consider the role of the proposed method within the larger framework of the entire simulation process, since the problem of simulation failures is an integral part of simulation verification and validation. Traditionally, a complete simulation process is comprised of a number of stages including choice of the simulator, associated field data

collection, model construction, model calibration, model validation, and model prediction. This research indicated that the detection and analysis of simulation failures can be viewed as a significant supplement to the process of developing and implementing micro-simulation models

In the early stages of simulation, the successful identification of simulation failures can provide important clues about a poor simulator choice, inaccurate input data, model coding errors, and inadequate user calibrations. In the later stages, the failure detection can assist transportation analysts evaluate the subject network by locating “vulnerable” locations on the network, which will serve as the basis for the identification and implementation of traffic improvement plans.

Objective 3: Developing and verifying contributing factors to simulation failures

In order to perform a higher-level analysis beyond simple detection of simulation failures, a synthetic method was developed to derive the spatial distribution of critical sites on a network, and to conduct a failure causal analysis based on its results. The first-failing links and nodes (those links and nodes having the earliest failure occurrence time) are aggregated across replications. The first failure frequencies for each site could then be plotted on the network map to illustrate the spatial pattern of failure occurrence. The resulting failure occurrence patterns were classified as global or local, with high or low frequency of failures. Possible parameters that are associated with different categories of contributing factors can be identified using this tabular method.

The latter application has demonstrated that the failure analysis results can provide important hints for the identification and mitigation of factors contributing to simulation failures. These findings can be further pursued by the user, using their own knowledge

about the simulator, the modeling stage, and the network. In particular, the method enables the user to focus their observations on a limited set of animation files to hone in on the problem areas and possible contributing factors.

Specific Conclusions

Based on the results and findings described above, a series of conclusions emerge. Those conclusions are categorized into three areas regarding: (a) the stochastic traffic simulation algorithms, (b) the procedure and results of failure detection, and (c) the procedure and results of failure analysis. In addition, two specific conclusions are derived regarding the test-bed simulator of CORSIM.

➤ Regarding Stochastic Traffic Simulation Algorithms

- 1) Simulation failures are currently an inherent obstacle to the effective implementation of stochastic traffic simulations.

Stochastic traffic simulations always have the likelihood to yield simulation failures, particularly in congested conditions. These failures cause bring bias to the simulation modeling process and in the analysis results. Thus, these failures must be successfully addressed during the process of simulation. However, associated with the use of a large sample size, it is difficult to detect and analyze the onset of simulation failure in a convenient way. Thus, it is essential to devise an innovative method to address and evaluate the impact of simulation failures in the applications of stochastic simulation.

- 2) Failure detection and analysis should become an essential part of the framework of simulation development and analysis.

Successful exclusion of simulation failure runs can effectively remove biased output data

and, therefore, improve the quality of simulation analysis. On the other hand, simulation failures can be attributed to a variety of contributing factors. These different causes are likely to lead to different failure occurrence patterns. Thus, the detection and analysis of failure failures has the potential to perform a diagnosis of traffic simulation. By discovering these contributing factors, simulation failure detection and analysis can become a significant tool to improve the overall process of simulation development and analysis.

➤ Regarding Failure Detection

- 3) The method of time series inspection provides an effective way to the detection of simulation failures.

In this research, an extensive failure detection method was proposed to identify traffic anomalies using the technique of time series inspection. The detection mechanism of this method is to inspect the time series of key indicator variables including interval link trips-in, interval link trips-out, and cumulative link content. Later applications of this method verified that time series inspection is effective and efficient to detect simulation failures in a quantitative and automated way.

- 4) Compared to conventional methods, the method of time series inspection provides superior performance in simulation failure detection.

Traditional methods, including animation observation and outlier detection, are inadequate or infeasible to detect the occurrence of simulation failures. Animation observation is a time consuming process when there are large number of replications, and it is often impossible to detect the onset of failure, especially if it occurs simultaneously

on many links. The outlier method (defined as the identification of those replications on the right tail of the system performance measure) was shown to be unreliable. For example, in one of the test networks, it was found that 61% of the failures were not associated with outlier runs. The application of the time series inspection method is demonstrably superior to conventional methods in terms of accuracy and efficiency. Time series inspection method is able to differentiate extreme situations such as normal runs with a high level of congestion, failure runs with late failure occurrence, and so on. In addition, it employs a quantitative method to identify the detection. The procedure has been automated by computer programming. Thus, the proposed time series inspection method is recommended as a supplemental tool for any simulation model to assist in the detection of the onset of simulation failures during a simulation process.

➤ Regarding Failure Analysis

5) Spatial analysis provides an important basis to perform an effective simulation failure causal analysis.

The occurrence of simulation failures may be caused by various contributing factors. In order to distinguish these different factors, a tabular method is used to associate different failure occurrence patterns with the general categories of contributing factors, namely simulator-related, simulation-related, and network related. The determination of categories can be also be supplemented by user knowledge about the simulation stage and network features. For example, simulation failures can be attributed to network-related factors if the simulation model is known to be fully calibrated and validated, for example in an application to a projected traffic scenario.

- 6) In the early stages of simulation, simulation failure analysis can be used to diagnose the simulation modeling efforts and provide a pre-calibration effort to guide subsequent simulation improvement through calibration and tuning.

In the early stages of simulation, the major concern is to choose an appropriate simulator, collect accurate input data, and to properly construct a site-specific simulation model. The failure analysis procedure can be used to assist such efforts and locate any possible errors during the conduct of these tasks. The utility of this process was demonstrated in the case studies, where the proposed procedure successfully identified inadequate calibrations of two case networks, and a coding error in the initial simulation of the NCSU campus network.

- 7) In the later stages of the simulation process, simulation failure analysis can serve as a convenient tool to diagnose the simulators, inspect capacity constraints of the subject network, and evaluate different transportation improvement plans.

In the later stages of simulation, the simulation model is often assumed to be fully tuned and calibrated. Thus, the main focus is to apply a valid simulation model to the analysis of a projected traffic scenario. In such a situation, the proposed failure detection and analysis procedure can locate network capacity constraints and evaluate the effectiveness of transportation improvement plans.

Finally, the case studies of the proposed method are based on the most recent version of CORSIM (version 5.1). Regarding the simulator, an experiment was performed to evaluate three recent releases of CORSIM. Some specific conclusions are derived regarding the simulator.

➤ Regarding CORSIM simulator

- 8) The upgrading of CORSIM tended to generate conservative estimates of traffic performance for the same standard input dataset.

Compared to versions 4.32 and 5.0, the suppliers of CORSIM 5.1 claimed to have incorporated an improved algorithm in the modeling of traffic spillback behavior. However, the application result demonstrated that with the same input dataset, CORSIM 5.1 generated a higher level of congestion and a higher probability of simulation failures.

- 9) CORSIM has limited capabilities in modeling un-signalized intersections, particularly for close-to-capacity traffic conditions.

The case studies indicate CORSIM has limited capabilities in modeling traffic behavior at un-signalized intersections, which would initiate simulation failures under heavy traffic demands. In addition, the tuning tests show that the tuning of existing traffic parameters governing the performance of these intersections in CORSIM could not effectively eliminate the problem.

9.3 Limitations and Further Actions

The current findings in this research provide strong evidence that the proposed failure detection and analysis procedure represents a rigorous and defensible approach toward the path of establishing more reliable, effective and efficient traffic simulation models. However, it is also noted that a number of limitations still exist at the conclusions of the current research.

Regarding the method development, it is desirable for the users and model developers alike to be able to apply the entire failure detection and analysis method in automated

fashion. It is realized that the complexities of simulation process and the difficulty in deriving the exact failure contributing factors are major issues, specifically when the simulator algorithms are black-boxes to most users. The proposed failure pattern matrix developed in this research is a key step in that direction. However, this matrix provides only general guidelines, and as such must be supplemented with the user knowledge of other aspects of the model and simulator, which varies widely among users.

As for the method application, the effectiveness of the failure detection and analysis procedure has been confined to the evaluation of the most three recent leases of CORSIM and at only three real-world networks. Since the objective is to provide a general and transferable algorithm across simulators and networks, further tests are necessary to confirm its validity and effectiveness with other simulator environments.

Further more, other features in CORSIM not considered in this research, provide strong potential for further improvement of the current failure analysis methodology. Specifically, the CORSIM animation files are accessible to researchers and advanced simulation users through a supplemental that enable the analyst to read information from the binary files. This provides the potential to identify vehicle trajectory data, which would be significant to assist in developing a micro-analysis of simulation failures. However, the current research chose not to progress along this direction and, instead, limits the study to aggregate measures of traffic within the time series data generated in discrete time intervals.

In consideration of these limitations, additional efforts are proposed for future research, as listed below:

- Conduct further investigations on the failure occurrence mechanisms in order to

mathematically formulate the entire failure analysis method, particularly the causal analysis procedure currently based on a tabular method. This could possibly be achieved by studying the correlation between failure occurrence patterns and factors such as transportation facility features and traffic demand patterns

- Research the potential of using vehicle trajectory data to improve the current analysis procedure; specifically, evaluate the role of vehicle trajectory data analysis as a focused analysis tool after the failure locations and time have been determined from the exploratory analysis.
- Apply the proposed failure detection and analysis method to other simulation networks using a different simulator to verify its validity and transferability
- Incorporate the proposed procedure into the larger framework of traffic simulation guidebooks, particularly under the ongoing NGSIM research program to highlight its important role in the construction, calibration and validation of new generation simulation models.
- Integrate a user-friendly version of the failure detection method into the CORSIM model to promote its use by software developers and end users.

CHAPTER 10: LIST OF REFERENCES

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APPENDIX 1: CASE SIMULATION INPUT FILES

File 1: AM89Base.trf

Am89Base - am time period 8 to 9 base network
 sink & source: no
 nb LaSalle speed limit: 30 mph
 turn probabilities on NB LaSalle at Huron (26=>86) changed:
 from (40,60,0) to (1,99,0)
 Clark and Erie control type: 05
 time interval length: 5 min
 number of time intervals: 12

```

Frg Flaw Detection PROJECT                                00
Baohong Wan                                             8 029000NISS                                1
  1  0      60 71892923      21 0000      308      2993602175667039  2
300 300 300 300 300 300 300 300 300 300 300 300 300  3
      75                                                4
  12      0 120  0      1                                                5
188 27 332 25      4 1      TTTT      28  4      20 18 35 111  11
8088 188      4      TTTT      27      0      11
8188 188      1      1      27      0      11
  27  4 324 25      4 1      7TTT      8  3 15      20 18 35 111  11
  4  3 322 25      4 1      TTTT      7  2      20 18 35 111  11
  3  2 347 25      4 1      4TTT      6  1 24      20 18 35 122  11
  2  1 326      4      4TTT      39 23      20 18 35 121  11
  1 39 440      3      TTT      8000      20 18 35 1 13  11
  5  6 335 45 45 3 1 1  TTT      2  7 10      20 18 35 111  11
  6  7 338      45 3  1  TTT      8 11      20 18 35 111  11
  7  8 324 45 45 3 1 1  TT8      4 28 12      20 18 35 111  11
  8 28 347      45 3  1  TTT      8089 29      20 18 35 111  11
 29 12 324      3      7T8      16 11  8      20 18 35 133  11
 90 29 332      3      TT8      40 12      35      11
8090 90      4      TTTT      29      0      11
8190 90      1      1      29      0      11
  87 38 243      3      TT8      8097 27      20 18 35 1  11
8087 87      3      T      38      0      11
8187 87      1      1      38      0      11
  38 27 244      3      7TT      28  4      20 18 35 1  11
  27 28 244      3      TT8      8089 29      20 18 35 1  11
  28 29 245      3      7TT      40 12      20 18 35 1  11
  29 40 240      3      TT8      80798091      20 18 35 1  11
  12 11 322      3      TT1      31 10      20 18 35 111  11
  11 10 347      2      78      32  9  6      9 20 18 35 111  11
  10 110 200      2      TT      11      20 18 35 1  11
 110 11 138      1      4      31      20 18 35 1  11
  10  9 326      3      7T1      33 34  5      34 20 18 35 111  11
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8096	2161	1010						195
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File 2: PM56Base.trf

Pm56Base - pm time period 5 to 6 base network
sink & source: no
nb LaSalle speed limit: 30 mph
Clark and Erie control type: 05
time interval length: 5 min
number of time intervals: 12

Frg Flaw Detection PROJECT																			00
Baohong Wan									8	029000NISS									1
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					75														4
	12		0	120	0						1								5
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	37	96	280	1	8	82968096		20	18	35	1	11		
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	20	80	243	1	T	8080		20	18	35	1	11		
8080	80	1	T			20		20	18	0		11		
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File 3: NcsuBaseE.trf

NCSU Campus simulation base network 4:30 to 6:00 PM
 time interval length: 5 min
 number of time intervals: 18
 major changes so far based on project requirement and hntb advice
 1. time interval specification: 5 min * 18
 2. lane channelization
 3. roundabout control type, turn probs, curve, lane width specification
 4. speed limits

```

Frg Flaw Detection PROJECT                               00
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                                     1                                             5
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209 16 967 121 2 1 7T 210 127 15 127 20 18 35 11 11
    16 209 967 2 8008 20 18 35 11 11
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127 16 566 180 2 1 7T 15 209 210 209 20 18 35 11 11
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    20 19 384 134 2 1 TT 123 18 18 20 18 25 11 11
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113	9933	11664	195
114	9762	10873	195
115	11900	10245	195
116	11939	10426	195
117	11053	10543	195
118	13107	10580	195
119	13052	10474	195
120	13016	10565	195
121	9420	9349	195
122	10262	10335	195

201	13833	8089	195
202	10502	8073	195
203	9245	8346	195
204	8139	8665	195
205	7277	9008	195
206	6194	9069	195
207	5263	10649	195
208	5635	12265	195
209	6206	14164	195
210	7382	14347	195
123	9934	11990	195
124	10320	11992	195
125	10971	11825	195
126	11857	11602	195
211	9612	12949	195
212	9411	11843	195
213	10365	12424	195
214	10294	11869	195
215	9653	11478	195
216	11035	12171	195
217	11921	11970	195
218	11863	11427	195
219	12235	11898	195
220	14137	10921	195
221	12106	10975	195
222	11108	10394	195
223	11975	10022	195
224	10180	10221	195
225	9508	9490	195
226	8135	10499	195
227	9642	10311	195
8000	14423	7890	195
8001	10471	7629	195
8002	8963	7904	195
8003	7782	8194	195
8004	7035	8499	195
8005	6057	8557	195
8006	4726	10673	195
8007	5147	12370	195
8008	5894	14544	195
8009	7660	14689	195
8010	9765	13399	195
8011	10417	12819	195
8012	11069	12674	195
8013	11965	12558	195
8014	12304	12457	195
228	13147	11848	195
8015	13174	12254	195
8016	14573	10818	195
8017	8325	10325	195
8018	9724	9630	195
8019	9751	10079	195
8020	10145	9934	195
8021	12060	9789	195
8022	11204	10224	195
8023	12291	11007	195
8024	11843	11224	195

8025	10322	11616			195
8026	9538	11519			195
8027	9374	11720			195
127	7459	13280			195
128	11319	11805			195
229	9678	11115			195
230	9981	11019			195
8028	9609	11128			195
8029	10134	10936			195
150	6288	11006			195
175	10795	8809			195
400	9437	12248			195
401	9557	12679			195
402	9482	12020			195
403	10400	12638			195
404	13649	11257			195
8030	13680	11338			195
405	8744	10569			195
406	9963	10483			195
407	8462	12171			195
408	8697	13034			195
8031	8826	13422			195
8032	8333	11821			195
420	11412	12223			195
8033	11458	12464			195
416	13924	11543			195
8034	13884	12086			195
417	13929	11784			195
430	9993	11306			195
450	6477	10514			195
109	10	0	108	107	196
10	109	0	108	107	196
120	119	502			196
119	118	552			196
118	120	502			196
0	3				210
0					170
0	3				210
0					170
0	3				210
209	16	13	77	10	21
127	16	16	79	5	21
18	19		75	25	21
20	19	25	75		21
23	24	5	80	15	21
25	6	30	70		21
9	115		100		21
115	4			100	21
3	4	10	90		21
10	110		100		21
106	10	40	60		21
11	12	4	79	17	21
12	11	8	67	25	21
13	12	17	82	1	21
120	119		12	88	21
119	118		19	81	21
118	120		69	31	21

15	27		100				21
112	27	40		60			21
3	122	50	50				21
203	11	45	21	34			21
206	14	25	63	12			21
207	14	10	75	15			21
223	115	60		40			21
406	122		80	20			21
8000	2011010		3		100		50
8001	202	200			100		50
8002	203	706	3		100		50
8003	204	150			100		50
8004	205	0			100		50
8005	206	398	3		100		50
8006	207	822	3		100		50
8007	208	64			100		50
8008	209	883	3		100		50
8009	210	357	3		100		50
8017	226	445			100		50
8026	215	232			100		50
8027	212	180			100		50
8010	211	150			100		50
8025	214	118			100		50
8013	217	103			100		50
8024	218	186			100		50
8014	219	99			100		50
8015	228	154			100		50
8023	221	200			100		50
8022	222	128			100		50
8021	223	225			100		50
8019	227	80			100		50
8016	2201204		3		100		50
8028	229	96			100		50
8029	230	84			100		50
8011	403	292			100		50
8034	417	492			100		50
0							170
0	3						210
0							170
0	3						210
0							170
0	3						210
16	15	7	89	4			21
18	19		83	17			21
20	19	17	83				21
23	24	5	79	16			21
24	6		96	4			21
25	6	34	66				21
9	115		100				21
115	9	84		16			21
115	4	50		50			21
3	4		100				21
10	110		100				21
110	108		74	26			21
106	10	35	65				21
11	12	5	83	12			21
12	11	8	67	25			21

12	13		100			21
13	12	17	82	1		21
112	27	87		13		21
3	122	54	46			21
203	11	45	20	35		21
204	12	46	19	35		21
206	14	25	63	12		21
207	14	11	78	11		21
223	115	69		31		21
227	103			100		21
406	122		65	35		21
14	450		100			21
450	13		100			21
13	450		100			21
8000	2011247	3		100		50
8001	202	200		100		50
8002	203	776	3	100		50
8003	204	150		100		50
8004	205	0		100		50
8005	206	487	3	100		50
8006	207	904	3	100		50
8007	208	112		100		50
8008	209	928	3	100		50
8009	210	374	3	100		50
8017	226	290		100		50
8026	215	164		100		50
8027	212	190		100		50
8010	211	157		100		50
8025	214	123		100		50
8013	217	108		100		50
8024	218	195		100		50
8014	219	103		100		50
8015	228	161		100		50
8023	221	325		100		50
8022	222	192		100		50
8021	223	550		100		50
8019	227	100		100		50
8016	2201248	3		100		50
8028	229	124		100		50
8029	230	112		100		50
8011	403	306		100		50
8034	417	528		100		50
0						170
0	3					210
0						170
0	3					210
0						170
0	3					210
18	19		83	17		21
20	19	20	80			21
23	24	5	81	14		21
24	6		98	2		21
25	6	34	66			21
9	115	100				21
115	4	25		75		21
3	4	20	80			21
10	110		100			21

