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Project Summary

Anthony Chen

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CAREER: An Integrated Transportation Network Reliability Analysis Framework

A. PROJECT SUMMARY

Recent earthquakes around the world have provided compelling evidence that transportation infrastructure is of paramount importance in restoring normalcy and have stressed the need for reliable transportation systems under natural or man-made disasters. However, reliability analysis has received very little attention in the study of transportation systems despite the critical status as a most important lifeline. Moreover, the value of time in recent years has increased considerably due to increased economic activity and improvements in the quality of life. Road travelers in the 21st century would prefer a more reliable transportation system with less travel time uncertainty where they can be confident of arriving at their destination on schedule. Transportation network reliability analysis will play an important role in the planning, design and management of transportation facilities and networks particularly in developed countries and/or metropolitan cities.

The research plan proposes to develop an integrated transportation network reliability analysis framework for studying the reliability issues of a transportation system. This integrated analysis framework involves modeling, evaluation, design, algorithm development, and implementation. The modeling aspect includes the estimation of the maximum capacity of a transportation network and development of stochastic route choice models; the evaluation aspect involves the assessment of travel time reliability and capacity reliability; the design aspect entails designing roadway networks that are both reliable and cost-effective and investigating the role of information and learning in travel decisions; and, finally, the algorithm development and implementation aspects are crucial to making the framework described in this CAREER proposal operational and successful. The contribution of this CAREER proposal is to synthesize various models, theories, and reliability measures into an integrated transportation network reliability analysis framework that will improve the understanding of the complex interactions between travelers and the transportation system, and lead to better utilization of network capacity and improvement in network performance. Specific objectives of the research plan include: (1) enhancing the network reserve capacity model and the risk-taking route choice model, (2) investigating the relationship between travel time and capacity reliability and integrating the two concepts into a comprehensive reliability measure, (3) conducting sensitivity and uncertainty analysis to identify critical roadway components to incorporate into a reliability-based network design problem, (4) extending the travel time reliability definition to include arrival schedule reliability through learning from day-to-day travel experience, and (5) developing the necessary algorithms and procedures to support the operations of the integrated analysis framework.

The education plan focuses on two important tasks: (1) enhancement of the undergraduate program to better prepare our students for engineering/technology careers in the 21st century, and (2) development of a graduate transportation curriculum and teaching program with emphasis in systems modeling. The Principal Investigator (PI) plans to achieve these two objectives by (a) providing hands-on, team experience through computer lab exercises to our students to promote active and collaborative learning, (b) exposing promising students at the undergraduate level to research opportunities in transportation, (c) building a graduate curriculum and teaching program that emphasizes systems modeling, and (d) developing a transportation research seminar to provide an informal forum for our students to discuss a wide range of topics related to transportation issues that do not necessarily fit into the course curriculum. In addition to the above educational activities, the PI plans to integrate research into teaching by bringing in new insights and results generated by this CAREER proposal into both undergraduate and graduate courses, to broaden the students’ educational experience based on the research plan, and to recruit and retain traditionally under-represented students to the transportation program.

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NSF Form 1359 (10/99)
CAREER: An Integrated Transportation Network Reliability Analysis Framework

C.1 RESEARCH PLAN

C.1.1 Research Significance and Objectives

With increasing demands for better and more reliable service, many systems (e.g. electrical power systems, water distribution systems, sewage and drainage systems, communication networks, etc.) have incorporated reliability analysis into the integral planning, design, and operation processes. However, very little attention has been paid to the issue of transportation system reliabilities despite their critical status as the most important lifelines in the event of natural disasters such as earthquakes, floods, tornadoes, hurricanes, landslides, and others (Nicholson and Du, 1997). Disasters of these kinds in recent years have exposed the vulnerability of lifeline systems and the need to mitigate the risk consequent to failure of these systems. In particular, recent events such as the 1989 Loma Prieta, 1994 Northridge, California, the 1995 Kobe, Japan earthquakes, and the recent earthquakes in Turkey, Taiwan, Mexico, and India have provided compelling evidence that transportation systems are of paramount importance to restoring normalcy. Because the restoration of other lifelines (e.g. water supply, electrical power, sewer, communication, and others) depends strongly on the ability to transport people and equipment to damaged sites, an unreliable transportation system will hinder the restoration process and increase not only economic loss but also fatalities that are difficult to quantify.