110	108		85	15		21
11	12	4	87	9		21
12	11	4	71	25		21
13	12	15	84	1		21
120	119		13	87		21
119	118		18	82		21
118	120		67	33		21
112	27	75		25		21
3	122	40	60			21
201	110		100			21
203	11	48	15	37		21
206	14	28	57	15		21
207	14	8	80	12		21
209	16	13	73	14		21
223	115	45		55		21
127	16	20	75	5		21
406	122		65	35		21
122	406		100			21
450	14	8	83	9		21
8000	2011359	3		100		50
8001	202	200		100		50
8002	203	953	3	100		50
8003	204	150		100		50
8004	205	0		100		50
8005	206	537	3	100		50
8006	2071109	3		100		50
8007	208	112		100		50
8008	2091138	3		100		50
8009	210	459	3	100		50
8017	226	266		100		50
8026	215	220		100		50
8027	212	192		100		50
8010	211	233		100		50
8025	214	151		100		50
8013	217	133		100		50
8024	218	240		100		50
8014	219	126		100		50
8015	228	197		100		50
8023	221	325		100		50
8022	222	116		100		50
8021	223	236		100		50
8019	227	180		100		50
8016	2201204	3		100		50
8028	229	52		100		50
8029	230	40		100		50
8011	403	376		100		50
8034	417	544		100		50
0						170
0	3					210
0						170
0	3					210
0						170
0	3					210
16	15	7	70	23		21
18	19		75	25		21
20	19	25	75			21
23	24	5	85	10		21

25	6	27	73			21
9	115		100			21
115	4	60		40		21
3	4		100			21
110	108		87	13		21
106	10	34	66			21
11	12	4	84	12		21
12	11	7	70	23		21
13	12	15	84	1		21
120	119		13	87		21
119	118		19	81		21
118	120		67	33		21
27	15	20	50	30		21
112	27	80		20		21
27	112		100			21
3	122	60	40			21
203	11	47	17	36		21
206	14	30	53	17		21
207	14	10	79	11		21
209	16	13	75	12		21
210	16	20	60	20		21
223	115	20		80		21
127	16	20	75	5		21
406	122		84	16		21
450	14	6	80	14		21
8000	2011409	3		100		50
8001	202	200		100		50
8002	203	988	3	100		50
8003	204	150		100		50
8004	205	0		100		50
8005	206	557	3	100		50
8006	2071150	3		100		50
8007	208	140		100		50
8008	2091180	3		100		50
8009	210	526	3	100		50
8017	226	339		100		50
8026	215	144		100		50
8027	212	242		100		50
8010	211	200		100		50
8025	214	157		100		50
8013	217	137		100		50
8024	218	249		100		50
8014	219	131		100		50
8015	228	205		100		50
8023	221	275		100		50
8022	222	164		100		50
8021	223	218		100		50
8019	227	250		100		50
8016	2201196	3		100		50
8028	229	104		100		50
8029	230	80		100		50
8011	403	390		100		50
8034	417	648		100		50
0						170
0	3					210
0						170
0	3					210

0					170
0	3				210
18	19		78	22	21
20	19	20	80		21
23	24	5	83	12	21
25	6	32	68		21
9	115	70	30		21
115	4	70		30	21
3	4		100		21
110	108		75	25	21
106	10	42	58		21
11	12	5	80	15	21
12	11	8	67	25	21
13	12	17	82	1	21
102	26	18	82		21
120	119		11	89	21
119	118		19	81	21
118	120		67	33	21
112	27	89		11	21
27	112		100		21
3	122	28	72		21
203	11	45	21	34	21
204	12	3	79	18	21
206	14	20	68	12	21
207	14	10	79	11	21
209	16	13	75	12	21
210	16	20	60	20	21
223	115			100	21
127	16	18	77	5	21
406	122		50	50	21
25	416		100		21
416	417		100		21
417	416		100		21
29	430		100		21
117	430		100		21
450	14	6	84	10	21
8000	2011035		3	100	50
8001	202	200		100	50
8002	203	811	3	100	50
8003	204	150		100	50
8004	205	0		100	50
8005	206	700	3	100	50
8006	207	945	3	100	50
8007	208	108		100	50
8008	209	970	3	100	50
8009	210	500	3	100	50
8017	226	160		100	50
8026	215	152		100	50
8027	212	199		100	50
8010	211	164		100	50
8025	214	129		100	50
8013	217	113		100	50
8024	218	204		100	50
8014	219	107		100	50
8015	228	168		100	50
8023	221	225		100	50
8022	222	148		100	50

8021	223	146		100	50
8019	227	150		100	50
8016	2201092		3	100	50
8028	229	88		100	50
8029	230	56		100	50
8011	403	320		100	50
8034	417	532		100	50
0					170
0	3				210
0					170
0	3				210
0					170
1		0			210

APPENDIX 2: FAILURE DETECTION PROGRAM CODES IN VBA

Module 1: ExpDesign

```
Option Explicit
```

```
Const RplNum = 100
```

```
Const CaseDir = "D:\flawdetection\Chapter7\"
```

```
Const CaseName = "Am89ErieDr"
```

```
Sub ExpDesign()
```

```
    Dim BaseFile, BaseLine, OutFile, OutLine, RplFile, RplLine, InpFile As String
```

```
    Dim RecType, Title, FpBaseLine, RpBaseLine As String
```

```
    Dim RplCnt, TpdCnt, TpdNum, BaseFileNum, OutFileNum, RplFileNum As Integer
```

```
    Dim LnkNum, LnkCnt, TrnNum, TrnCnt, IntNum, IntCnt, DmdNum, DmdCnt As Integer
```

```
    Dim a, b, c, i, j, k, count, CursorRow, anode, bnode, cnode As Integer
```

```
    Dim cf, o, p, q As Object
```

```
    Dim Ending, LocalLink As Boolean
```

```
    ' control if the link stl and qdh change locally or globally
```

```
    LocalLink = False
```

```
    Dim ParFile, ParLine As String
```

```
    Dim ParNum, ParSetCnt, ParSetNum, ParFileNum As Integer
```

```
    Dim ParInp(30, 8), ParVal(30, 8)
```

```
    Dim LnkAnode(150), LnkBnode(150), LnkLnode(150), LnkTnode(150), LnkRnode(150)
```

```
    Dim LnkLength(150), LnkLanes(150), LnkLtPct(150), LnkThPct(150), LnkRtPct(150)
```

```
    Dim IntID(60), IntType(60), IntOffset(60), IntPhases(60), IntCycLng(60)
```

```
    Dim DmdSnode(40), DmdEnode(40), DmdFlRate(40), DmdHvPct(40)
```

```
    Dim r1, r2, r3 As String
```

```
    Dim rs1(RplNum), rs2(RplNum), rs3(RplNum)
```

```
    Dim l1, l2 As String
```

```
    Dim slt(RplNum), qdh(RplNum), sbp(RplNum), llp(RplNum), ljp(RplNum)
```

```
    Dim NewSheet As Object
```

```
    'create worksheets for experiment data record
```

```
    Application.DisplayAlerts = False
```

```
    For a = 1 To Worksheets.count - 1
```

```
        If Worksheets(a).Name = "ExpDesign" Then
```

```
            Application.DisplayAlerts = False
```

```
            Worksheets(a).Delete
```

```
            Application.DisplayAlerts = True
```

```
        End If
```

```
    Next a
```

```
    Set NewSheet = Worksheets.Add
```

```
    NewSheet.Name = "ExpDesign"
```

```
    Application.DisplayAlerts = True
```

```
    'record basic experiment information
```

```
    With Worksheets("ExpDesign").Range("B2", "E20")
```

```
        .Font.Bold = True
```

```
        Cells(2, 2).Value = "Corsim Analysis Experiment"
```



```
Cells(3, 2).Value = CaseDir & CaseName
Cells(5, 2).Value = Date & Space(3) & Time()
Cells(6, 2).Value = "by Baohong"
End With

'read parameter values from input file
ParNum = 8: ParSetNum = 0
ParFile = "D:\flawdetection\VBA\ExpCv Design_Oct 06.txt"
ParFileNum = FreeFile()
Open ParFile For Input Access Read As #ParFileNum

i = 0
While Not EOF(ParFileNum)
    Line Input #ParFileNum, ParLine
    i = i + 1
    For j = 1 To ParNum
        ParInp(i, j) = CSng(Mid(ParLine, j * 11 - 4, 9))
    Next j
Wend
ParSetNum = i
Close #ParFileNum

'transform parameter values into input values
For i = 1 To ParSetNum
    For j = 1 To ParNum
        Select Case j
            Case 1
                k = Int(ParInp(i, j) * 5) + 1
                If k > 5 Then k = 5
                Select Case k
                    Case 1: ParVal(i, j) = 100
                    Case 2: ParVal(i, j) = 105
                    Case 3: ParVal(i, j) = 110
                    Case 4: ParVal(i, j) = 115
                    Case 5: ParVal(i, j) = 120
                    Case Else
                End Select
            Case 2
                k = Int(ParInp(i, j) * 7) + 1
                If k > 7 Then k = 7
                Select Case k
                    Case 1: ParVal(i, j) = 16
                    Case 2: ParVal(i, j) = 17
                    Case 3: ParVal(i, j) = 18
                    Case 4: ParVal(i, j) = 19
                    Case 5: ParVal(i, j) = 20
                    Case 6: ParVal(i, j) = 21
                    Case 7: ParVal(i, j) = 22
                    Case Else
                End Select
            Case 3
                k = Int(ParInp(i, j) * 6) + 1
                If k > 6 Then k = 6
                Select Case k
                    Case 1: ParVal(i, j) = 14
                    Case 2: ParVal(i, j) = 17
                    Case 3: ParVal(i, j) = 18
```

```
Case 4: ParVal(i, j) = 20
Case 5: ParVal(i, j) = 22
Case 6: ParVal(i, j) = 24
Case Else
End Select
Case 4
k = Int(ParInp(i, j) * 5) + 1
If k > 5 Then k = 5
Select Case k
Case 1: ParVal(i, j) = 70
Case 2: ParVal(i, j) = 75
Case 3: ParVal(i, j) = 80
Case 4: ParVal(i, j) = 85
Case 5: ParVal(i, j) = 90
Case Else
End Select
Case 5
k = Int(ParInp(i, j) * 5) + 1
If k > 5 Then k = 5
Select Case k
Case 1: ParVal(i, j) = 20
Case 2: ParVal(i, j) = 30
Case 3: ParVal(i, j) = 40
Case 4: ParVal(i, j) = 50
Case 5: ParVal(i, j) = 60
Case Else
End Select
Case 6
k = Int(ParInp(i, j) * 5) + 1
If k > 5 Then k = 5
k = 1 ' Arbitrary value to test
Select Case k
Case 1: ParVal(i, j) = 50
Case 2: ParVal(i, j) = 60
Case 3: ParVal(i, j) = 70
Case 4: ParVal(i, j) = 80
Case 5: ParVal(i, j) = 90
End Select
Case 7
k = Int(ParInp(i, j) * 5) + 1
If k > 5 Then k = 5
k = 2 ' Arbitrary value to test
Select Case k
Case 1: ParVal(i, j) = "05"
Case 2: ParVal(i, j) = 15
Case 3: ParVal(i, j) = 25
Case 4: ParVal(i, j) = 35
Case 5: ParVal(i, j) = 45
Case Else
End Select
Case 8
k = Int(ParInp(i, j) * 6) + 1
If k > 6 Then k = 6
Select Case k
Case 1: ParVal(i, j) = "00"
Case 2: ParVal(i, j) = "08"
Case 3: ParVal(i, j) = 16
```

```

        Case 4: ParVal(i, j) = 24
        Case 5: ParVal(i, j) = 32
        Case 6: ParVal(i, j) = 38
        Case Else
        End Select
    Case Else
    End Select
Next j
Next i

'create replication batch input file
InpFile = CaseDir & CaseName & ".inp"
Set cf = CreateObject("Scripting.FileSystemObject")
Set o = cf.CreateTextFile(InpFile, True)

For RplCnt = 1 To RplNum
    'open corsim input file
    BaseFile = CaseDir & CaseName & ".trf"
    BaseFileNum = FreeFile()
    Open BaseFile For Input Access Read As #BaseFileNum

    'create replication input file
    RplFile = CaseDir & CaseName & CStr(RplCnt) & ".trf"
    o.WriteLine (RplFile)
    Cells(RplCnt + 7, 2).Value = RplFile
    Set cf = CreateObject("Scripting.FileSystemObject")
    Set p = cf.CreateTextFile(RplFile, True)

    ParSetCnt = Int(RplCnt / (RplNum + 1) * ParSetNum) + 1

    While Not EOF(BaseFileNum)
        Line Input #BaseFileNum, BaseLine
        RecType = 0
        If Trim(Mid(BaseLine, 78, 3)) <> "" Then RecType = CInt(Mid(BaseLine, 78, 3))
        Select Case RecType
            Case 2
                r1 = Mid(BaseLine, 22, 8)
                r2 = Mid(BaseLine, 61, 8)
                r3 = Mid(BaseLine, 69, 8)

                rs1(RplCnt) = ""
                For i = 1 To 7
                    rs1(RplCnt) = rs1(RplCnt) & CStr(Int(Rnd() * 10))
                Next i
                Ending = False
                While Ending = False
                    a = Int(Rnd() * 5)
                    If a <> 2 Then
                        rs1(RplCnt) = rs1(RplCnt) & CStr(a * 2 + 1)
                        Ending = True
                    End If
                Wend
                rs2(RplCnt) = ""
                For i = 1 To 7
                    rs2(RplCnt) = rs2(RplCnt) & CStr(Int(Rnd() * 10))
                Next i
                Ending = False

```

```

While Ending = False
  a = Int(Rnd() * 5)
  If a <> 2 Then
    rs2(RplCnt) = rs2(RplCnt) & CStr(a * 2 + 1)
    Ending = True
  End If
Wend
rs3(RplCnt) = ""
For i = 1 To 7
  rs3(RplCnt) = rs3(RplCnt) & CStr(Int(Rnd() * 10))
Next i
Ending = False
While Ending = False
  a = Int(Rnd() * 5)
  If a <> 2 Then
    rs3(RplCnt) = rs3(RplCnt) & CStr(a * 2 + 1)
    Ending = True
  End If
Wend

Cells(RplCnt + 7, 4).Value = rs1(RplCnt)
Cells(RplCnt + 7, 5).Value = rs2(RplCnt)
Cells(RplCnt + 7, 6).Value = rs3(RplCnt)

RplLine = BaseLine
RplLine = Replace(RplLine, r1, rs1(RplCnt))
RplLine = Replace(RplLine, r2, rs2(RplCnt))
RplLine = Replace(RplLine, r3, rs3(RplCnt))
Case 11
  anode = CInt(Mid(BaseLine, 1, 4))
  bnode = CInt(Mid(BaseLine, 5, 4))
  If anode = 118 Or anode = 119 Or anode = 120 Then LocalLink = True
  If bnode = 118 Or bnode = 119 Or bnode = 120 Then LocalLink = True
  LocalLink = True

  If LocalLink = True Then
    l1 = Mid(BaseLine, 59, 2)
    l2 = Mid(BaseLine, 63, 2)
    slt(RplCnt) = ParVal(ParSetCnt, 2)
    qdh(RplCnt) = ParVal(ParSetCnt, 3)
    FpBaseLine = Left(BaseLine, 58)
    RpBaseLine = Right(BaseLine, 16)
    RplLine = FpBaseLine & slt(RplCnt) & Space(2) & qdh(RplCnt) &
RpBaseLine

    Cells(RplCnt + 7, 9).Value = slt(RplCnt)
    Cells(RplCnt + 7, 10).Value = qdh(RplCnt)

  Else
    RplLine = BaseLine
  End If

  LocalLink = False

Case 50
  l1 = Mid(BaseLine, 9, 4)
  l2 = CStr(Int(CInt(l1) * ParVal(ParSetCnt, 1) / 100 + 0.5))

```

```

        l2 = Space(4 - Len(l2)) & l2
        RplLine = Replace(BaseLine, l1, l2)
        Cells(RplCnt + 7, 8).Value = ParVal(ParSetCnt, 1)

    Case 140
        ljp(RplCnt) = ""
        For i = 1 To 7
            ljp(RplCnt) = ljp(RplCnt) & Space(3) & i & Space(2) &
ParVal(ParSetCnt, 8)
        Next i

        RplLine = BaseLine
        l1 = Mid(RplLine, 1, 56)
        RplLine = Replace(RplLine, l1, ljp(RplCnt))
        Cells(RplCnt + 7, 13).Value = ljp(RplCnt)

    Case 141
        RplLine = BaseLine
        l1 = Mid(RplLine, 1, 16)
        l2 = Mid(RplLine, 17, 12)

        sbp(RplCnt) = Space(2) & CStr(ParVal(ParSetCnt, 4))
        sbp(RplCnt) = sbp(RplCnt) & Space(2) & CStr(ParVal(ParSetCnt, 5))
        sbp(RplCnt) = sbp(RplCnt) & " 0 0"
        llp(RplCnt) = Space(2) & CStr(ParVal(ParSetCnt, 6))
        llp(RplCnt) = llp(RplCnt) & Space(2) & CStr(ParVal(ParSetCnt, 7))
        llp(RplCnt) = llp(RplCnt) & " 0"

        RplLine = Replace(RplLine, l1, sbp(RplCnt))
        RplLine = Replace(RplLine, l2, llp(RplCnt))

        Cells(RplCnt + 7, 11).Value = sbp(RplCnt)
        Cells(RplCnt + 7, 12).Value = llp(RplCnt)

    Case Else
        RplLine = BaseLine
    End Select
    p.WriteLine (RplLine)
Wend

    p.Close
    Close #BaseFileNum

Next RplCnt
o.Close

End Sub

```

Module 2: Am89VbaAggCode

```

Option Explicit
    Const RplNum = 100 ' total number of replications
in an experiment
    Const CaseDir = "D:\flawdetection\Chapter7\" ' root directory for the
experiment
    Const CaseName = "Am89ErieDr" ' case name for the experiment
    Const StRpl = 1 ' starting replication number for
the run
    Dim TpdNum ' time period number

    Const FLTsd = 0, CntTsd = 1, BbTsd = 0, DtcTsd = 5 ' failure detection threshold for
link vehicle trips
' failure detection threshold for
number of failure links
' failure detection threshold for
number of initial trips
' failure detection threshold for
number of fluctuation trips

Sub main()
    GetInfo ' subprogram for gathering experiment information
    FlwDtc ' subprogram for detecting simulation failures
    CslAnl ' subprogram for analyzing failure patterns
End Sub

Sub GetInfo()
    Dim BaseFile, BaseLine, OutFile, OutLine As String
    Dim RecType, Title As String
    Dim RplCnt, TpdCnt, BaseFileNum, OutFileNum As Integer
    Dim LnkNum, LnkCnt, TrnNum, TrnCnt, IntNum, IntCnt, DmdNum, DmdCnt As Integer
    Dim a, b, c, i, j, k, count, CursorRow, anode, bnode, cnode As Integer

    Dim LnkAnode(150), LnkBnode(150), LnkLnode(150), LnkTnode(150), LnkRnode(150)
    Dim LnkLength(150), LnkLanes(150), LnkLtPct(150), LnkThPct(150), LnkRtPct(150)
    Dim IntID(60), IntType(60), IntOffset(60), IntPhases(60), IntCycLng(60)
    Dim DmdSnode(40), DmdEnode(40), DmdFlRate(40), DmdHvPct(40)

    Dim NewSheet As Object
    Dim firstP1, firstP2, firstP3, firstP4, firstP5, firstP6, firstP7, firstP8 As Boolean

    'create worksheets for experiment data record
    Application.DisplayAlerts = False
    For a = 1 To Worksheets.count - 1
        If Worksheets(a).Name = "CorAnl" Then
            Application.DisplayAlerts = False
            Worksheets(a).Delete
            Application.DisplayAlerts = True
        End If
    Next a
    Set NewSheet = Worksheets.Add
    NewSheet.Name = "CorAnl"
    Application.DisplayAlerts = True

    'record basic experiment information

```

```

With Worksheets("CorAn1").Range("B2", "E30")           ' initial worksheet as
CorAn1
    .Font.Bold = True
    Cells(2, 2).Value = "Corsim Analysis Experiment"
    Cells(3, 2).Value = CaseDir & CaseName
    Cells(5, 2).Value = Date & Space(3) & Time()
    Cells(6, 2).Value = "by Baohong Wan, Phd Candidate, North Carolina State
University"

    Cells(7, 2).Value = "Start time: " & Time()
    Cells(11, 2).Value = "Beginning output data collection ... "
End With

'create excel file for analysis output
Workbooks.Add
ActiveWorkbook.SaveAs Filename:="An1" & CaseName & ".xls" ' specify the workbook to
save analysis outputs

' *****
' ***** corsim input file analysis *****
' *****

'create worksheets for input data analysis results
Application.DisplayAlerts = False
Worksheets("sheet1").Name = "InputInfo"                ' specify the worksheet
to save analysis outputs
Worksheets("sheet2").Name = "Validation"                ' specify the worksheet
to save validation results
Worksheets("sheet3").Delete
Application.DisplayAlerts = True
CursorRow = 0

'open corsim input file
BaseFile = CaseDir & CaseName & ".trf"                 ' Specify base experiment
file to work with
BaseFileNum = FreeFile()
Open BaseFile For Input Access Read As #BaseFileNum
Range(Cells(1, 1), Cells(3, 10)).Font.Bold = True
Cells(2, 2).Value = "Name of Input File:"              ' record base experiment
file information
Cells(3, 2).Value = BaseFile
CursorRow = CursorRow + 5

'read corsim input file part 1 to 8
firstP1 = 1: firstP2 = 1: firstP3 = 1: firstP4 = 1
firstP5 = 1: firstP6 = 1: firstP7 = 1: firstP8 = 1
TpdCnt = 0: LnkCnt = 0: TrnCnt = 0: IntCnt = 0: DmdCnt = 0

While Not EOF(BaseFileNum)
    Line Input #BaseFileNum, BaseLine
    RecType = Mid(BaseLine, 78, 3)

    If RecType <> "" Then
        Select Case CInt(RecType)
            'part 1: corsim input file header
            Case 0, 1
                ' judge if it is the first line of part 1

```

```

If firstP1 = 1 Then
  With Cells(CursorRow, 2)
    .Font.Bold = True
    .Value = "Part 1: Input File Header"
  End With
  CursorRow = CursorRow + 1
  firstP1 = 0
End If

' copy evething in the header
Cells(CursorRow, 2).Value = Left(BaseLine, 78)
CursorRow = CursorRow + 1

'part 2: corsim input general information
Case 2, 3, 4, 5
  ' judge if it is the first line of part 2
  If firstP2 = 1 Then
    CursorRow = CursorRow + 1
    With Cells(CursorRow, 2)
      .Font.Bold = True
      .Value = "Part 2: General Information"
    End With
    CursorRow = CursorRow + 1
    firstP2 = 0
  End If

  Select Case CInt(RecType)
    ' gather values of random number seeds
    Case 2
      Cells(CursorRow, 2).Value = "Random number seeds:"
      Cells(CursorRow, 5).Value = Mid(BaseLine, 22, 8)
      Cells(CursorRow, 7).Value = Mid(BaseLine, 61, 8)
      Cells(CursorRow, 9).Value = Mid(BaseLine, 69, 8)
      CursorRow = CursorRow + 1

      'gather parameters of simulation time period
      Case 3
        Cells(CursorRow, 2).Value = "Time period lengths:"
        TpdCnt = 0
        While Not Trim(Mid(BaseLine, TpdCnt * 4 + 1, 4)) = ""
          TpdCnt = TpdCnt + 1
          Cells(CursorRow, 5 + (TpdCnt - 1) * 1).Value = Mid(BaseLine,
(TpdCnt - 1) * 4 + 1, 4)
        Wend
        TpdNum = TpdCnt
        CursorRow = CursorRow + 1
        Cells(CursorRow, 2).Value = "Number of time periods:"
        Cells(CursorRow, 5).Value = TpdNum
        CursorRow = CursorRow + 1

        'gather parameters of simulation time interval
        Case 4
          If Trim(Mid(BaseLine, 17, 4)) <> "" Then
            Cells(CursorRow, 2).Value = "Time interval Duration:"
            Cells(CursorRow, 5).Value = Mid(BaseLine, 17, 4)
            CursorRow = CursorRow + 1
          End If

```



```

' other information
Case 5

End Select

'part 3: corsim network links information
Case 11
' judge if it is the first line of part 3
If firstP3 = 1 Then
    CursorRow = CursorRow + 1
    With Cells(CursorRow, 2)
        .Font.Bold = True
        .Value = "Part 3: Network Links Information"
    End With
    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Value = "Anode"
    Cells(CursorRow, 3).Value = "Bnode"
    Cells(CursorRow, 4).Value = "Lnode"
    Cells(CursorRow, 5).Value = "Tnode"
    Cells(CursorRow, 6).Value = "Rnode"
    Cells(CursorRow, 7).Value = "Length"
    Cells(CursorRow, 8).Value = "Lanes"
    CursorRow = CursorRow + 1
    firstP3 = 0
End If

'gather geometry information for each link
LnkCnt = LnkCnt + 1
LnkAnode(LnkCnt) = CInt(Mid(BaseLine, 1, 4))
LnkBnode(LnkCnt) = CInt(Mid(BaseLine, 5, 4))
If Trim(Mid(BaseLine, 9, 4)) <> "" Then LnkLength(LnkCnt) =
CInt(Mid(BaseLine, 9, 4))
If Trim(Mid(BaseLine, 22, 1)) <> "" Then LnkLanes(LnkCnt) =
CInt(Mid(BaseLine, 22, 1))
If Trim(Mid(BaseLine, 37, 4)) <> "" Then LnkLnode(LnkCnt) =
CInt(Mid(BaseLine, 37, 4))
If Trim(Mid(BaseLine, 41, 4)) <> "" Then LnkTnode(LnkCnt) =
CInt(Mid(BaseLine, 41, 4))
If Trim(Mid(BaseLine, 45, 4)) <> "" Then LnkRnode(LnkCnt) =
CInt(Mid(BaseLine, 45, 4))

Cells(CursorRow, 2).Value = LnkAnode(LnkCnt)
Cells(CursorRow, 3).Value = LnkBnode(LnkCnt)
Cells(CursorRow, 4).Value = LnkLnode(LnkCnt)
Cells(CursorRow, 5).Value = LnkTnode(LnkCnt)
Cells(CursorRow, 6).Value = LnkRnode(LnkCnt)
Cells(CursorRow, 7).Value = LnkLength(LnkCnt)
Cells(CursorRow, 8).Value = LnkLanes(LnkCnt)
CursorRow = CursorRow + 1

' summarize number of links analyzed
LnkNum = LnkCnt
Cells(CursorRow, 2).Value = " Number of Links Analyzed : " &
Str(LnkNum)

'part 4: corsim link turn percentage information

```

```

Case 21
' judge if it is the first line of part 4
If firstP4 = 1 Then
    CursorRow = CursorRow + 2
    With Cells(CursorRow, 2)
        .Font.Bold = True
        .Value = "Part 4: Turn Percentage Information"
    End With
    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Value = "Anode"
    Cells(CursorRow, 3).Value = "Bnode"
    Cells(CursorRow, 4).Value = "LT Pct"
    Cells(CursorRow, 5).Value = "TH Pct"
    Cells(CursorRow, 6).Value = "RT Pct"
    CursorRow = CursorRow + 1
    firstP4 = 0
End If

' gather link turning probability information
anode = CInt(Mid(BaseLine, 1, 4))
bnode = CInt(Mid(BaseLine, 5, 4))
For LnkCnt = 1 To LnkNum
    ' match the link order in record type 21 to rt 11
    If anode = LnkAnode(LnkCnt) And bnode = LnkBnode(LnkCnt) Then
        TrnCnt = TrnCnt + 1
        If Trim(Mid(BaseLine, 9, 4)) <> "" Then LnkLtPct(LnkCnt) =
CInt(Mid(BaseLine, 9, 4))
        If Trim(Mid(BaseLine, 13, 4)) <> "" Then LnkThPct(LnkCnt) =
CInt(Mid(BaseLine, 13, 4))
        If Trim(Mid(BaseLine, 17, 4)) <> "" Then LnkRtPct(LnkCnt) =
CInt(Mid(BaseLine, 17, 4))

        Cells(CursorRow, 2).Value = LnkAnode(LnkCnt)
        Cells(CursorRow, 3).Value = LnkBnode(LnkCnt)
        Cells(CursorRow, 4).Value = LnkLtPct(LnkCnt)
        Cells(CursorRow, 5).Value = LnkThPct(LnkCnt)
        Cells(CursorRow, 6).Value = LnkRtPct(LnkCnt)
        CursorRow = CursorRow + 1
    End If
Next LnkCnt

'summarize number of links whose turning probabilities analyzed
TrnNum = TrnCnt
Cells(CursorRow, 2).Value = " Number of Links Analyzed : " &
Str(TrnNum)

'part 5: corsim signal type and phase information
Case 35, 36
' judge if it is the first line of part 5
If firstP5 = 1 Then
    CursorRow = CursorRow + 2
    With Cells(CursorRow, 2)
        .Font.Bold = True
        .Value = "Part 5: Signal Information"
    End With
    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Value = "Intersection"

```

```

        Cells(CursorRow, 3).Value = "Type"
        Cells(CursorRow, 4).Value = "Offset"
        Cells(CursorRow, 5).Value = "Phases"
        Cells(CursorRow, 6).Value = "Cycle Length"
        CursorRow = CursorRow + 1
        firstP5 = 0
    End If

    ' collect information about intersection control types
    Select Case Cint(RecType)
    Case 35
        IntCnt = IntCnt + 1
        IntID(IntCnt) = Cint(Mid(BaseLine, 1, 4))
        If Trim(Mid(BaseLine, 5, 4)) <> "" Then
            IntOffset(IntCnt) = Cint(Mid(BaseLine, 5, 4))
            IntType(IntCnt) = "Sig"
            IntPhases(IntCnt) = 0: IntCycLng(IntCnt) = 0
            While Trim(Mid(BaseLine, IntPhases(IntCnt) * 4 + 29, 4)) <>
"" And Trim(Mid(BaseLine, IntPhases(IntCnt) * 4 + 29, 4)) <> "0"
                IntPhases(IntCnt) = IntPhases(IntCnt) + 1
                IntCycLng(IntCnt) = IntCycLng(IntCnt) + Cint(Mid(BaseLine,
IntPhases(IntCnt) * 4 + 25, 4))
            Wend
        Else
            IntType(IntCnt) = "Unsig"
        End If

        Cells(CursorRow, 2).Value = IntID(IntCnt)
        Cells(CursorRow, 3).Value = IntType(IntCnt)
        Cells(CursorRow, 4).Value = IntOffset(IntCnt)
        Cells(CursorRow, 5).Value = IntPhases(IntCnt)
        Cells(CursorRow, 6).Value = IntCycLng(IntCnt)
        CursorRow = CursorRow + 1

        'summarize number of intersections analyzed
        IntNum = IntCnt
        Cells(CursorRow, 2).Value = " Number of Intersections Analyzed :
" & Str(IntNum)

    Case 36
    Case Else
    End Select

    'part 6: corsim network demand information
    Case 50
        ' judge if it is the first line of part 6
        If firstP6 = 1 Then
            CursorRow = CursorRow + 2
            With Cells(CursorRow, 2)
                .Font.Bold = True
                .Value = "Part 6: Network Demand Information"
            End With
            CursorRow = CursorRow + 1
            Cells(CursorRow, 2).Value = "Source Node"
            Cells(CursorRow, 3).Value = "Entry Node"
            Cells(CursorRow, 4).Value = "Flow Rate"
            Cells(CursorRow, 5).Value = "HV Pct"

```

```

        CursorRow = CursorRow + 1
        firstP6 = 0
    End If

    ' gather network demand information
    DmdCnt = DmdCnt + 1
    DmdSnode(DmdCnt) = CInt(Mid(BaseLine, 1, 4))
    DmdEnode(DmdCnt) = CInt(Mid(BaseLine, 5, 4))
    DmdFlRate(DmdCnt) = CInt(Mid(BaseLine, 9, 4))
    DmdHvPct(DmdCnt) = CInt(Mid(BaseLine, 13, 4))
    Cells(CursorRow, 2).Value = DmdSnode(DmdCnt)
    Cells(CursorRow, 3).Value = DmdEnode(DmdCnt)
    Cells(CursorRow, 4).Value = DmdFlRate(DmdCnt)
    Cells(CursorRow, 5).Value = DmdHvPct(DmdCnt)
    CursorRow = CursorRow + 1

    'summarize number of demand analyzed
    DmdNum = DmdCnt
    Cells(CursorRow, 2).Value = " Number of Input Demand Analyzed : " &
Str(DmdNum)

    'part 7: corsim traffic parameter information
    Case 81, 140, 141, 144, 145, 153
    ' judge if it is the first line of part 7
    If firstP7 = 1 Then
        CursorRow = CursorRow + 2
        With Cells(CursorRow, 2)
            .Font.Bold = True
            .Value = "Part 7: Traffic Parameter Information"
        End With
        CursorRow = CursorRow + 1
        firstP7 = 0
    End If

    ' copy traffic parameter input line
    Cells(CursorRow, 2).Value = Left(BaseLine, 80)
    CursorRow = CursorRow + 1

    'part 8: other corsim information
    Case Else

        End Select
    End If
Wend
Close #BaseFileNum

' *****
' ***** corsim output file analysis *****
' *****

Dim LnkTrips(150, 12), LnkVehStTime(150, 12), LnkCtDelay(150, 12)
Dim LnkVehQuTime(150, 12), LnkStPct(150, 12), LnkSpeed(150, 12)
Dim LnkLtTrips(150, 12), LnkThTrips(150, 12), LnkRtTrips(150, 12)
Dim LnkQuTime(150, 12), LnkStTime(150, 12)
Dim LnkLtQuTime(150, 12), LnkThQuTime(150, 12), LnkRtQuTime(150, 12)
Dim LnkLtStTime(150, 12), LnkThStTime(150, 12), LnkRtStTime(150, 12)
Dim LnkCntTrips(150, 12), LnkInpTrips(150, 12), LnkOutTrips(150, 12)

```

```

Dim SysQuTime, SysStTime, SysVehMile, SysVehHour

Dim V1LnkAnode(3), V1LnkBnode(3) As Integer
Dim V1LnkTrips(3, 12), V1LnkStTime(3, 12), V1LnkVehTrips(3), V1LnkVehStTime(3)

' input validation link information
V1LnkAnode(1) = 7: V1LnkBnode(1) = 8: V1LnkVehTrips(1) = 2790: V1LnkVehStTime(1) = 9
V1LnkAnode(2) = 4: V1LnkBnode(2) = 8: V1LnkVehTrips(2) = 1650: V1LnkVehStTime(2) = 14
V1LnkAnode(3) = 3: V1LnkBnode(3) = 7: V1LnkVehTrips(3) = 693: V1LnkVehStTime(3) = 33

'create corsim output analysis summary worksheet
For a = 1 To Worksheets.count - 1
    If Worksheets(a).Name = "Summary" Then
        Application.DisplayAlerts = False
        Worksheets(a).Delete
        Application.DisplayAlerts = True
    End If
Next a
Set NewSheet = Worksheets.Add
NewSheet.Name = "Summary"

' head info for output analysis
With Cells(2, 2)
    .Font.Bold = True
    .Value = "Summary output of the test case:"
End With
With Cells(3, 2)
    .Font.Bold = True
    .Value = CaseDir & CaseName
End With
With Cells(4, 2)
    .Font.Bold = True
    .Value = "Total number of replication analyzed:"
End With

Cells(6, 2).Font.Italic = True
Cells(6, 2).Value = "Network analysis started from " & Time() & ", " & Date
Range(Cells(7, 1), Cells(7, 8)).Font.Italic = True
Cells(7, 2).Value = "Replication"
Cells(7, 3).Value = "SysQuTime"
Cells(7, 4).Value = "SysStTime"
Cells(7, 5).Value = "SysVehHour"
Cells(7, 6).Value = "SysVehMile"

'extract corsim output information from .out files
For RplCnt = StRpl To RplNum
    OutFileNum = FreeFile()
    OutFile = CaseDir & CaseName & CStr(RplCnt) & ".out"
    Open OutFile For Input Access Read As #OutFileNum

    'create worksheet for corsim replicational output data
    For a = 1 To Worksheets.count - 1
        If Worksheets(a).Name = "OutputInfo" & CStr(RplCnt) Then
            Application.DisplayAlerts = False
            Worksheets(a).Delete
            Application.DisplayAlerts = True
        End If
    Next a
End For

```

```

        End If
    Next a
    Set NewSheet = Worksheets.Add
    NewSheet.Name = "OutputInfo" & CStr(RplCnt)
    CursorRow = 0

    ' head information for replication analysis
    With Cells(2, 2)
        .Value = "Output analysis results from the file:"
        .Font.Bold = True
    End With
    With Cells(3, 2)
        .Value = OutFile
        .Font.Bold = True
    End With
    CursorRow = 5

    For i = 1 To LnkNum: For j = 1 To TpdNum
        LnkCntTrips(i, j) = 0: LnkInpTrips(i, j) = 0: LnkOutTrips(i, j) = 0
    Next j: Next i

    a = 0: b = 0
    While Not EOF(OutFileNum)
        Line Input #OutFileNum, OutLine

        'header tagging the beginning of link output statistics table for time
interval 1
        If Mid(OutLine, 5, 46) = "LINK      MILES TRIPS      TIME      TIME      TIME" And
a = 0 Then
            a = a + 1: count = 0

            ' exit loop after analyzing one complete cycle of corsim links
            While count < LnkNum
                Line Input #OutFileNum, OutLine
                If Mid(OutLine, 2, 1) = "(" Then
                    count = count + 1
                    anode = CInt(Mid(OutLine, 3, 4))
                    bnode = CInt(Mid(OutLine, 8, 4))

                    ' collect interval output information for corresponding corsim
links in input file analysis
                    For LnkCnt = 1 To LnkNum
                        If LnkAnode(LnkCnt) = anode And LnkBnode(LnkCnt) = bnode Then
                            If Trim(Mid(OutLine, 22, 5)) <> "" Then LnkTrips(LnkCnt,
a) = CSng(Mid(OutLine, 22, 5))
                            If Trim(Mid(OutLine, 92, 5)) <> "" Then LnkCtDelay(LnkCnt,
a) = CSng(Mid(OutLine, 92, 5))
                            If Trim(Mid(OutLine, 100, 5)) <> "" Then
LnkVehQuTime(LnkCnt, a) = CSng(Mid(OutLine, 100, 5))
                            If Trim(Mid(OutLine, 108, 5)) <> "" Then
LnkVehStTime(LnkCnt, a) = CSng(Mid(OutLine, 108, 5))
                            If Trim(Mid(OutLine, 113, 5)) <> "" Then LnkStPct(LnkCnt,
a) = CSng(Mid(OutLine, 113, 5))
                            If Trim(Mid(OutLine, 126, 5)) <> "" Then LnkSpeed(LnkCnt,
a) = CSng(Mid(OutLine, 126, 5))
                        End If
                    Next LnkCnt
                End If
            End While
        End If
    End While