Moreover, when planning a reliable transportation system, one should consider not only natural disasters, but also everyday disturbances, such as traffic congestion arising from daily traffic peaking or irregular traffic accidents. A system should provide an acceptable level-of-service in spite of the disruption of certain links or nodes in the network. The reliability of the transportation system reflects the quality of service it would normally provide. Iida (1999) argues that because of the increased value of time, travelers in the 21st century will desire a more stable transportation system with less travel time uncertainty so that they can be confident of arriving at their destination on schedule. In fact, a reliable transportation system would not only provide better travel service for travelers but also a competitive edge in the global economy for the United States. Thus, the importance of developing a sound methodology to analyze the reliability of a transportation system cannot be overemphasized. Compared to other lifelines such as power transmission, water distribution, and communication networks, reliability issues related to the transportation systems have been virtually unexplored in the United States and await much study. This is probably because the importance of reliability analysis in transportation is perhaps best appreciated in situations where it is severely disrupted, for example by an earthquake, as occurred in Kobe, Japan, on 17 January 1995 (Bell and Cassir, 2000).

The research plan proposes to develop an integrated transportation network reliability analysis framework as depicted in Figure 1 for studying the reliability issues of a transportation system. The integrated analysis framework involves modeling, evaluation, design, algorithm development, and implementation. The modeling aspect includes the estimation of the maximum capacity of a transportation network and development of stochastic route choice models that account for both the traveler perception error as well as the uncertainty of network travel times; the evaluation aspect involves the assessment of transportation reliability measures: travel time reliability is concerned with the probability that a trip between a given origin-destination pair can be made within a given time interval and a specified level-of-service, and capacity reliability is concerned with the probability that the network capacity can accommodate a certain volume of traffic demand at a required service level; the design aspect entails designing roadway networks that are both reliable and cost-effective and investigating the role of information and learning in travel decisions; and, finally, the algorithm development and implementation aspects are crucial to making the framework described in this CAREER proposal operational and successful. Though

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the proposed research seems ambitious, the Principal Investigator (PI) has done considerable research in many aspects relevant to transportation network reliability analysis (see Section C.1.6 for a summary of relevant research accomplished by the PI). The contribution of this CAREER proposal is to synthesize various models, theories, and reliability measures into an integrated transportation network reliability analysis framework that will improve the understanding of the complex interactions between travelers and the transportation system, and lead to better utilization of network capacity and improvement in network performance. Specific objectives of the research plan include: (1) enhancing the network reserve capacity model and the risk-taking route choice model, (2) investigating the relationship between travel time and capacity reliability and integrating the two concepts into a comprehensive reliability measure, (3) conducting sensitivity and uncertainty analysis to identify critical roadway components to incorporate into a reliability-based network design problem, (4) extending the travel time reliability definition to include arrival schedule reliability through learning from day-to-day travel experience, and (5) developing the necessary algorithms and procedures to support the operations of the integrated analysis framework.

![Figure 1. An Integrated Transportation Network Reliability Analysis Framework](image)

C.1.2 Modeling Aspect

C.1.2.1 Network Reserve Capacity Model

Transportation network capacity is concerned with the question: what is the maximum capacity of the transportation network? Traditionally, capacity has been measured only at an individual basis such as nodes (e.g. signalized intersections) or links (e.g. road segments). These measures obviously do not constitute the transportation network capacity. However, assuming that capacities of links are known (assuming node capacities can be transformed into equivalent link capacities), the maximal network capacity can be determined by the classical maximal flow problem, which is formulated as a network-programming problem to find a feasible flow that leads to maximum flow capacity (Ahuja et al., 1993). This method has been used in communication networks (Aggarwal, 1985; Chan et al., 1997), water distribution systems (Li et al., 1993), electric power systems (Billington and Li, 1994), and others to determine the maximum flow capacity of the network.
However, the approach is not directly applicable to a transportation network where capacity modeling characteristics are quite different for the following reasons: (a) the movement in a transportation network involves flows of people rather than pure physical commodities as treated in the classical maximal flow problem, (b) travel delay increases with increasing flow as a result of congestion as opposed to fixed cost, (c) route choice behavior has to be considered in determining maximum flow of a congested transportation network, (d) the traditional maximal flow problem does not consider level of service when finding the maximum throughput; however, transportation network capacity should be specified with a level of service such as origin-destination (O-D) travel time, and (e) multiple O-D pairs exist and the flow between different O-D pairs are not exchangeable or substitutable in a transportation network capacity problem; thus, it is important to define the O-D demand pattern that greatly influences the resultant value of transportation network capacity. These characteristics make the modeling of transportation network capacity a quite complex, yet intriguing problem to solve.

In this research, the concept of network reserve capacity will be used to model the transportation network capacity problem accounting for the issues highlighted above. The concept of reserve capacity was originally proposed by Webster and Cobbe (1966) to analyze a simple, isolated signal-controlled intersection. Allsop (1972) generalized it to a more complex, isolated signal-controlled intersection using linear programming. Wong (1996) applied it to study the reserve capacity of priority junctions and roundabouts. Recently, Wong and Yang (1997) further extended the concept of reserve capacity to a general signal-controlled road network to estimate the maximum network capacity under a route choice model. Here network reserve capacity is defined as the largest multiplier applied to a given existing O-D demand matrix that can be allocated to a network without violating the link capacities or exceeding a prespecified volume to capacity ratio (i.e., level of service). Mathematically stated, the network reserve capacity problem is to find the maximum O-D demand matrix multiplier subject to link flows resulting from the route choice problem not exceeding the link capacities:

$$\begin{align*}
\text{Max} & \quad \mu \\
\text{subject to:} & \quad v_a(\mu q) \leq c_a, \quad \forall a,
\end{align*}$$

where \(v_a(\mu q)\) is the flow on link \(a\), with the demands of all O-D pairs being uniformly scaled by \(\mu\) times the existing O-D demands \(q\), obtained by solving the route choice problem (see Section C.1.2.2 for different route choice models), and \(c_a\) is the capacity of link \(a\). The value of the largest \(\mu\) indicates whether the current network has spare capacity or is overloaded. For example, if \(\mu > 1\), then the network has reserve capacity amounting to 100(\(1 - \mu\)) percent; otherwise, the network is overloaded by 100(\(1 - \mu\)) percent by the existing O-D demands \(q\). The common multiplier assumption can be relaxed by adopting a combined trip distribution and assignment model to allow the maximum throughput to be scaled by individual O-D pairs reflecting the non-uniform growth of the spatial demand pattern (see Section C.1.6 for an enhanced network reserve capacity model).

The above formulation falls within the bi-level mathematical programming approach, and it has the following features: (a) the movements of multi-commodity flows are considered in the O-D demands \(q\), (b) congestion effect is captured by using a travel delay function that increases with flow for each link in the transportation network, (c) level of service constraints such as O-D travel time or volume to capacity ratio can be easily added to the bi-level mathematical program when determining the maximum throughput, and (d) since path flows for each O-D pair are explicitly estimated in the route choice problem, the issue associated with exchangeable or substitutable flows does not exist.
C.1.2.2 Route Choice Models

In the route choice literature, several models have been proposed which differ in (a) the characterization of the arc travel times, (b) the traveler's knowledge of the travel times on the network, and (c) the route choice criteria of each individual traveler. In general, these route choice models under the presence of congestion can be grouped into two factors:

1. Introduction of perception errors for the traveler to account for imperfect information.
2. Inclusion of network uncertainty to account for the stochasticity of network travel times.

A broad classification of route choice models based on the inclusion of both factors is provided in Table 1. In each model, the travel time for every arc on the network is assumed to be an increasing function of the flow of vehicles on the arc. Each traveler is assumed to make route choices to minimize his or her cost, which is a direct function of the travel time on the network.

<table>
<thead>
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<td>Network Uncertainty?</td>
<td>DN-DUE</td>
<td>DN-SUE</td>
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<tr>
<td>DN</td>
<td>SN-DUE</td>
<td>SN-SUE</td>
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where DN = Deterministic Network
SN = Stochastic Network
DUE = Deterministic User Equilibrium
SUE = Stochastic User Equilibrium

The widely accepted route choice model (i.e., DN-DUE) originally proposed by Beckman et al. (1956) is based on strong assumptions that the network travel times are deterministic for a given flow pattern and that all travelers are perfectly aware of the travel times on the network and always capable of identifying the shortest travel time route. To overcome the deficiencies of the deterministic model, some researchers have proposed different stochastic user equilibrium models (i.e., DN-SUE) to relax the assumption of perfect knowledge of network travel times, allowing travelers to select routes based on their perceived travel times (Daganzo and Sheffi, 1977; Fisk, 1980; Sheffi and Powell, 1982). Due to variations in travelers' perceptions of travel times, travelers do not always end up picking the correct shortest travel time route. However, both DN-DUE and DN-SUE models ignore network uncertainty and assume that the network is deterministic.