```

```

' collect interval output information for corresponding corsim
links for validation
For c = 1 To 3
  If V1LnkAnode(c) = anode And V1LnkBnode(c) = bnode Then
    If Trim(Mid(OutLine, 22, 5)) <> "" Then V1LnkTrips(c, a)
= CSng(Mid(OutLine, 22, 5))
    If Trim(Mid(OutLine, 108, 5)) <> "" Then V1LnkStTime(c, a)
= CSng(Mid(OutLine, 108, 5))
  End If
Next c
End If
Wend
End If

'table title tagging interval specific link output for time intervals 2 and
thereafter
If Mid(OutLine, 45, 26) = "SPECIFIC NETSIM STATISTICS" Then
  ' a denotes time interval number
  a = a + 1: count = 0

  ' exit loop after analyzing a complete cycle of corsim links
  While count < LnkNum
    Line Input #OutFileNum, OutLine
    If Mid(OutLine, 2, 1) = "(" Then
      count = count + 1
      anode = CInt(Mid(OutLine, 3, 4))
      bnode = CInt(Mid(OutLine, 8, 4))

      ' collect interval output information for corresponding corsim
links in input file analysis
      For LnkCnt = 1 To LnkNum
        If LnkAnode(LnkCnt) = anode And LnkBnode(LnkCnt) = bnode Then
          If Trim(Mid(OutLine, 22, 5)) <> "" Then LnkTrips(LnkCnt,
a) = CSng(Mid(OutLine, 22, 5))
          If Trim(Mid(OutLine, 92, 5)) <> "" Then LnkCtDelay(LnkCnt,
a) = CSng(Mid(OutLine, 92, 5))
          If Trim(Mid(OutLine, 100, 5)) <> "" Then
LnkVehQuTime(LnkCnt, a) = CSng(Mid(OutLine, 100, 5))
          If Trim(Mid(OutLine, 108, 5)) <> "" Then
LnkVehStTime(LnkCnt, a) = CSng(Mid(OutLine, 108, 5))
          If Trim(Mid(OutLine, 113, 5)) <> "" Then LnkStPct(LnkCnt,
a) = CSng(Mid(OutLine, 113, 5))
          If Trim(Mid(OutLine, 126, 5)) <> "" Then LnkSpeed(LnkCnt,
a) = CSng(Mid(OutLine, 126, 5))
        End If
      Next LnkCnt

      ' collect interval output information for corresponding corsim
links for validation
      For c = 1 To 3
        If V1LnkAnode(c) = anode And V1LnkBnode(c) = bnode Then
          If Trim(Mid(OutLine, 22, 5)) <> "" Then V1LnkTrips(c, a)
= CSng(Mid(OutLine, 22, 5))
          If Trim(Mid(OutLine, 108, 5)) <> "" Then V1LnkStTime(c, a)
= CSng(Mid(OutLine, 108, 5))
        End If
      Next c
    End If
  End While
End If

```

```

        Next c
      End If
    Wend

  End If

  ' title tagging corsim movement statistics table I for all time intervals
  If Trim(Mid(OutLine, 10, 120)) = "NETSIM MOVEMENT SPECIFIC STATISTICS - TABLE
I" Then
    b = b + 1: count = 0
    While count < LnkNum
      Line Input #OutFileNum, OutLine
      If Mid(OutLine, 6, 1) = "(" Then
        count = count + 1
        anode = CInt(Mid(OutLine, 7, 4))
        bnode = CInt(Mid(OutLine, 12, 4))

        For LnkCnt = 1 To LnkNum
          If LnkAnode(LnkCnt) = anode And LnkBnode(LnkCnt) = bnode Then
            ' link left-turn movement trips
            If Trim(Mid(OutLine, 51, 4)) <> "" Then
              LnkLtTrips(LnkCnt, b) = CSng(Mid(OutLine, 51, 4))

              'cumulate link dsicharged trips for downstream link
input trips

              For i = 1 To LnkNum
                If LnkAnode(i) = LnkBnode(LnkCnt) And LnkBnode(i)
= LnkLnode(LnkCnt) Then
                  LnkInpTrips(i, b) = LnkInpTrips(i, b) +
LnkLtTrips(LnkCnt, b)

                  End If
                Next i
              End If

              ' link through movement trips
              If Trim(Mid(OutLine, 59, 4)) <> "" Then
                LnkThTrips(LnkCnt, b) = CSng(Mid(OutLine, 59, 4))

                'cumulate link dsicharged trips for downstream link
input trips

                For i = 1 To LnkNum
                  If LnkAnode(i) = LnkBnode(LnkCnt) And LnkBnode(i)
= LnkTnode(LnkCnt) Then
                    LnkInpTrips(i, b) = LnkInpTrips(i, b) +
LnkThTrips(LnkCnt, b)

                    End If
                  Next i
                End If

                ' link right-turn movement trips
                If Trim(Mid(OutLine, 68, 4)) <> "" Then
                  LnkRtTrips(LnkCnt, b) = CSng(Mid(OutLine, 68, 4))

                  'cumulate link dsicharged trips for downstream link
input trips

                  For i = 1 To LnkNum

```



```

                                If LnkAnode(i) = LnkBnode(LnkCnt) And LnkBnode(i)
= LnkRnode(LnkCnt) Then
                                LnkInpTrips(i, b) = LnkInpTrips(i, b) +
LnkRtTrips(LnkCnt, b)
                                End If
                                Next i
                                End If
                                End If
                                Next LnkCnt
                                End If
                                Wend
                                End If

' title tagging corsim movement statistics table III for all time intervals
If Trim(Mid(OutLine, 10, 120)) = "NETSIM MOVEMENT SPECIFIC STATISTICS - TABLE
III" Then
    count = 0

    ' exit loop after analyzing a complete cycle of links
    While count < LnkNum
        Line Input #OutFileNum, OutLine
        If Mid(OutLine, 6, 1) = "(" Then
            count = count + 1
            anode = CInt(Mid(OutLine, 7, 4))
            bnode = CInt(Mid(OutLine, 12, 4))

            'collect movement specific traffic MOE for corresponding links in
input file analysis
            For LnkCnt = 1 To LnkNum
                If LnkAnode(LnkCnt) = anode And LnkBnode(LnkCnt) = bnode Then
                    If Trim(Mid(OutLine, 78, 7)) <> "" Then
LnkLtQuTime(LnkCnt, b) = CSng(Mid(OutLine, 78, 7))
                    If Trim(Mid(OutLine, 86, 7)) <> "" Then
LnkThQuTime(LnkCnt, b) = CSng(Mid(OutLine, 86, 7))
                    If Trim(Mid(OutLine, 95, 7)) <> "" Then
LnkRtQuTime(LnkCnt, b) = CSng(Mid(OutLine, 95, 7))
                    If Trim(Mid(OutLine, 107, 7)) <> "" Then
LnkLtStTime(LnkCnt, b) = CSng(Mid(OutLine, 107, 7))
                    If Trim(Mid(OutLine, 115, 7)) <> "" Then
LnkThStTime(LnkCnt, b) = CSng(Mid(OutLine, 115, 7))
                    If Trim(Mid(OutLine, 124, 7)) <> "" Then
LnkRtStTime(LnkCnt, b) = CSng(Mid(OutLine, 124, 7))

                                '!!!LnkQuTime(,) and LnkStTime(,) are both cumulative
statistics for system info derivation
                                If Trim(Mid(OutLine, 78, 21)) <> "" Then
                                    LnkQuTime(LnkCnt, b) = LnkLtQuTime(LnkCnt, b) +
LnkThQuTime(LnkCnt, b) + LnkRtQuTime(LnkCnt, b)
                                    End If
                                    If Trim(Mid(OutLine, 107, 21)) <> "" Then
                                        LnkStTime(LnkCnt, b) = LnkLtStTime(LnkCnt, b) +
LnkThStTime(LnkCnt, b) + LnkRtStTime(LnkCnt, b)
                                        End If
                                    End If
                                End If
                                Next LnkCnt
                            End If
                        Wend
                    
```

```

End If

Wend
Close #OutFileNum

'cumulate system level statistics
SysQuTime = 0: SysStTime = 0: SysVehHour = 0: SysVehMile = 0
For LnkCnt = 1 To LnkNum
  For TpdCnt = 1 To TpdNum
    'cumulate system level statistics
    If LnkLength(LnkCnt) <> "" Then
      If TpdCnt = TpdNum Then
        SysQuTime = SysQuTime + LnkQuTime(LnkCnt, TpdCnt) / 60
        SysStTime = SysStTime + LnkStTime(LnkCnt, TpdCnt) / 60
      End If
      SysVehMile = SysVehMile + LnkTrips(LnkCnt, TpdCnt) * LnkLength(LnkCnt)
/ 5280

      If LnkSpeed(LnkCnt, TpdCnt) <> 0 Then
        SysVehHour = SysVehHour + LnkTrips(LnkCnt, TpdCnt) *
LnkLength(LnkCnt) / 5280 / LnkSpeed(LnkCnt, TpdCnt)
      End If
    End If
  End If

  ' derive link output trips for each time interval
  If TpdCnt = 1 Then
    LnkOutTrips(LnkCnt, TpdCnt) = LnkTrips(LnkCnt, TpdCnt)
  Else
    LnkOutTrips(LnkCnt, TpdCnt) = LnkOutTrips(LnkCnt, TpdCnt - 1) +
LnkTrips(LnkCnt, TpdCnt)
  End If
  ' derive link content trips for each time interval
  LnkCntTrips(LnkCnt, TpdCnt) = LnkInpTrips(LnkCnt, TpdCnt) -
LnkOutTrips(LnkCnt, TpdCnt)
Next TpdCnt
Next LnkCnt

'record corsim network link and system information
With Cells(CursorRow, 2)
  .Font.Bold = True
  .Font.Color = RGB(255, 0, 0)
  .Value = "Network cumulative statistics:"
End With
CursorRow = CursorRow + 1
Cells(CursorRow, 2).Value = "System Queue Time =": Cells(CursorRow,
2).Font.Italic = True
Cells(CursorRow, 5).Value = SysQuTime: Cells(CursorRow, 5).Font.Color = RGB(255,
0, 0)
CursorRow = CursorRow + 1
Cells(CursorRow, 2).Value = "System Stop Time =": Cells(CursorRow, 2).Font.Italic
= True
Cells(CursorRow, 5).Value = SysStTime: Cells(CursorRow, 5).Font.Color = RGB(255,
0, 0)
CursorRow = CursorRow + 1
Cells(CursorRow, 2).Value = "System Vehicle Miles =": Cells(CursorRow,
2).Font.Italic = True
Cells(CursorRow, 5).Value = SysVehMile: Cells(CursorRow, 5).Font.Color = RGB(255,
0, 0)

```

```

    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Value = "System Vehicle Hours =": Cells(CursorRow,
2).Font.Italic = True
    Cells(CursorRow, 5).Value = SysVehHour: Cells(CursorRow, 5).Font.Color = RGB(255,
0, 0)
    CursorRow = CursorRow + 1

' record link MOE for each time interval
For i = 1 To 12
    For LnkCnt = 1 To LnkNum
        ' add header information
        If LnkCnt = 1 Then
            CursorRow = CursorRow + 2
            With Cells(CursorRow, 2)
                .Font.Bold = True
                Select Case i
                    Case 1
                        .Value = "Link vehicle trips by time period:"
                    Case 2
                        .Value = "Link vehicle control delay by time period
(sec/veh):"
                    Case 3
                        .Value = "Link vehicle queue time by time period
(sec/veh):"
                    Case 4
                        .Value = "Link vehicle stop time by time period
(sec/veh):"
                    Case 5
                        .Value = "Link vehicle stop percentage by time period
(%):"
                    Case 6
                        .Value = "Link vehicle speed by time period (mph):"
                    Case 7
                        .Value = "Link vehicle left turn trips by time period:"
                    Case 8
                        .Value = "Link vehicle through trips by time period:"
                    Case 9
                        .Value = "Link vehicle right turn trips by time period:"
                    Case 10
                        .Value = "Link cumulative queue time by time period:"
                    Case 11
                        .Value = "Link cumulative stop time by time period:"
                    Case 12
                        .Value = "Link content trips by time period:"
                    Case Else
                End Select
            End With
            CursorRow = CursorRow + 1
        End If

        ' add link information
        Cells(CursorRow, 2).Value = LnkAnode(LnkCnt)
        Cells(CursorRow, 2).Font.Italic = True
        Cells(CursorRow, 3).Value = LnkBnode(LnkCnt)
        Cells(CursorRow, 3).Font.Italic = True
        Cells(CursorRow, 4) = "::~"
    End For
End For

```

```

' record link MOE for each time interval
For TpdCnt = 1 To TpdNum
  Select Case i
    Case 1
      Cells(CursorRow, TpdCnt + 4).Value = LnkTrips(LnkCnt,
TpdCnt)
    Case 2
      Cells(CursorRow, TpdCnt + 4).Value = LnkCtDelay(LnkCnt,
TpdCnt)
    Case 3
      Cells(CursorRow, TpdCnt + 4).Value = LnkVehQuTime(LnkCnt,
TpdCnt)
    Case 4
      Cells(CursorRow, TpdCnt + 4).Value = LnkVehStTime(LnkCnt,
TpdCnt)
    Case 5
      Cells(CursorRow, TpdCnt + 4).Value = LnkStPct(LnkCnt,
TpdCnt)
    Case 6
      Cells(CursorRow, TpdCnt + 4).Value = LnkSpeed(LnkCnt,
TpdCnt)
    Case 7
      Cells(CursorRow, TpdCnt + 4).Value = LnkLtTrips(LnkCnt,
TpdCnt)
    Case 8
      Cells(CursorRow, TpdCnt + 4).Value = LnkThTrips(LnkCnt,
TpdCnt)
    Case 9
      Cells(CursorRow, TpdCnt + 4).Value = LnkRtTrips(LnkCnt,
TpdCnt)
    Case 10
      Cells(CursorRow, TpdCnt + 4).Value = LnkQuTime(LnkCnt,
TpdCnt)
    Case 11
      Cells(CursorRow, TpdCnt + 4).Value = LnkStTime(LnkCnt,
TpdCnt)
    Case 12
      Cells(CursorRow, TpdCnt + 4).Value = LnkCntTrips(LnkCnt,
TpdCnt)
    Case Else
  End Select
  Next TpdCnt
  CursorRow = CursorRow + 1

Next LnkCnt
Next i

' summarize replication system information
With Worksheets("Summary")
  .Cells(4, 6).Font.Size = 12
  .Cells(4, 6).Value = RplCnt
  .Cells(RplCnt + 7, 2).Value = RplCnt
  .Cells(RplCnt + 7, 3).Value = SysQuTime
  .Cells(RplCnt + 7, 4).Value = SysStTime
  .Cells(RplCnt + 7, 5).Value = SysVehHour
  .Cells(RplCnt + 7, 6).Value = SysVehMile
End With

```

```

For i = 1 To 3
    VLNkVehTrips(i) = 0: VLNkVehStTime(i) = 0
    For j = 1 To 12
        c = VLNkVehTrips(i) * VLNkVehStTime(i) + VLNkTrips(i, j) *
VLNkStTime(i, j)
        VLNkVehTrips(i) = VLNkVehTrips(i) + VLNkTrips(i, j)
        VLNkVehStTime(i) = c / VLNkVehTrips(i)
    Next j
Next i

With Worksheets("validation")
    If RplCnt = 1 Then
        .Cells(RplCnt + 1, 2).Value = "Anode(1)"
        .Cells(RplCnt + 1, 3).Value = "Bnode(1)"
        .Cells(RplCnt + 1, 4).Value = "Trips(1)"
        .Cells(RplCnt + 1, 5).Value = "Time(1)"
        .Cells(RplCnt + 1, 7).Value = "Anode(2)"
        .Cells(RplCnt + 1, 8).Value = "Bnode(2)"
        .Cells(RplCnt + 1, 9).Value = "Trips(2)"
        .Cells(RplCnt + 1, 10).Value = "StTime(2)"
        .Cells(RplCnt + 1, 12).Value = "Anode(3)"
        .Cells(RplCnt + 1, 13).Value = "Bnode(3)"
        .Cells(RplCnt + 1, 14).Value = "Trips(3)"
        .Cells(RplCnt + 1, 15).Value = "StTime(3)"
    End If

    .Cells(RplCnt + 2, 2).Value = VLNkAnode(1)
    .Cells(RplCnt + 2, 3).Value = VLNkBnode(1)
    .Cells(RplCnt + 2, 4).Value = VLNkVehTrips(1)
    .Cells(RplCnt + 2, 5).Value = VLNkVehStTime(1)
    .Cells(RplCnt + 2, 6).Value = "&"
    .Cells(RplCnt + 2, 7).Value = VLNkAnode(2)
    .Cells(RplCnt + 2, 8).Value = VLNkBnode(2)
    .Cells(RplCnt + 2, 9).Value = VLNkVehTrips(2)
    .Cells(RplCnt + 2, 10).Value = VLNkVehStTime(2)
    .Cells(RplCnt + 2, 11).Value = "&"
    .Cells(RplCnt + 2, 12).Value = VLNkAnode(3)
    .Cells(RplCnt + 2, 13).Value = VLNkBnode(3)
    .Cells(RplCnt + 2, 14).Value = VLNkVehTrips(3)
    .Cells(RplCnt + 2, 15).Value = VLNkVehStTime(3)

End With
Next RplCnt

Worksheets("Summary").Activate
Cells(RplNum + 8, 2).Font.Italic = True
Cells(RplNum + 8, 2).Value = "Network analysis ended at " & Time() & ", " & Date

ActiveWorkbook.Close saveChanges:=True

Cells(12, 2).Value = "Part 1: collect information end time: " & Time()
ActiveWorkbook.Save

End Sub

Sub FlwDtc()

```

```

Dim BaseFile, BaseLine, OutFile, OutLine As String
Dim NewSheet As Object
Dim Ending, FlSim As Boolean
Dim RplCnt, TpdCnt, FlRplCnt, FlRplNum, BaseFileNum, OutFileNum As Integer
Dim LnkNum, LnkCnt, TrnNum, TrnCnt, IntNum, IntCnt, DmdNum, DmdCnt As Integer
Dim a, b, c, i, j, k, count, CursorRow, CursorCol, anode, bnode, cnode As Integer

Dim LnkAnode(150), LnkBnode(150), LnkLnode(150), LnkTnode(150), LnkRnode(150)
Dim LnkLength(150), LnkLanes(150), LnkLtPct(150), LnkThPct(150), LnkRtPct(150)
Dim IntID(60), IntType(60), IntOffset(60), IntPhases(60), IntCycLng(60)
Dim DmdSnode(40), DmdEnode(40), DmdFlRate(40), DmdHvPct(40)

Dim LnkTrips(150, 12), LnkVehStTime(150, 12), LnkCtDelay(150, 12)
Dim LnkVehQuTime(150, 12), LnkStPct(150, 12), LnkSpeed(150, 12)
Dim LnkLtTrips(150, 12), LnkThTrips(150, 12), LnkRtTrips(150, 12)
Dim LnkQuTime(150, 12), LnkStTime(150, 12)
Dim LnkLtQuTime(150, 12), LnkThQuTime(150, 12), LnkRtQuTime(150, 12)
Dim LnkLtStTime(150, 12), LnkThStTime(150, 12), LnkRtStTime(150, 12)
Dim LnkCntTrips(150, 12), LnkInpTrips(150, 12), LnkOutTrips(150, 12)
Dim LnkFlStTpd(150), FlLnkNum(RplNum), FlStTpd(RplNum)

Dim SysQuTime, SysStTime, SysVehMile, SysVehHour

For i = 1 To 150: For j = 1 To 12
    LnkCntTrips(i, j) = 0: LnkInpTrips(i, j) = 0: LnkOutTrips(i, j) = 0
Next j: Next i

'record experiment information
With Worksheets("CorAn1").Range("B2", "E20")
    Cells(13, 2).Value = "Beginning output data analysis ..."
End With

'open the target workbook generated by sub "GetInfo"
Workbooks.Open Filename:="An1" & CaseName & ".xls"
Worksheets.Add before:=Worksheets("InputInfo")
ActiveSheet.Name = "FlwDtc"

' record header information
With Worksheets("FlwDtc")
    .Cells(2, 2).Font.Bold = True
    .Cells(2, 2) = Date & Time()
    .Cells(3, 2).Font.Bold = True
    .Cells(3, 2) = "Corsim Flaw Detection Procedure"
    .Cells(5, 2).Font.Italic = True
    .Cells(5, 2) = "Part II: Network flaw detection results: "
End With

'collect network links information from GetInfo output
Worksheets("InputInfo").Activate
CursorRow = 1: count = 0 'counting the number of blank lines
' end loop after meeting 10 consecutive blank lines
While count < 10
    If Trim(Cells(CursorRow, 2).Value) <> "" Then
        i = 0
        If Cells(CursorRow, 2).Value = "Part 3: Network Links Information" Then
            CursorRow = CursorRow + 2
        End If
    Else
        count = count + 1
    End If
End While

```

```

While Left(Cells(CursorRow, 2).Value, 27) <> " Number of Links
Analyzed : "
    i = i + 1
    LnkAnode(i) = CInt(Cells(CursorRow, 2).Value)
    LnkBnode(i) = CInt(Cells(CursorRow, 3).Value)
    LnkLnode(i) = CInt(Cells(CursorRow, 4).Value)
    LnkTnode(i) = CInt(Cells(CursorRow, 5).Value)
    LnkRnode(i) = CInt(Cells(CursorRow, 6).Value)
    CursorRow = CursorRow + 1
Wend
LnkNum = i: count = 0
End If
Else
    count = count + 1
End If
CursorRow = CursorRow + 1
Wend

FlRplCnt = 0: FlRplNum = 0
'collect corsim output information
For RplCnt = StRpl To RplNum
    With Worksheets("FlwDtc")
        .Cells(RplCnt + 5, 2).Font.Italic = True
        .Cells(RplCnt + 5, 2).Value = "Currently analyzing replication number " &
RplCnt & "... "
    End With

Worksheets("OutputInfo" & RplCnt).Activate

'collect corsim link trips and content trips information from GetInfo output
count = 0: CursorRow = 1: Ending = False
' exit loop after meeting 10 consecutive blank lines
While Ending = False
    CursorRow = CursorRow + 1
    If Trim(Cells(CursorRow, 2).Value) <> "" Then
        ' collect link discharged trips for each time interval
        If Cells(CursorRow, 2).Value = "Link vehicle trips by time period:" Then
            CursorRow = CursorRow + 1
            While Trim(Cells(CursorRow, 4).Value) = ":::"
                For i = 1 To LnkNum
                    If LnkAnode(i) = Cells(CursorRow, 2).Value And LnkBnode(i) =
Cells(CursorRow, 3).Value Then
                        For j = 1 To 12
                            LnkTrips(i, j) = Cells(CursorRow, j + 4).Value
                        Next j
                    End If
                Next i
                CursorRow = CursorRow + 1
            Wend
        End If
    End If
    ' collect link content trips for each time interval
    If Cells(CursorRow, 2).Value = "Link content trips by time period:" Then
        CursorRow = CursorRow + 1
        While Trim(Cells(CursorRow, 4).Value) = ":::"
            For i = 1 To LnkNum
                If LnkAnode(i) = Cells(CursorRow, 2).Value And LnkBnode(i) =
Cells(CursorRow, 3).Value Then

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```

                For j = 1 To 12
                    LnkCntTrips(i, j) = Cells(CursorRow, j + 4).Value
                Next j
            End If
        Next i
        CursorRow = CursorRow + 1
    Wend
End If
count = 0
Else
    count = count + 1
End If
If count > 10 Then Ending = True
Wend

'add header information for failure detection
With Cells(CursorRow, 2)
    .Font.Bold = True
    .Font.Color = RGB(255, 0, 0)
    .Value = "Network failure detection results:"
End With
CursorRow = CursorRow + 1

'judge occurrence of failure
For LnkCnt = 1 To LnkNum
    LnkFlStTpd(LnkCnt) = TpdNum + 1

    ' exclude source links, exit links, and minor links
    If LnkAnode(LnkCnt) < 8000 And LnkBnode(LnkCnt) < 8000 And LnkTrips(LnkCnt, 1)
> DtcTsd Then
        For TpdCnt = 1 To TpdNum
            ' judge first time interval blockage
            If TpdCnt = 1 Then
                If LnkTrips(LnkCnt, TpdCnt) <= FlTsd And LnkCntTrips(LnkCnt,
TpdCnt) > CntTsd Then
                    LnkFlStTpd(LnkCnt) = 1
                Else
                    LnkFlStTpd(LnkCnt) = TpdNum + 1
                End If
            Else
                ' judge the occurrence of link blockage
                If LnkFlStTpd(LnkCnt) > TpdCnt Then
                    If LnkTrips(LnkCnt, TpdCnt) <= FlTsd And LnkCntTrips(LnkCnt,
TpdCnt) > CntTsd Then
                        LnkFlStTpd(LnkCnt) = TpdCnt
                    End If
                    ' judge the recovery of link blockage
                    Else
                        If LnkTrips(LnkCnt, TpdCnt) - LnkTrips(LnkCnt,
LnkFlStTpd(LnkCnt)) > BbTsd Then
                            LnkFlStTpd(LnkCnt) = TpdNum + 1
                        End If
                    End If
                End If
            Next TpdCnt
        End If
    End If

```



```

' record link blockage information for each link in each replication output
If LnkCnt = 1 Then
    Cells(CursorRow, 2).Value = "Link failure time period information:"
    CursorRow = CursorRow + 1
End If
Cells(CursorRow, 2).Value = LnkAnode(LnkCnt)
Cells(CursorRow, 3).Value = LnkBnode(LnkCnt)
Cells(CursorRow, 4).Value = "::"
Cells(CursorRow, 5).Value = LnkFlStTpd(LnkCnt)
CursorRow = CursorRow + 1
Next LnkCnt

' copy link blockage information
Range(Cells(CursorRow - 150, 2), Cells(CursorRow - 1, 5)).Select
Selection.Copy
Range(Cells(CursorRow - 150, 7), Cells(CursorRow - 1, 10)).Select
ActiveSheet.Paste

' sort link blockage information according to blockage time, Bnode, Anode
Selection.Sort Key1:=Columns("J"), Order1:=xlAscending, key2:=Columns("H"), _
Order2:=xlAscending, key3:=Columns("G"), order3:=xlAscending

' derive the earliest link blockage time
FlStTpd(RplCnt) = Cells(CursorRow - 150, 10).Value

' conclude number of failure links and replication failure occurrence
FlSim = False: FlLnkNum(RplCnt) = 0
For LnkCnt = 1 To LnkNum
    If LnkFlStTpd(LnkCnt) < TpdNum + 1 Then
        FlSim = True: FlLnkNum(RplCnt) = FlLnkNum(RplCnt) + 1
    End If
Next LnkCnt

CursorCol = 2
For i = CursorRow - 150 To CursorRow - 1
    If Cells(i, 10) < TpdNum + 1 Then
        ' cumulate number of failure replications
        If i = CursorRow - 150 Then FlRplCnt = FlRplCnt + 1

        ' record first failed links in the summary worksheet
        With Worksheets("flwDtc")
            .Rows(RplNum + FlRplCnt + 8).Font.Italic = True
            .Rows(RplNum + FlRplCnt + 8).HorizontalAlignment = xlCenter

            ' add replication index info
            If CursorCol = 2 Then
                .Cells(RplNum + FlRplCnt + 8, CursorCol).HorizontalAlignment =
xlRight
                .Cells(RplNum + FlRplCnt + 8, CursorCol).Value = "Repl'n " &
CStr(RplCnt)
                .Cells(RplNum + FlRplCnt + 8, CursorCol + 1).Value = ":"
                .Cells(RplNum + FlRplCnt + 8, CursorCol + 1).Font.Bold = True
                CursorCol = CursorCol + 2
            End If

            ' Record first failed link(s) in the replication
            If FlSim = True And Cells(i, 10) = Cells(CursorRow - 150, 10) Then

```

```

        If CursorCol <> 4 Then .Cells(RplNum + FlRplCnt + 8, CursorCol -
1).Value = ";"
        .Cells(RplNum + FlRplCnt + 8, CursorCol).Value = Cells(i,
7).Value
        .Cells(RplNum + FlRplCnt + 8, CursorCol + 1).Value = ">>>>"
        .Cells(RplNum + FlRplCnt + 8, CursorCol + 2).Value = Cells(i,
8).Value
        End If
        CursorCol = CursorCol + 4
    End With
End If
Next i

' record failure detection results for each replication
With Worksheets("FlwDtc")
    .Cells(RplCnt + 5, 8).Font.Italic = True
    .Cells(RplCnt + 5, 8).Value = "Replication Failure:"
    .Cells(RplCnt + 5, 10).Font.Bold = True
    .Cells(RplCnt + 5, 10).Value = FlSim
    .Cells(RplCnt + 5, 12).Font.Italic = True
    .Cells(RplCnt + 5, 12).Value = "# of Failure Links:"
    .Cells(RplCnt + 5, 14).Font.Bold = True
    .Cells(RplCnt + 5, 14).Value = FlLnkNum(RplCnt)
    .Cells(RplCnt + 5, 16).Font.Italic = True
    .Cells(RplCnt + 5, 16).Value = "First Failure Time:"
    .Cells(RplCnt + 5, 18).Font.Bold = True
    .Cells(RplCnt + 5, 18).Value = FlStTpd(RplCnt)
End With

Next RplCnt
FlRplNum = FlRplCnt

With Worksheets("FlwDtc")
    .Cells(RplNum + 6, 2).Font.Italic = True
    .Cells(RplNum + 6, 2).Value = "There are " & CStr(FlRplNum) & " failures found."
    .Cells(RplNum + 7, 2).Font.Italic = True
    .Cells(RplNum + 7, 2).Value = "Network analysis ended at " & Time() & ", " & Date
End With

Worksheets("FlwDtc").Activate
ActiveWorkbook.Close saveChanges:=True

Cells(14, 2).Value = "Part 2: failure detection end time: " & Time()
ActiveWorkbook.Save

End Sub

Sub CslAnl()
    Dim BaseFile, BaseLine, OutFile, OutLine, RecType As String
    Dim NewSheet As Object
    Dim Ending, FlSim As Boolean
    Dim RplCnt, TpdCnt, FlRplCnt, FlRplNum, BaseFileNum, OutFileNum As Integer
    Dim LnkNum, LnkCnt, TrnNum, TrnCnt, IntNum, IntCnt, DmdNum, DmdCnt As Integer
    Dim a, b, c, i, j, k, count, CursorRow, CursorCol, anode, bnode, cnode As Integer
    Dim firstP1, firstP2, firstP3, firstP4, firstP5, firstP6, firstP7, firstP8 As Boolean

```

```

Dim LnkAnode(150), LnkBnode(150), LnkLnode(150), LnkTnode(150), LnkRnode(150)
Dim LnkLength(150), LnkLanes(150), LnkLtPct(150), LnkThPct(150), LnkRtPct(150)
Dim IntID(60), IntType(60), IntOffset(60), IntPhases(60), IntCycLng(60)
Dim DmdSnode(40), DmdEnode(40), DmdFlRate(40), DmdHvPct(40)

Dim LnkFlFrq(150), IntFlFrq(60), IntAdded(150)

'record experiment information
With Worksheets("CorAn1").Range("B2", "E20")
    Cells(15, 2).Value = "Beginning failure causal analysis ..."
End With

'open the target workbook generated by sub "FlwDtc"
Workbooks.Open Filename:="An1" & CaseName & ".xls"
Worksheets("FlwDtc").Activate

With Worksheets("FlwDtc")
    .Cells(2, 12).Font.Bold = True
    .Cells(2, 12) = Date & Time()
    .Cells(3, 12).Font.Bold = True
    .Cells(3, 12) = "Corsim Flaw Detection Procedure started from " & Time() & ", " &
Date
End With

'collect network links and nodes information
Worksheets("InputInfo").Activate
CursorRow = 1: count = 0          'counting the number of blank lines
While count < 10
    If Trim(Cells(CursorRow, 2).Value) <> "" Then
        i = 0: j = 0

        ' collect network links information
        If Cells(CursorRow, 2).Value = "Part 3: Network Links Information" Then
            CursorRow = CursorRow + 2
            While Left(Cells(CursorRow, 2).Value, 27) <> " Number of Links
Analyzed : "
                i = i + 1
                LnkAnode(i) = CInt(Cells(CursorRow, 2).Value)
                LnkBnode(i) = CInt(Cells(CursorRow, 3).Value)
                LnkLnode(i) = CInt(Cells(CursorRow, 4).Value)
                LnkTnode(i) = CInt(Cells(CursorRow, 5).Value)
                LnkRnode(i) = CInt(Cells(CursorRow, 6).Value)
                CursorRow = CursorRow + 1
            Wend
            LnkNum = i: count = 0
        End If

        ' collect network nodes information
        If Cells(CursorRow, 2).Value = "Part 5: Signal Information" Then
            CursorRow = CursorRow + 2
            While Left(Cells(CursorRow, 2).Value, 35) <> " Number of Intersections
Analyzed : "
                j = j + 1
                IntID(j) = CInt(Cells(CursorRow, 2).Value)
                IntType(j) = Cells(CursorRow, 3).Value
                CursorRow = CursorRow + 1
            Wend
        End While
    End If
End While

```

```

        Wend
        IntNum = j: count = 0
    End If
Else
    count = count + 1
End If
    CursorRow = CursorRow + 1
Wend

Worksheets("FlwDtc").Activate
For i = 1 To LnkNum: LnkFlFrq(i) = 0: Next i
For i = 1 To IntNum: IntFlFrq(i) = 0: Next i

CursorRow = 1: count = 0: Ending = False
While Ending = False
    CursorRow = CursorRow + 1
    While Left(CStr(Cells(CursorRow, 2).Value), 22) = "Network analysis ended"
        CursorRow = CursorRow + 2

        ' gather data for first blocked links in each replication
        While Left(CStr(Cells(CursorRow, 2).Value), 6) = "Repl'n"
            count = count + 1: CursorCol = 5
            For i = 1 To IntNum: IntAdded(i) = False: Next i
            While Cells(CursorRow, CursorCol) = ">>>>"
                anode = CInt(Cells(CursorRow, CursorCol - 1).Value)
                bnode = CInt(Cells(CursorRow, CursorCol + 1).Value)

                ' cumulate frequency of first failures for each link
                For LnkCnt = 1 To LnkNum
                    If LnkAnode(LnkCnt) = anode And LnkBnode(LnkCnt) = bnode Then
                        LnkFlFrq(LnkCnt) = LnkFlFrq(LnkCnt) + 1
                    End If
                Next LnkCnt

                ' cumulate frequency of first failures for each node
                For IntCnt = 1 To IntNum
                    If IntID(IntCnt) = bnode And IntAdded(IntCnt) = False Then
                        IntFlFrq(IntCnt) = IntFlFrq(IntCnt) + 1
                        IntAdded(IntCnt) = True
                    End If
                Next IntCnt

                CursorCol = CursorCol + 4
            Wend
            CursorRow = CursorRow + 1
        Wend
    Ending = True
Wend
FlRplNum = count

CursorRow = CursorRow + 1
With Cells(CursorRow, 2)
    .Font.Bold = True
    .Value = "Part III: Network Causal Analysis Results (" & CStr(FlRplNum) & "
failure replications analyzed)"
End With

```

```

CursorRow = CursorRow + 1
With Cells(CursorRow, 2)
    .Font.Italic = True
    .Value = "Network link failure frequencies:"
End With

' record link failure frequency information
For i = 1 To LnkNum
    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Value = LnkAnode(i)
    Cells(CursorRow, 3).Value = ">>>>"
    Cells(CursorRow, 4).Value = LnkBnode(i)
    Cells(CursorRow, 5).Value = "::"
    Cells(CursorRow, 6).Value = LnkFlFrq(i)
Next i

Range(Cells(CursorRow, 6), Cells(CursorRow - LnkNum + 1, 2)).Select
Selection.Copy
Range(Cells(CursorRow, 12), Cells(CursorRow - LnkNum + 1, 8)).Select
ActiveSheet.Paste
Selection.HorizontalAlignment = xlCenter
Selection.Interior.ColorIndex = 19

Selection.Sort Key1:=Columns("L"), Order1:=xlDescending, key2:=Columns("J"), _
Order2:=xlAscending, key3:=Columns("H"), order3:=xlAscending

CursorRow = CursorRow + 1
With Cells(CursorRow, 2)
    .Font.Italic = True
    .Value = "Network intersection failure frequencies:"
End With

' record intersection failure frequency information
For i = 1 To IntNum
    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Font.Italic = True
    Cells(CursorRow, 2).Value = IntID(i)
    Cells(CursorRow, 3).Font.Bold = True
    Cells(CursorRow, 3).Value = "::"
    Cells(CursorRow, 4).Value = IntFlFrq(i)
Next i

Range(Cells(CursorRow, 4), Cells(CursorRow - IntNum + 1, 2)).Select
Selection.Copy
Range(Cells(CursorRow, 8), Cells(CursorRow - IntNum + 1, 6)).Select
ActiveSheet.Paste
Selection.HorizontalAlignment = xlCenter
Selection.Interior.ColorIndex = 19

Selection.Sort Key1:=Columns("H"), Order1:=xlDescending, _
key2:=Columns("F"), Order2:=xlAscending

ActiveWorkbook.Close saveChanges:=True

Cells(16, 2).Value = "Part 3: causal analysis end time: " & Time()
ActiveWorkbook.Save

```

End Sub

Module 3: NcsuVbaAggCode

```

Option Explicit
    Const RplNum = 30 ' total number of replications in
an experiment
    Const CaseDir = "D:\flawdetection\test\" ' root directory for the
experiment
    Const CaseName = "NcsuBaseF3" ' case name for the experiment
    Const StRpl = 1 ' starting replication number for
the run
    Dim TpdNum ' time period number

    Const FLTsd = 0, CntTsd = 1, BbTsd = 0, DtcTsd = 5 ' failure detection threshold for
link vehicle trips
' failure detection threshold for
number of failure links
' failure detection threshold for
number of initial trips
' failure detection threshold for
number of fluctuation trips

Sub main()
    GetInfo ' subprogram for gathering experiment information
    FlwDtc ' subprogram for detecting simulation failures
    CslAnl ' subprogram for analyzing failure patterns
End Sub

Sub GetInfo()
    Dim BaseFile, BaseLine, OutFile, OutLine As String
    Dim RecType, Title As String
    Dim RplCnt, TpdCnt, BaseFileNum, OutFileNum As Integer
    Dim LnkNum, LnkCnt, TrnNum, TrnCnt, IntNum, IntCnt, DmdNum, DmdCnt As Integer
    Dim a, b, c, i, j, k, count, CursorRow, anode, bnode, cnode As Integer

    Dim LnkAnode(300), LnkBnode(300), LnkLnode(300), LnkTnode(300), LnkRnode(300)
    Dim LnkLength(300), LnkLanes(300), LnkLtPct(300, 18), LnkThPct(300, 18), LnkRtPct(300,
18)
    Dim IntID(150), IntType(150), IntOffset(150), IntPhases(150), IntCycLng(150)
    Dim DmdSnode(40), DmdEnode(40), DmdFlRate(40, 18), DmdHvPct(40, 18)

    Dim NewSheet As Object
    Dim firstP1, firstP2, firstP3, firstP4, firstP5, firstP6, firstP7, firstP8 As Boolean
    Dim TrnStRow, DmdStRow As Integer

    'create worksheets for experiment data record
    Application.DisplayAlerts = False
    For a = 1 To Worksheets.count - 1
        If Worksheets(a).Name = "CorAnl" Then
            Application.DisplayAlerts = False
            Worksheets(a).Delete
            Application.DisplayAlerts = True
        End If
    Next a
    Set NewSheet = Worksheets.Add
    NewSheet.Name = "CorAnl"
    Application.DisplayAlerts = True

```

```

'record basic experiment information
With Worksheets("CorAn1").Range("B2", "E30")           ' initial worksheet as
CorAn1
    .Font.Bold = True
    Cells(2, 2).Value = "Corsim Analysis Experiment"
    Cells(3, 2).Value = CaseDir & CaseName
    Cells(5, 2).Value = Date & Space(3) & Time()
    Cells(6, 2).Value = "by Baohong Wan, Phd Candidate, North Carolina State
University"

    Cells(7, 2).Value = "Start time: " & Time()
    Cells(11, 2).Value = "Beginning output data collection ... "
End With

'create excel file for analysis output
Workbooks.Add
ActiveWorkbook.SaveAs Filename:="An1" & CaseName & ".xls" ' specify the workbook to
save analysis outputs

' *****
' ***** corsim input file analysis *****
' *****

'create worksheets for input data analysis results
Application.DisplayAlerts = False
Worksheets("sheet1").Name = "InputInfo"           ' specify the worksheet
to save analysis outputs
Worksheets("sheet2").Name = "Validation"         ' specify the worksheet
to save validation results
Worksheets("sheet3").Delete
Application.DisplayAlerts = True
CursorRow = 0

'open corsim input file
BaseFile = CaseDir & CaseName & ".trf"           ' Specify base experiment
file to work with
BaseFileNum = FreeFile()
Open BaseFile For Input Access Read As #BaseFileNum
Range(Cells(1, 1), Cells(3, 10)).Font.Bold = True
Cells(2, 2).Value = "Name of Input File:"       ' record base experiment
file information
Cells(3, 2).Value = BaseFile
CursorRow = CursorRow + 5

'read corsim input file part 1 to 8
firstP1 = 1: firstP2 = 1: firstP3 = 1: firstP4 = 1
firstP5 = 1: firstP6 = 1: firstP7 = 1: firstP8 = 1
TpdCnt = 0: LnkCnt = 0: TrnCnt = 0: IntCnt = 0: DmdCnt = 0

While Not EOF(BaseFileNum)
    Line Input #BaseFileNum, BaseLine
    RecType = Mid(BaseLine, 78, 3)

    If RecType <> "" Then
        Select Case CInt(RecType)
            'part 1: corsim input file header
            Case 0, 1

```



```

' judge if it is the first line of part 1
If firstP1 = 1 Then
  With Cells(CursorRow, 2)
    .Font.Bold = True
    .Value = "Part 1: Input File Header"
  End With
  CursorRow = CursorRow + 1
  firstP1 = 0
End If

' copy evething in the header
Cells(CursorRow, 2).Value = Left(BaseLine, 78)
CursorRow = CursorRow + 1

'part 2: corsim input general information
Case 2, 3, 4, 5
  ' judge if it is the first line of part 2
  If firstP2 = 1 Then
    CursorRow = CursorRow + 1
    With Cells(CursorRow, 2)
      .Font.Bold = True
      .Value = "Part 2: General Information"
    End With
    CursorRow = CursorRow + 1
    firstP2 = 0
  End If

  Select Case CInt(RecType)
    ' gather values of random number seeds
    Case 2
      Cells(CursorRow, 2).Value = "Random number seeds:"
      Cells(CursorRow, 5).Value = Mid(BaseLine, 22, 8)
      Cells(CursorRow, 7).Value = Mid(BaseLine, 61, 8)
      Cells(CursorRow, 9).Value = Mid(BaseLine, 69, 8)
      CursorRow = CursorRow + 1

      'gather parameters of simulation time period
      Case 3
        Cells(CursorRow, 2).Value = "Time period lengths:"
        While Not Trim(Mid(BaseLine, TpdCnt * 4 + 1, 4)) = ""
          TpdCnt = TpdCnt + 1
          Cells(CursorRow, 5 + (TpdCnt - 1) * 1).Value = Mid(BaseLine,
(TpdCnt - 1) * 4 + 1, 4)
        Wend
        TpdNum = TpdCnt: TpdCnt = 1
        CursorRow = CursorRow + 1
        Cells(CursorRow, 2).Value = "Number of time periods:"
        Cells(CursorRow, 5).Value = TpdNum
        CursorRow = CursorRow + 1

      'gather parameters of simulation time interval
      Case 4
        If Trim(Mid(BaseLine, 17, 4)) <> "" Then
          Cells(CursorRow, 2).Value = "Time interval Duration:"
          Cells(CursorRow, 5).Value = Mid(BaseLine, 17, 4)
          CursorRow = CursorRow + 1
        End If

```

```

' other information
Case 5

End Select

'part 3: corsim network links information
Case 11
  If TpdCnt = 1 Then
    ' judge if it is the first line of part 3
    If firstP3 = 1 Then
      CursorRow = CursorRow + 1
      With Cells(CursorRow, 2)
        .Font.Bold = True
        .Value = "Part 3: Network Links Information"
      End With
      CursorRow = CursorRow + 1
      Cells(CursorRow, 2).Value = "Anode"
      Cells(CursorRow, 3).Value = "Bnode"
      Cells(CursorRow, 4).Value = "Lnode"
      Cells(CursorRow, 5).Value = "Tnode"
      Cells(CursorRow, 6).Value = "Rnode"
      Cells(CursorRow, 7).Value = "Length"
      Cells(CursorRow, 8).Value = "Lanes"
      CursorRow = CursorRow + 1
      firstP3 = 0
    End If

    'gather geometry information for each link
    LnkCnt = LnkCnt + 1
    LnkAnode(LnkCnt) = CInt(Mid(BaseLine, 1, 4))
    LnkBnode(LnkCnt) = CInt(Mid(BaseLine, 5, 4))
    If Trim(Mid(BaseLine, 9, 4)) <> "" Then LnkLength(LnkCnt) =
CInt(Mid(BaseLine, 9, 4))
    If Trim(Mid(BaseLine, 22, 1)) <> "" Then LnkLanes(LnkCnt) =
CInt(Mid(BaseLine, 22, 1))
    If Trim(Mid(BaseLine, 37, 4)) <> "" Then LnkLnode(LnkCnt) =
CInt(Mid(BaseLine, 37, 4))
    If Trim(Mid(BaseLine, 41, 4)) <> "" Then LnkTnode(LnkCnt) =
CInt(Mid(BaseLine, 41, 4))
    If Trim(Mid(BaseLine, 45, 4)) <> "" Then LnkRnode(LnkCnt) =
CInt(Mid(BaseLine, 45, 4))

    Cells(CursorRow, 2).Value = LnkAnode(LnkCnt)
    Cells(CursorRow, 3).Value = LnkBnode(LnkCnt)
    Cells(CursorRow, 4).Value = LnkLnode(LnkCnt)
    Cells(CursorRow, 5).Value = LnkTnode(LnkCnt)
    Cells(CursorRow, 6).Value = LnkRnode(LnkCnt)
    Cells(CursorRow, 7).Value = LnkLength(LnkCnt)
    Cells(CursorRow, 8).Value = LnkLanes(LnkCnt)
    CursorRow = CursorRow + 1

    ' summarize number of links analyzed
    LnkNum = LnkCnt
    Cells(CursorRow, 2).Value = " Number of Links Analyzed : " &
Str(LnkNum)

  End If

```

```

'part 4: corsim link turn percentage information
Case 21
  If TpdCnt = 1 Then
    ' judge if it is the first line of part 4
    If firstP4 = 1 Then
      CursorRow = CursorRow + 2
      With Cells(CursorRow, 2)
        .Font.Bold = True
        .Value = "Part 4: Turn Percentage Information"
      End With
      CursorRow = CursorRow + 1
      Cells(CursorRow, 2).Value = "Anode"
      Cells(CursorRow, 3).Value = "Bnode"
      Cells(CursorRow, 4).Value = "LT Pct"
      Cells(CursorRow, 5).Value = "TH Pct"
      Cells(CursorRow, 6).Value = "RT Pct"
      CursorRow = CursorRow + 1: TrnStRow = CursorRow - 1
      firstP4 = 0
    End If

    ' gather link turning probability information
    anode = CInt(Mid(BaseLine, 1, 4))
    bnode = CInt(Mid(BaseLine, 5, 4))
    For LnkCnt = 1 To LnkNum
      ' match the link order in record type 21 to rt 11
      If anode = LnkAnode(LnkCnt) And bnode = LnkBnode(LnkCnt) Then
        TrnCnt = TrnCnt + 1
        If Trim(Mid(BaseLine, 9, 4)) <> "" Then LnkLtPct(LnkCnt,
TpdCnt) = CInt(Mid(BaseLine, 9, 4))
        If Trim(Mid(BaseLine, 13, 4)) <> "" Then LnkThPct(LnkCnt,
TpdCnt) = CInt(Mid(BaseLine, 13, 4))
        If Trim(Mid(BaseLine, 17, 4)) <> "" Then LnkRtPct(LnkCnt,
TpdCnt) = CInt(Mid(BaseLine, 17, 4))

        Cells(TrnStRow + LnkCnt, 2).Value = LnkAnode(LnkCnt)
        Cells(TrnStRow + LnkCnt, 3).Value = LnkBnode(LnkCnt)
        Cells(TrnStRow + LnkCnt, 1 + TpdCnt * 3).Value =
LnkLtPct(LnkCnt, TpdCnt)
        Cells(TrnStRow + LnkCnt, 2 + TpdCnt * 3).Value =
LnkThPct(LnkCnt, TpdCnt)
        Cells(TrnStRow + LnkCnt, 3 + TpdCnt * 3).Value =
LnkRtPct(LnkCnt, TpdCnt)
        CursorRow = CursorRow + 1
      End If
    Next LnkCnt

    'summarize number of links whose turning probabilities analyzed
    TrnNum = TrnCnt
    Cells(CursorRow, 2).Value = " Number of Links Analyzed : " &
Str(TrnNum)
  Else
    ' gather link turning probability information
    anode = CInt(Mid(BaseLine, 1, 4))
    bnode = CInt(Mid(BaseLine, 5, 4))
    For LnkCnt = 1 To LnkNum
      ' match the link order in record type 21 to rt 11

```

```

        If anode = LnkAnode(LnkCnt) And bnode = LnkBnode(LnkCnt) Then
            If Trim(Mid(BaseLine, 9, 4)) <> "" Then LnkLtPct(LnkCnt,
TpdCnt) = CInt(Mid(BaseLine, 9, 4))
            If Trim(Mid(BaseLine, 13, 4)) <> "" Then LnkThPct(LnkCnt,
TpdCnt) = CInt(Mid(BaseLine, 13, 4))
            If Trim(Mid(BaseLine, 17, 4)) <> "" Then LnkRtPct(LnkCnt,
TpdCnt) = CInt(Mid(BaseLine, 17, 4))

            Cells(TrnStRow + LnkCnt, 1 + TpdCnt * 3).Value =
LnkLtPct(LnkCnt, TpdCnt)
            Cells(TrnStRow + LnkCnt, 2 + TpdCnt * 3).Value =
LnkThPct(LnkCnt, TpdCnt)
            Cells(TrnStRow + LnkCnt, 3 + TpdCnt * 3).Value =
LnkRtPct(LnkCnt, TpdCnt)
        End If
    Next LnkCnt
End If
'part 5: corsim signal type and phase information
Case 35, 36
    ' judge if it is the first line of part 5
    If firstP5 = 1 Then
        CursorRow = CursorRow + 2
        With Cells(CursorRow, 2)
            .Font.Bold = True
            .Value = "Part 5: Signal Information"
        End With
        CursorRow = CursorRow + 1
        Cells(CursorRow, 2).Value = "Intersection"
        Cells(CursorRow, 3).Value = "Type"
        Cells(CursorRow, 4).Value = "Offset"
        Cells(CursorRow, 5).Value = "Phases"
        Cells(CursorRow, 6).Value = "Cycle Length"
        CursorRow = CursorRow + 1
        firstP5 = 0
    End If

    ' collect information about intersection control types
    Select Case CInt(RecType)
    Case 35
        IntCnt = IntCnt + 1
        IntID(IntCnt) = CInt(Mid(BaseLine, 1, 4))
        If Trim(Mid(BaseLine, 5, 4)) <> "" Then
            IntOffset(IntCnt) = CInt(Mid(BaseLine, 5, 4))
            IntType(IntCnt) = "Sig"
            IntPhases(IntCnt) = 0: IntCycLng(IntCnt) = 0
            While Trim(Mid(BaseLine, IntPhases(IntCnt) * 4 + 29, 4)) <>
"" And Trim(Mid(BaseLine, IntPhases(IntCnt) * 4 + 29, 4)) <> "0"
                IntPhases(IntCnt) = IntPhases(IntCnt) + 1
                IntCycLng(IntCnt) = IntCycLng(IntCnt) + CInt(Mid(BaseLine,
IntPhases(IntCnt) * 4 + 25, 4))
            Wend
        Else
            IntType(IntCnt) = "Unsig"
        End If

        Cells(CursorRow, 2).Value = IntID(IntCnt)
        Cells(CursorRow, 3).Value = IntType(IntCnt)

```

```

Cells(CursorRow, 4).Value = IntOffset(IntCnt)
Cells(CursorRow, 5).Value = IntPhases(IntCnt)
Cells(CursorRow, 6).Value = IntCycLng(IntCnt)
CursorRow = CursorRow + 1

'summarize number of intersections analyzed
IntNum = IntCnt
Cells(CursorRow, 2).Value = " Number of Intersections Analyzed :
" & Str(IntNum)

Case 36
Case Else
End Select

'part 6: corsim network demand information
Case 50
If TpdCnt = 1 Then
' judge if it is the first line of part 6
If firstP6 = 1 Then
CursorRow = CursorRow + 2
With Cells(CursorRow, 2)
.Font.Bold = True
.Value = "Part 6: Network Demand Information"
End With
CursorRow = CursorRow + 1
Cells(CursorRow, 2).Value = "Source Node"
Cells(CursorRow, 3).Value = "Entry Node"
Cells(CursorRow, 4).Value = "Flow Rate"
Cells(CursorRow, 5).Value = "HV Pct"
CursorRow = CursorRow + 1: DmdStRow = CursorRow - 1
firstP6 = 0
End If

' gather network demand information
DmdCnt = DmdCnt + 1
DmdSnode(DmdCnt) = CInt(Mid(BaseLine, 1, 4))
DmdEnode(DmdCnt) = CInt(Mid(BaseLine, 5, 4))
anode = CInt(Mid(BaseLine, 1, 4))
bnode = CInt(Mid(BaseLine, 5, 4))
If Mid(BaseLine, 9, 4) <> " " Then
DmdFlRate(DmdCnt, TpdCnt) = CInt(Mid(BaseLine, 9, 4))
Else: DmdFlRate(DmdCnt, TpdCnt) = 0: End If
If Mid(BaseLine, 13, 4) <> " " Then
DmdHvPct(DmdCnt, TpdCnt) = CInt(Mid(BaseLine, 13, 4))
Else: DmdHvPct(DmdCnt, TpdCnt) = 0: End If

Cells(DmdStRow + DmdCnt, 2).Value = DmdSnode(DmdCnt)
Cells(DmdStRow + DmdCnt, 3).Value = DmdEnode(DmdCnt)
Cells(DmdStRow + DmdCnt, 2 + TpdCnt * 2).Value = DmdFlRate(DmdCnt,
TpdCnt)

Cells(DmdStRow + DmdCnt, 3 + TpdCnt * 2).Value = DmdHvPct(DmdCnt,
TpdCnt)

CursorRow = CursorRow + 1

'summarize number of demand analyzed
DmdNum = DmdCnt

```

```

Cells(CursorRow, 2).Value = " Number of Input Demand Analyzed : "
& Str(DmdNum)
Else
  ' gather network demand information
  anode = CInt(Mid(BaseLine, 1, 4))
  bnode = CInt(Mid(BaseLine, 5, 4))
  For DmdCnt = 1 To DmdNum
    If DmdSnode(DmdCnt) = anode And DmdEnode(DmdCnt) = bnode Then
      If Mid(BaseLine, 9, 4) <> "    " Then
        DmdFlRate(DmdCnt, TpdCnt) = CInt(Mid(BaseLine, 9, 4))
      Else: DmdFlRate(DmdCnt, TpdCnt) = 0: End If
      If Mid(BaseLine, 13, 4) <> "    " Then
        DmdHvPct(DmdCnt, TpdCnt) = CInt(Mid(BaseLine, 13, 4))
      Else: DmdHvPct(DmdCnt, TpdCnt) = 0: End If
      Cells(DmdStRow + DmdCnt, 2 + TpdCnt * 2).Value =
DmdFlRate(DmdCnt, TpdCnt)
      Cells(DmdStRow + DmdCnt, 3 + TpdCnt * 2).Value =
DmdHvPct(DmdCnt, TpdCnt)
    End If
  Next DmdCnt
End If
'part 7: corsim traffic parameter information
Case 81, 140, 141, 142, 143, 144, 145, 153
  ' judge if it is the first line of part 7
  If firstP7 = 1 Then
    CursorRow = CursorRow + 2
    With Cells(CursorRow, 2)
      .Font.Bold = True
      .Value = "Part 7: Traffic Parameter Information"
    End With
    CursorRow = CursorRow + 1
    firstP7 = 0
  End If

  ' copy traffic parameter input line
  Cells(CursorRow, 2).Value = Left(BaseLine, 80)
  CursorRow = CursorRow + 1

Case 170
  firstP1 = 1: firstP2 = 1: firstP3 = 1: firstP4 = 1
  firstP5 = 1: firstP6 = 1: firstP7 = 1: firstP8 = 1
  TpdCnt = TpdCnt + 1
'part 8: other corsim information
Case Else

End Select
End If
Wend
Close #BaseFileNum

' *****
' ***** corsim output file analysis *****
' *****

Dim LnkTrips(300, 18), LnkVehStTime(300, 18), LnkCtDelay(300, 18)
Dim LnkVehQuTime(300, 18), LnkStPct(300, 18), LnkSpeed(300, 18)
Dim LnkLtTrips(300, 18), LnkThTrips(300, 18), LnkRtTrips(300, 18)

```

```

Dim LnkQuTime(300, 18), LnkStTime(300, 18)
Dim LnkLtQuTime(300, 18), LnkThQuTime(300, 18), LnkRtQuTime(300, 18)
Dim LnkLtStTime(300, 18), LnkThStTime(300, 18), LnkRtStTime(300, 18)
Dim LnkCntTrips(300, 18), LnkInpTrips(300, 18), LnkOutTrips(300, 18)

Dim SysQuTime, SysStTime, SysVehMile, SysVehHour

Dim V1LnkAnode(3), V1LnkBnode(3) As Integer
Dim V1LnkTrips(3, 18), V1LnkStTime(3, 18), V1LnkVehTrips(3), V1LnkVehStTime(3)

' input validation link information
V1LnkAnode(1) = 4: V1LnkBnode(1) = 5: V1LnkVehTrips(1) = 2790: V1LnkVehStTime(1) = 9
V1LnkAnode(2) = 105: V1LnkBnode(2) = 104: V1LnkVehTrips(2) = 1650: V1LnkVehStTime(2)
= 14
V1LnkAnode(3) = 26: V1LnkBnode(3) = 102: V1LnkVehTrips(3) = 693: V1LnkVehStTime(3) =
33

'create corsim output analysis summary worksheet
For a = 1 To Worksheets.count - 1
    If Worksheets(a).Name = "Summary" Then
        Application.DisplayAlerts = False
        Worksheets(a).Delete
        Application.DisplayAlerts = True
    End If
Next a
Set NewSheet = Worksheets.Add
NewSheet.Name = "Summary"

' head info for output analysis
With Cells(2, 2)
    .Font.Bold = True
    .Value = "Summary output of the test case:"
End With
With Cells(3, 2)
    .Font.Bold = True
    .Value = CaseDir & CaseName
End With
With Cells(4, 2)
    .Font.Bold = True
    .Value = "Total number of replication analyzed:"
End With

Cells(6, 2).Font.Italic = True
Cells(6, 2).Value = "Network analysis started from " & Time() & ", " & Date
Range(Cells(7, 1), Cells(7, 8)).Font.Italic = True
Cells(7, 2).Value = "Replication"
Cells(7, 3).Value = "SysQuTime"
Cells(7, 4).Value = "SysStTime"
Cells(7, 5).Value = "SysVehHour"
Cells(7, 6).Value = "SysVehMile"

'extract corsim output information from .out files
For RplCnt = StRpl To RplNum
    OutFileNum = FreeFile()
    OutFile = CaseDir & CaseName & CStr(RplCnt) & ".out"
    Open OutFile For Input Access Read As #OutFileNum

```

```

'create worksheet for corsim replicational output data
For a = 1 To Worksheets.count - 1
    If Worksheets(a).Name = "OutputInfo" & CStr(RplCnt) Then
        Application.DisplayAlerts = False
        Worksheets(a).Delete
        Application.DisplayAlerts = True
    End If
Next a
Set NewSheet = Worksheets.Add
NewSheet.Name = "OutputInfo" & CStr(RplCnt)
CursorRow = 0

' head information for replication analysis
With Cells(2, 2)
    .Value = "Output analysis results from the file:"
    .Font.Bold = True
End With
With Cells(3, 2)
    .Value = OutFile
    .Font.Bold = True
End With
CursorRow = 5

For i = 1 To LnkNum: For j = 1 To TpdNum
LnkCntTrips(i, j) = 0: LnkInpTrips(i, j) = 0: LnkOutTrips(i, j) = 0
Next j: Next i

a = 0: b = 0
While Not EOF(OutFileNum)
    Line Input #OutFileNum, OutLine

    'header tagging the beginning of link output statistics table for time
interval 1
    If Mid(OutLine, 5, 46) = "LINK      MILES TRIPS      TIME      TIME      TIME" And
a = 0 Then
        a = a + 1: count = 0

        ' exit loop after analyzing one complete cycle of corsim links
        While count < LnkNum
            Line Input #OutFileNum, OutLine
            If Mid(OutLine, 2, 1) = "(" Then
                count = count + 1
                anode = CInt(Mid(OutLine, 3, 4))
                bnode = CInt(Mid(OutLine, 8, 4))

                ' collect interval output information for corresponding corsim
links in input file analysis
                For LnkCnt = 1 To LnkNum
                    If LnkAnode(LnkCnt) = anode And LnkBnode(LnkCnt) = bnode Then
                        If Trim(Mid(OutLine, 22, 5)) <> "" Then LnkTrips(LnkCnt,
a) = CSng(Mid(OutLine, 22, 5))
                        If Trim(Mid(OutLine, 92, 5)) <> "" Then LnkCtDelay(LnkCnt,
a) = CSng(Mid(OutLine, 92, 5))
                        If Trim(Mid(OutLine, 100, 5)) <> "" Then
LnkVehQuTime(LnkCnt, a) = CSng(Mid(OutLine, 100, 5))
                        If Trim(Mid(OutLine, 108, 5)) <> "" Then
LnkVehStTime(LnkCnt, a) = CSng(Mid(OutLine, 108, 5))

```



```

                If V1LnkAnode(c) = anode And V1LnkBnode(c) = bnode Then
                    If Trim(Mid(OutLine, 22, 5)) <> "" Then V1LnkTrips(c, a)
= CSng(Mid(OutLine, 22, 5))
                    If Trim(Mid(OutLine, 108, 5)) <> "" Then V1LnkStTime(c, a)
= CSng(Mid(OutLine, 108, 5))
                End If
            Next c
        End If
    Wend

End If

' title tagging corsim movement statistics table I for all time intervals
If Trim(Mid(OutLine, 10, 120)) = "NETSIM MOVEMENT SPECIFIC STATISTICS - TABLE
I" Then
    b = b + 1: count = 0
    While count < LnkNum
        Line Input #OutFileNum, OutLine
        If Mid(OutLine, 6, 1) = "(" Then
            count = count + 1
            anode = CInt(Mid(OutLine, 7, 4))
            bnode = CInt(Mid(OutLine, 12, 4))

            For LnkCnt = 1 To LnkNum
                If LnkAnode(LnkCnt) = anode And LnkBnode(LnkCnt) = bnode Then
                    ' link left-turn movement trips
                    If Trim(Mid(OutLine, 51, 4)) <> "" Then
                        LnkLtTrips(LnkCnt, b) = CSng(Mid(OutLine, 51, 4))

                        'cumulate link dsicharged trips for downstream link
input trips

                        For i = 1 To LnkNum
                            If LnkAnode(i) = LnkBnode(LnkCnt) And LnkBnode(i)
= LnkLnode(LnkCnt) Then
                                LnkInpTrips(i, b) = LnkInpTrips(i, b) +
LnkLtTrips(LnkCnt, b)

                                End If
                            Next i
                        End If

                        ' link through movement trips
                        If Trim(Mid(OutLine, 59, 4)) <> "" Then
                            LnkThTrips(LnkCnt, b) = CSng(Mid(OutLine, 59, 4))

                            'cumulate link dsicharged trips for downstream link
input trips

                            For i = 1 To LnkNum
                                If LnkAnode(i) = LnkBnode(LnkCnt) And LnkBnode(i)
= LnkTnode(LnkCnt) Then
                                    LnkInpTrips(i, b) = LnkInpTrips(i, b) +
LnkThTrips(LnkCnt, b)

                                    End If
                                Next i
                            End If

                            ' link right-turn movement trips
                            If Trim(Mid(OutLine, 68, 4)) <> "" Then

```

```

LnkRtTrips(LnkCnt, b) = CSng(Mid(OutLine, 68, 4))

'cumulate link dsicharged trips for downstream link
input trips
      For i = 1 To LnkNum
        If LnkAnode(i) = LnkBnode(LnkCnt) And LnkBnode(i)
= LnkRnode(LnkCnt) Then
          LnkInpTrips(i, b) = LnkInpTrips(i, b) +
LnkRtTrips(LnkCnt, b)
        End If
      Next i
    End If
  End If
Next LnkCnt
End If
Wend
End If

' title tagging corsim movement statistics table III for all time intervals
If Trim(Mid(OutLine, 10, 120)) = "NETSIM MOVEMENT SPECIFIC STATISTICS - TABLE
III" Then
  count = 0

  ' exit loop after analyzing a complete cycle of links
  While count < LnkNum
    Line Input #OutFileNum, OutLine
    If Mid(OutLine, 6, 1) = "(" Then
      count = count + 1
      anode = CInt(Mid(OutLine, 7, 4))
      bnode = CInt(Mid(OutLine, 12, 4))

      'collect movement specific traffic MOE for corresponding links in
input file analysis
      For LnkCnt = 1 To LnkNum
        If LnkAnode(LnkCnt) = anode And LnkBnode(LnkCnt) = bnode Then
          If Trim(Mid(OutLine, 78, 7)) <> "" Then
LnkLtQuTime(LnkCnt, b) = CSng(Mid(OutLine, 78, 7))
          If Trim(Mid(OutLine, 86, 7)) <> "" Then
LnkThQuTime(LnkCnt, b) = CSng(Mid(OutLine, 86, 7))
          If Trim(Mid(OutLine, 95, 7)) <> "" Then
LnkRtQuTime(LnkCnt, b) = CSng(Mid(OutLine, 95, 7))
          If Trim(Mid(OutLine, 107, 7)) <> "" Then
LnkLtStTime(LnkCnt, b) = CSng(Mid(OutLine, 107, 7))
          If Trim(Mid(OutLine, 115, 7)) <> "" Then
LnkThStTime(LnkCnt, b) = CSng(Mid(OutLine, 115, 7))
          If Trim(Mid(OutLine, 124, 7)) <> "" Then
LnkRtStTime(LnkCnt, b) = CSng(Mid(OutLine, 124, 7))

          '!!!LnkQuTime(,) and LnkStTime(,) are both cumulative
statistics for system info derivation
          If Trim(Mid(OutLine, 78, 21)) <> "" Then
            LnkQuTime(LnkCnt, b) = LnkLtQuTime(LnkCnt, b) +
LnkThQuTime(LnkCnt, b) + LnkRtQuTime(LnkCnt, b)
          End If
          If Trim(Mid(OutLine, 107, 21)) <> "" Then
            LnkStTime(LnkCnt, b) = LnkLtStTime(LnkCnt, b) +
LnkThStTime(LnkCnt, b) + LnkRtStTime(LnkCnt, b)

```

```

                End If
            End If
        Next LnkCnt
    End If
Wend
End If

Wend
Close #OutFileNum

'cumulate system level statistics
SysQuTime = 0: SysStTime = 0: SysVehHour = 0: SysVehMile = 0
For LnkCnt = 1 To LnkNum
    For TpdCnt = 1 To TpdNum
        'cumulate system level statistics
        If LnkLength(LnkCnt) <> "" Then
            If TpdCnt = TpdNum Then
                SysQuTime = SysQuTime + LnkQuTime(LnkCnt, TpdCnt) / 60
                SysStTime = SysStTime + LnkStTime(LnkCnt, TpdCnt) / 60
            End If
            SysVehMile = SysVehMile + LnkTrips(LnkCnt, TpdCnt) * LnkLength(LnkCnt)
/ 5280
            If LnkSpeed(LnkCnt, TpdCnt) <> 0 Then
                SysVehHour = SysVehHour + LnkTrips(LnkCnt, TpdCnt) *
LnkLength(LnkCnt) / 5280 / LnkSpeed(LnkCnt, TpdCnt)
            End If
        End If
    End If

    ' derive link output trips for each time interval
    If TpdCnt = 1 Then
        LnkOutTrips(LnkCnt, TpdCnt) = LnkTrips(LnkCnt, TpdCnt)
    Else
        LnkOutTrips(LnkCnt, TpdCnt) = LnkOutTrips(LnkCnt, TpdCnt - 1) +
LnkTrips(LnkCnt, TpdCnt)
    End If
    ' derive link content trips for each time interval
    LnkCntTrips(LnkCnt, TpdCnt) = LnkInpTrips(LnkCnt, TpdCnt) -
LnkOutTrips(LnkCnt, TpdCnt)
Next TpdCnt
Next LnkCnt

'record corsim network link and system information
With Cells(CursorRow, 2)
    .Font.Bold = True
    .Font.Color = RGB(255, 0, 0)
    .Value = "Network cumulative statistics:"
End With
CursorRow = CursorRow + 1
Cells(CursorRow, 2).Value = "System Queue Time =": Cells(CursorRow,
2).Font.Italic = True
Cells(CursorRow, 5).Value = SysQuTime: Cells(CursorRow, 5).Font.Color = RGB(255,
0, 0)
CursorRow = CursorRow + 1
Cells(CursorRow, 2).Value = "System Stop Time =": Cells(CursorRow, 2).Font.Italic
= True
Cells(CursorRow, 5).Value = SysStTime: Cells(CursorRow, 5).Font.Color = RGB(255,
0, 0)

```

```

    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Value = "System Vehicle Miles =": Cells(CursorRow,
2).Font.Italic = True
    Cells(CursorRow, 5).Value = SysVehMile: Cells(CursorRow, 5).Font.Color = RGB(255,
0, 0)
    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Value = "System Vehicle Hours =": Cells(CursorRow,
2).Font.Italic = True
    Cells(CursorRow, 5).Value = SysVehHour: Cells(CursorRow, 5).Font.Color = RGB(255,
0, 0)
    CursorRow = CursorRow + 1

' record link MOE for each time interval
For i = 1 To 12
    For LnkCnt = 1 To LnkNum
        ' add header information
        If LnkCnt = 1 Then
            CursorRow = CursorRow + 2
            With Cells(CursorRow, 2)
                .Font.Bold = True
                Select Case i
                    Case 1
                        .Value = "Link vehicle trips by time period:"
                    Case 2
                        .Value = "Link vehicle control delay by time period
(sec/veh):"
                    Case 3
                        .Value = "Link vehicle queue time by time period
(sec/veh):"
                    Case 4
                        .Value = "Link vehicle stop time by time period
(sec/veh):"
                    Case 5
                        .Value = "Link vehicle stop percentage by time period
(%):"
                    Case 6
                        .Value = "Link vehicle speed by time period (mph):"
                    Case 7
                        .Value = "Link vehicle left turn trips by time period:"
                    Case 8
                        .Value = "Link vehicle through trips by time period:"
                    Case 9
                        .Value = "Link vehicle right turn trips by time period:"
                    Case 10
                        .Value = "Link cumulative queue time by time period:"
                    Case 11
                        .Value = "Link cumulative stop time by time period:"
                    Case 12
                        .Value = "Link content trips by time period:"
                    Case Else
                End Select
            End With
            CursorRow = CursorRow + 1
        End If

        ' add link information
        Cells(CursorRow, 2).Value = LnkAnode(LnkCnt)

```

```

Cells(CursorRow, 2).Font.Italic = True
Cells(CursorRow, 3).Value = LnkBnode(LnkCnt)
Cells(CursorRow, 3).Font.Italic = True
Cells(CursorRow, 4) = ":@"

' record link MOE for each time interval
For TpdCnt = 1 To TpdNum
  Select Case i
    Case 1
      Cells(CursorRow, TpdCnt + 4).Value = LnkTrips(LnkCnt,
TpdCnt)
    Case 2
      Cells(CursorRow, TpdCnt + 4).Value = LnkCtDelay(LnkCnt,
TpdCnt)
    Case 3
      Cells(CursorRow, TpdCnt + 4).Value = LnkVehQuTime(LnkCnt,
TpdCnt)
    Case 4
      Cells(CursorRow, TpdCnt + 4).Value = LnkVehStTime(LnkCnt,
TpdCnt)
    Case 5
      Cells(CursorRow, TpdCnt + 4).Value = LnkStPct(LnkCnt,
TpdCnt)
    Case 6
      Cells(CursorRow, TpdCnt + 4).Value = LnkSpeed(LnkCnt,
TpdCnt)
    Case 7
      Cells(CursorRow, TpdCnt + 4).Value = LnkLtTrips(LnkCnt,
TpdCnt)
    Case 8
      Cells(CursorRow, TpdCnt + 4).Value = LnkThTrips(LnkCnt,
TpdCnt)
    Case 9
      Cells(CursorRow, TpdCnt + 4).Value = LnkRtTrips(LnkCnt,
TpdCnt)
    Case 10
      Cells(CursorRow, TpdCnt + 4).Value = LnkQuTime(LnkCnt,
TpdCnt)
    Case 11
      Cells(CursorRow, TpdCnt + 4).Value = LnkStTime(LnkCnt,
TpdCnt)
    Case 12
      Cells(CursorRow, TpdCnt + 4).Value = LnkCntTrips(LnkCnt,
TpdCnt)
    Case Else
  End Select
  Next TpdCnt
  CursorRow = CursorRow + 1

Next LnkCnt
Next i

' summarize replication system information
With Worksheets("Summary")
  .Cells(4, 6).Font.Size = 12
  .Cells(4, 6).Value = RplCnt
  .Cells(RplCnt + 7, 2).Value = RplCnt

```

```

        .Cells(RplCnt + 7, 3).Value = SysQuTime
        .Cells(RplCnt + 7, 4).Value = SysStTime
        .Cells(RplCnt + 7, 5).Value = SysVehHour
        .Cells(RplCnt + 7, 6).Value = SysVehMile
    End With

    For i = 1 To 3
        VLnkVehTrips(i) = 0: VLnkVehStTime(i) = 0
        For j = 1 To TpdNum
            c = VLnkVehTrips(i) * VLnkVehStTime(i) + VLnkTrips(i, j) *
VLnkStTime(i, j)
            VLnkVehTrips(i) = VLnkVehTrips(i) + VLnkTrips(i, j)
            If VLnkVehTrips(i) <> 0 Then VLnkVehStTime(i) = c / VLnkVehTrips(i)
        Next j
    Next i

    With Worksheets("validation")
        If RplCnt = 1 Then
            .Cells(RplCnt + 1, 2).Value = "Anode(1)"
            .Cells(RplCnt + 1, 3).Value = "Bnode(1)"
            .Cells(RplCnt + 1, 4).Value = "Trips(1)"
            .Cells(RplCnt + 1, 5).Value = "Time(1)"
            .Cells(RplCnt + 1, 7).Value = "Anode(2)"
            .Cells(RplCnt + 1, 8).Value = "Bnode(2)"
            .Cells(RplCnt + 1, 9).Value = "Trips(2)"
            .Cells(RplCnt + 1, 10).Value = "StTime(2)"
            .Cells(RplCnt + 1, 12).Value = "Anode(3)"
            .Cells(RplCnt + 1, 13).Value = "Bnode(3)"
            .Cells(RplCnt + 1, 14).Value = "Trips(3)"
            .Cells(RplCnt + 1, 15).Value = "StTime(3)"
        End If

        .Cells(RplCnt + 2, 2).Value = VLnkAnode(1)
        .Cells(RplCnt + 2, 3).Value = VLnkBnode(1)
        .Cells(RplCnt + 2, 4).Value = VLnkVehTrips(1)
        .Cells(RplCnt + 2, 5).Value = VLnkVehStTime(1)
        .Cells(RplCnt + 2, 6).Value = "&"
        .Cells(RplCnt + 2, 7).Value = VLnkAnode(2)
        .Cells(RplCnt + 2, 8).Value = VLnkBnode(2)
        .Cells(RplCnt + 2, 9).Value = VLnkVehTrips(2)
        .Cells(RplCnt + 2, 10).Value = VLnkVehStTime(2)
        .Cells(RplCnt + 2, 11).Value = "&"
        .Cells(RplCnt + 2, 12).Value = VLnkAnode(3)
        .Cells(RplCnt + 2, 13).Value = VLnkBnode(3)
        .Cells(RplCnt + 2, 14).Value = VLnkVehTrips(3)
        .Cells(RplCnt + 2, 15).Value = VLnkVehStTime(3)

    End With
Next RplCnt

Worksheets("Summary").Activate
Cells(RplNum + 8, 2).Font.Italic = True
Cells(RplNum + 8, 2).Value = "Network analysis ended at " & Time() & ", " & Date

ActiveWorkbook.Close saveChanges:=True

Cells(12, 2).Value = "Part 1: collect information end time: " & Time()

```

```
ActiveWorkbook.Save
```

```
End Sub
```

```
Sub FlwDtc()
```

```
Dim BaseFile, BaseLine, OutFile, OutLine As String
Dim NewSheet As Object
Dim Ending, FlSim As Boolean
Dim RplCnt, TpdCnt, FlRplCnt, FlRplNum, BaseFileNum, OutFileNum As Integer
Dim LnkNum, LnkCnt, TrnNum, TrnCnt, IntNum, IntCnt, DmdNum, DmdCnt As Integer
Dim a, b, c, i, j, k, count, CursorRow, CursorCol, anode, bnode, cnode As Integer
```

```
Dim LnkAnode(300), LnkBnode(300), LnkLnode(300), LnkTnode(300), LnkRnode(300)
Dim LnkLength(300), LnkLanes(300), LnkLtPct(300), LnkThPct(300), LnkRtPct(300)
Dim IntID(150), IntType(150), IntOffset(150), IntPhases(150), IntCycLng(150)
Dim DmdSnode(40), DmdEnode(40), DmdFlRate(40), DmdHvPct(40)
```

```
Dim LnkTrips(300, 18), LnkVehStTime(300, 18), LnkCtDelay(300, 18)
Dim LnkVehQuTime(300, 18), LnkStPct(300, 18), LnkSpeed(300, 18)
Dim LnkLtTrips(300, 18), LnkThTrips(300, 18), LnkRtTrips(300, 18)
Dim LnkQuTime(300, 18), LnkStTime(300, 18)
Dim LnkLtQuTime(300, 18), LnkThQuTime(300, 18), LnkRtQuTime(300, 18)
Dim LnkLtStTime(300, 18), LnkThStTime(300, 18), LnkRtStTime(300, 18)
Dim LnkCntTrips(300, 18), LnkInpTrips(300, 18), LnkOutTrips(300, 18)
Dim LnkFlStTpd(300), FlLnkNum(RplNum), FlStTpd(RplNum)
```

```
Dim SysQuTime, SysStTime, SysVehMile, SysVehHour
```

```
For i = 1 To 300: For j = 1 To 18
    LnkCntTrips(i, j) = 0: LnkInpTrips(i, j) = 0: LnkOutTrips(i, j) = 0
Next j: Next i
```

```
'record experiment information
With Worksheets("CorAnl").Range("B2", "E20")
    Cells(13, 2).Value = "Beginning output data analysis ..."
End With
```

```
'open the target workbook generated by sub "GetInfo"
Workbooks.Open Filename:="Anl" & CaseName & ".xls"
Worksheets.Add before:=Worksheets("InputInfo")
ActiveSheet.Name = "FlwDtc"
```

```
' record header information
With Worksheets("FlwDtc")
    .Cells(2, 2).Font.Bold = True
    .Cells(2, 2) = Date & Time()
    .Cells(3, 2).Font.Bold = True
    .Cells(3, 2) = "Corsim Flaw Detection Procedure"
    .Cells(5, 2).Font.Italic = True
    .Cells(5, 2) = "Part II: Network flaw detection results: "
End With
```

```
'collect network links information from GetInfo output
Worksheets("InputInfo").Activate
CursorRow = 1: count = 0 'counting the number of blank lines
' end loop after meeting 10 consecutive blank lines
While count < 10
```



```

If Trim(Cells(CursorRow, 2).Value) <> "" Then
    i = 0
    If Cells(CursorRow, 2).Value = "Part 3: Network Links Information" Then
        CursorRow = CursorRow + 2
        While Left(Cells(CursorRow, 2).Value, 27) <> " Number of Links
Analyzed : "
            i = i + 1
            LnkAnode(i) = CInt(Cells(CursorRow, 2).Value)
            LnkBnode(i) = CInt(Cells(CursorRow, 3).Value)
            LnkLnode(i) = CInt(Cells(CursorRow, 4).Value)
            LnkTnode(i) = CInt(Cells(CursorRow, 5).Value)
            LnkRnode(i) = CInt(Cells(CursorRow, 6).Value)
            CursorRow = CursorRow + 1
        Wend
        LnkNum = i: count = 0
    End If
Else
    count = count + 1
End If
CursorRow = CursorRow + 1
Wend

FlRplCnt = 0: FlRplNum = 0
'collect corsim output information
For RplCnt = StRpl To RplNum
    With Worksheets("FlwDtc")
        .Cells(RplCnt + 5, 2).Font.Italic = True
        .Cells(RplCnt + 5, 2).Value = "Currently analyzing replication number " &
RplCnt & "..."
    End With

    Worksheets("OutputInfo" & RplCnt).Activate

    'collect corsim link trips and content trips information from GetInfo output
    count = 0: CursorRow = 1: Ending = False
    ' exit loop after meeting 10 consecutive blank lines
    While Ending = False
        CursorRow = CursorRow + 1
        If Trim(Cells(CursorRow, 2).Value) <> "" Then
            ' collect link discharged trips for each time interval
            If Cells(CursorRow, 2).Value = "Link vehicle trips by time period:" Then
                CursorRow = CursorRow + 1
                While Trim(Cells(CursorRow, 4).Value) = ":@"
                    For i = 1 To LnkNum
                        If LnkAnode(i) = Cells(CursorRow, 2).Value And LnkBnode(i) =
Cells(CursorRow, 3).Value Then
                            For j = 1 To 18
                                LnkTrips(i, j) = Cells(CursorRow, j + 4).Value
                            Next j
                        End If
                    Next i
                    CursorRow = CursorRow + 1
                Wend
            End If
            ' collect link content trips for each time interval
            If Cells(CursorRow, 2).Value = "Link content trips by time period:" Then
                CursorRow = CursorRow + 1
            End If
        End If
    End While
End For

```

```

        While Trim(Cells(CursorRow, 4).Value) = "::"
            For i = 1 To LnkNum
                If LnkAnode(i) = Cells(CursorRow, 2).Value And LnkBnode(i) =
Cells(CursorRow, 3).Value Then
                    For j = 1 To 18
                        LnkCntTrips(i, j) = Cells(CursorRow, j + 4).Value
                    Next j
                End If
            Next i
            CursorRow = CursorRow + 1
        Wend
    End If
    count = 0
Else
    count = count + 1
End If
If count > 10 Then Ending = True
Wend

'add header information for failure detection
With Cells(CursorRow, 2)
    .Font.Bold = True
    .Font.Color = RGB(255, 0, 0)
    .Value = "Network failure detection results:"
End With
CursorRow = CursorRow + 1

'judge occurrence of failure
For LnkCnt = 1 To LnkNum
    LnkFlStTpd(LnkCnt) = TpdNum + 1

    ' exclude source links, exit links, and minor links
    If LnkAnode(LnkCnt) < 8000 And LnkBnode(LnkCnt) < 8000 And LnkTrips(LnkCnt, 1)
> DtcTsd Then
        For TpdCnt = 1 To TpdNum
            ' judge first time interval blockage
            If TpdCnt = 1 Then
                If LnkTrips(LnkCnt, TpdCnt) <= FlTsd And LnkCntTrips(LnkCnt,
TpdCnt) > CntTsd Then
                    LnkFlStTpd(LnkCnt) = 1
                Else
                    LnkFlStTpd(LnkCnt) = TpdNum + 1
                End If
            Else
                ' judge the occurrence of link blockage
                If LnkFlStTpd(LnkCnt) > TpdCnt Then
                    If LnkTrips(LnkCnt, TpdCnt) <= FlTsd And LnkCntTrips(LnkCnt,
TpdCnt) > CntTsd Then
                        LnkFlStTpd(LnkCnt) = TpdCnt
                    End If
                ' judge the recovery of link blockage
                Else
                    If LnkTrips(LnkCnt, TpdCnt) - LnkTrips(LnkCnt,
LnkFlStTpd(LnkCnt)) > BbTsd Then
                        LnkFlStTpd(LnkCnt) = TpdNum + 1
                    End If
                End If
            End If
        Next TpdCnt
    End If
Next LnkCnt

```

```

        End If
    Next TpdCnt
End If

' record link blockage information for each link in each replication output
If LnkCnt = 1 Then
    Cells(CursorRow, 2).Value = "Link failure time period information:"
    CursorRow = CursorRow + 1
End If
Cells(CursorRow, 2).Value = LnkAnode(LnkCnt)
Cells(CursorRow, 3).Value = LnkBnode(LnkCnt)
Cells(CursorRow, 4).Value = ":"
Cells(CursorRow, 5).Value = LnkFlStTpd(LnkCnt)
CursorRow = CursorRow + 1
Next LnkCnt

' copy link blockage information
Range(Cells(CursorRow - LnkNum, 2), Cells(CursorRow - 1, 5)).Select
Selection.Copy
Range(Cells(CursorRow - LnkNum, 7), Cells(CursorRow - 1, 10)).Select
ActiveSheet.Paste

' sort link blockage information according to blockage time, Bnode, Anode
Selection.Sort Key1:=Columns("J"), Order1:=xlAscending, key2:=Columns("H"), _
Order2:=xlAscending, key3:=Columns("G"), order3:=xlAscending

' derive the earliest link blockage time
FlStTpd(RplCnt) = Cells(CursorRow - LnkNum, 10).Value

' conclude number of failure links and replication failure occurrence
FlSim = False: FlLnkNum(RplCnt) = 0
For LnkCnt = 1 To LnkNum
    If LnkFlStTpd(LnkCnt) < TpdNum + 1 Then
        FlSim = True: FlLnkNum(RplCnt) = FlLnkNum(RplCnt) + 1
    End If
Next LnkCnt

CursorCol = 2
For i = CursorRow - LnkNum To CursorRow - 1
    If Cells(i, 10) < TpdNum + 1 Then
        ' cumulate number of failure replications
        If i = CursorRow - LnkNum Then FlRplCnt = FlRplCnt + 1

        ' record first failed links in the summary worksheet
        With Worksheets("flwDtc")
            .Rows(RplNum + FlRplCnt + 8).Font.Italic = True
            .Rows(RplNum + FlRplCnt + 8).HorizontalAlignment = xlCenter

            ' add replication index info
            If CursorCol = 2 Then
                .Cells(RplNum + FlRplCnt + 8, CursorCol).HorizontalAlignment =
xlRight
                .Cells(RplNum + FlRplCnt + 8, CursorCol).Value = "Repl'n " &
CStr(RplCnt)
                .Cells(RplNum + FlRplCnt + 8, CursorCol + 1).Value = ":"
                .Cells(RplNum + FlRplCnt + 8, CursorCol + 1).Font.Bold = True
                CursorCol = CursorCol + 2
            End If
        End With
    End If
Next i

```

```

        End If

        ' Record first failed link(s) in the replication
        If FlSim = True And Cells(i, 10) = Cells(CursorRow - LnNum, 10) Then
            If CursorCol <> 4 Then .Cells(RplNum + FlRplCnt + 8, CursorCol -
1).Value = ";"
                .Cells(RplNum + FlRplCnt + 8, CursorCol).Value = Cells(i,
7).Value
                    .Cells(RplNum + FlRplCnt + 8, CursorCol + 1).Value = ">>>"
                    .Cells(RplNum + FlRplCnt + 8, CursorCol + 2).Value = Cells(i,
8).Value
            End If

            CursorCol = CursorCol + 4
        End With
    End If
Next i

' record failure detection results for each replication
With Worksheets("FlwDtc")
    .Cells(RplCnt + 5, 8).Font.Italic = True
    .Cells(RplCnt + 5, 8).Value = "Replication Failure:"
    .Cells(RplCnt + 5, 10).Font.Bold = True
    .Cells(RplCnt + 5, 10).Value = FlSim
    .Cells(RplCnt + 5, 12).Font.Italic = True
    .Cells(RplCnt + 5, 12).Value = "# of Failure Links:"
    .Cells(RplCnt + 5, 14).Font.Bold = True
    .Cells(RplCnt + 5, 14).Value = FlLnkNum(RplCnt)
    .Cells(RplCnt + 5, 16).Font.Italic = True
    .Cells(RplCnt + 5, 16).Value = "First Failure Time:"
    .Cells(RplCnt + 5, 18).Font.Bold = True
    .Cells(RplCnt + 5, 18).Value = FlStTpd(RplCnt)
End With

Next RplCnt
FlRplNum = FlRplCnt

With Worksheets("FlwDtc")
    .Cells(RplNum + 6, 2).Font.Italic = True
    .Cells(RplNum + 6, 2).Value = "There are " & CStr(FlRplNum) & " failures found."
    .Cells(RplNum + 7, 2).Font.Italic = True
    .Cells(RplNum + 7, 2).Value = "Network analysis ended at " & Time() & ", " & Date
End With

Worksheets("FlwDtc").Activate
ActiveWorkbook.Close saveChanges:=True

Cells(14, 2).Value = "Part 2: failure detection end time: " & Time()
ActiveWorkbook.Save

End Sub

Sub CslAnl()
    Dim BaseFile, BaseLine, OutFile, OutLine, RecType As String
    Dim NewSheet As Object
    Dim Ending, FlSim As Boolean

```

```

Dim RplCnt, TpdCnt, FlRplCnt, FlRplNum, BaseFileNum, OutFileNum As Integer
Dim LnkNum, LnkCnt, TrnNum, TrnCnt, IntNum, IntCnt, DmdNum, DmdCnt As Integer
Dim a, b, c, i, j, k, count, CursorRow, CursorCol, anode, bnode, cnode As Integer
Dim firstP1, firstP2, firstP3, firstP4, firstP5, firstP6, firstP7, firstP8 As Boolean

Dim LnkAnode(300), LnkBnode(300), LnkLnode(300), LnkTnode(300), LnkRnode(300)
Dim LnkLength(300), LnkLanes(300), LnkLtPct(300), LnkThPct(300), LnkRtPct(300)
Dim IntID(150), IntType(150), IntOffset(150), IntPhases(150), IntCycLng(150)
Dim DmdSnode(40), DmdEnode(40), DmdFlRate(40), DmdHvPct(40)

Dim LnkFlFrq(300), IntFlFrq(150), IntAdded(300)

'record experiment information
With Worksheets("CorAn1").Range("B2", "E20")
    Cells(15, 2).Value = "Beginning failure causal analysis ..."
End With

'open the target workbook generated by sub "FlwDtc"
Workbooks.Open Filename:="An1" & CaseName & ".xls"
Worksheets("FlwDtc").Activate

With Worksheets("FlwDtc")
    .Cells(2, 12).Font.Bold = True
    .Cells(2, 12) = Date & Time()
    .Cells(3, 12).Font.Bold = True
    .Cells(3, 12) = "Corsim Flaw Detection Procedure started from " & Time() & ", " &
Date
End With

'collect network links and nodes information
Worksheets("InputInfo").Activate
CursorRow = 1: count = 0          'counting the number of blank lines
While count < 10
    If Trim(Cells(CursorRow, 2).Value) <> "" Then
        i = 0: j = 0

        ' collect network links information
        If Cells(CursorRow, 2).Value = "Part 3: Network Links Information" Then
            CursorRow = CursorRow + 2
            While Left(Cells(CursorRow, 2).Value, 27) <> " Number of Links
Analyzed : "
                i = i + 1
                LnkAnode(i) = CInt(Cells(CursorRow, 2).Value)
                LnkBnode(i) = CInt(Cells(CursorRow, 3).Value)
                LnkLnode(i) = CInt(Cells(CursorRow, 4).Value)
                LnkTnode(i) = CInt(Cells(CursorRow, 5).Value)
                LnkRnode(i) = CInt(Cells(CursorRow, 6).Value)
                CursorRow = CursorRow + 1
            Wend
            LnkNum = i: count = 0
        End If

        ' collect network nodes information
        If Cells(CursorRow, 2).Value = "Part 5: Signal Information" Then
            CursorRow = CursorRow + 2
            While Left(Cells(CursorRow, 2).Value, 35) <> " Number of Intersections
Analyzed : "

```

```

        j = j + 1
        IntID(j) = CInt(Cells(CursorRow, 2).Value)
        IntType(j) = Cells(CursorRow, 3).Value
        CursorRow = CursorRow + 1
    Wend
    IntNum = j: count = 0
End If
Else
    count = count + 1
End If
CursorRow = CursorRow + 1
Wend

Worksheets("FlwDtc").Activate
For i = 1 To LnkNum: LnkFlFrq(i) = 0: Next i
For i = 1 To IntNum: IntFlFrq(i) = 0: Next i

CursorRow = 1: count = 0: Ending = False
While Ending = False
    CursorRow = CursorRow + 1
    While Left(CStr(Cells(CursorRow, 2).Value), 22) = "Network analysis ended"
        CursorRow = CursorRow + 2

        ' gather data for first blocked links in each replication
        While Left(CStr(Cells(CursorRow, 2).Value), 6) = "Repl'n"
            count = count + 1: CursorCol = 5
            For i = 1 To IntNum: IntAdded(i) = False: Next i
            While Cells(CursorRow, CursorCol) = ">>>>"
                anode = CInt(Cells(CursorRow, CursorCol - 1).Value)
                bnode = CInt(Cells(CursorRow, CursorCol + 1).Value)

                ' cumulate frequency of first failures for each link
                For LnkCnt = 1 To LnkNum
                    If LnkAnode(LnkCnt) = anode And LnkBnode(LnkCnt) = bnode Then
                        LnkFlFrq(LnkCnt) = LnkFlFrq(LnkCnt) + 1
                    End If
                Next LnkCnt

                ' cumulate frequency of first failures for each node
                For IntCnt = 1 To IntNum
                    If IntID(IntCnt) = bnode And IntAdded(IntCnt) = False Then
                        IntFlFrq(IntCnt) = IntFlFrq(IntCnt) + 1
                        IntAdded(IntCnt) = True
                    End If
                Next IntCnt

                CursorCol = CursorCol + 4
            Wend
            CursorRow = CursorRow + 1
        Wend
        Ending = True
    Wend
Wend
FLRplNum = count

CursorRow = CursorRow + 1
With Cells(CursorRow, 2)

```

```

        .Font.Bold = True
        .Value = "Part III: Network Causal Analysis Results (" & CStr(FlRp1Num) & "
failure replications analyzed)"
    End With
    CursorRow = CursorRow + 1
    With Cells(CursorRow, 2)
        .Font.Italic = True
        .Value = "Network link failure frequencies:"
    End With

' record link failure frequency information
For i = 1 To LnkNum
    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Value = LnkAnode(i)
    Cells(CursorRow, 3).Value = ">>>>"
    Cells(CursorRow, 4).Value = LnkBnode(i)
    Cells(CursorRow, 5).Value = "::"
    Cells(CursorRow, 6).Value = LnkFlFrq(i)
Next i

Range(Cells(CursorRow, 6), Cells(CursorRow - LnkNum + 1, 2)).Select
Selection.Copy
Range(Cells(CursorRow, 12), Cells(CursorRow - LnkNum + 1, 8)).Select
ActiveSheet.Paste
Selection.HorizontalAlignment = xlCenter
Selection.Interior.ColorIndex = 19

Selection.Sort Key1:=Columns("L"), Order1:=xlDescending, key2:=Columns("J"), _
Order2:=xlAscending, key3:=Columns("H"), order3:=xlAscending

CursorRow = CursorRow + 1
With Cells(CursorRow, 2)
    .Font.Italic = True
    .Value = "Network intersection failure frequencies:"
End With

' record intersection failure frequency information
CursorRow = CursorRow + 1
For i = 1 To IntNum
    CursorRow = CursorRow + 1
    Cells(CursorRow, 2).Font.Italic = True
    Cells(CursorRow, 2).Value = IntID(i)
    Cells(CursorRow, 3).Font.Bold = True
    Cells(CursorRow, 3).Value = "::"
    Cells(CursorRow, 4).Value = IntFlFrq(i)
Next i

Range(Cells(CursorRow, 4), Cells(CursorRow - IntNum + 1, 2)).Select
Selection.Copy
Range(Cells(CursorRow, 8), Cells(CursorRow - IntNum + 1, 6)).Select
ActiveSheet.Paste
Selection.HorizontalAlignment = xlCenter
Selection.Interior.ColorIndex = 19

Selection.Sort Key1:=Columns("H"), Order1:=xlDescending, _
key2:=Columns("F"), Order2:=xlAscending

```

```
ActiveWorkbook.Close saveChanges:=True
```

```
Cells(16, 2).Value = "Part 3: causal analysis end time: " & Time()  
ActiveWorkbook.Save
```

```
End Sub
```