In reality, link travel times are random variables. For a given set of flows, there is a probability distribution associated with the link travel times, which describes the variations in the travel times experienced by the travelers on the network. Such variations could result from the differences in the mix of vehicle types on the network for the same flow rates, differences in driver reactions under various weather and driving conditions, differences in delays experienced by different vehicles at intersections, etc. Because travel time variability is explicitly included in the route choice model, it allows us to capture how travelers make tradeoff decisions between a route that is longer but has reliable travel time versus another route that is shorter but has unreliable travel time according to their risk taking behaviors. Depending on the behavioral nature of travelers, they are classified as risk averse, risk prone, or risk neutral. The risk in this case is the variability associated with network travel times. For instance, a risk averse traveler will trade off a reduction in travel time variability with some increase in expected travel time, whereas a risk prone traveler...
may choose a route with a greater variability so as to increase the possibility of a smaller travel time. A risk neutral traveler would choose a route based on only expected travel times without consideration of its variability.

For the SN-DUE model, travelers are assumed to have perfect knowledge of the variable nature of network travel times. This model may be suitable for peak-hour traffic where regular commuters have a good idea of the mean and variance of network travel times. However, a truly stochastic model should consider both the traveler perception errors as well as the stochasticity of network travel times. The SN-SUE model that accounts for both variable network travel times as well as a method to model different traveler responses to network travel time variability by assuming different risk taking behaviors was presented in (Mirchandani and Soroush, 1987). This model also accounts for the variations in each individual traveler's perception errors.

C.1.3 Evaluation Aspect

C.1.3.1 Transportation Reliability Measures

Reliability is generally defined as the probability that the system of interest has the ability to perform an intended function or goal (Ang and Tang, 1990). Despite the importance of assessing the reliability of a transportation system, there exist only a few reliability studies limited to two aspects: connectivity and travel time reliability (Bell and Iida, 1997). Recently, the PI of this CAREER proposal has introduced "capacity reliability" as a new performance index (Chen et al., 1999). This measure addresses the issue of planning for adequate capacity in a highway network to accommodate the growing passenger traffic demand. It has the potential of being useful at the system level, in planning and deciding roadway capacity expansion projects, planning the timing and location of various road improvement projects and so forth. Here we summarize three reliability measures for the transportation network.

*Connectivity reliability* is concerned with the probability that network nodes are connected. A special case of connectivity reliability is terminal reliability which determines the existence of a path between a specific O-D pair (Iida and Wakabayashi, 1989). For each node pair, the network is considered successful if at least one path is operational. A path consists of a set of roadways or links which are characterized by zero-one variables denoting the state of each link (operating or failed). Capacity constraints on the links are not accounted for when determining connectivity reliability. This type of connectivity reliability analysis may be suitable for abnormal situations such as earthquakes but there is an inherent deficiency in the sense that it only allows for two operating states: operating at full capacity or complete failure with zero capacity. The binary state approach limits the application to everyday situations where arcs are operating in-between these two extremes. Therefore, the reliability and risk assessment results obtained through this approach may be misleading for normal conditions.

*Travel time reliability* is concerned with the probability that a trip between a given O-D pair can be made successfully within a given time interval and a specified level-of-service (Asukara and Kashiwadani, 1991; Bell et al., 1999). This measure is useful when evaluating network performance under normal daily flow variations. Bell et al. (1999) proposed a sensitivity analysis based procedure to estimate the variance of travel time arising from daily demand fluctuations. Asakura (1996) extended the travel time reliability to consider capacity degradation due to deteriorated roads. He defined travel time reliability as a function of the ratio of travel times under the degraded and non-degraded states. Chen and Recker (2001) further examined the effect of considering risk-taking behavior in the calculation travel time reliability.
Capacity reliability is concerned with the probability that the network capacity can accommodate a certain volume of traffic demand at a required service level (Chen et al., 1999). Link capacities for a road network can change from time to time due to various reasons such as the blockage of one or more lanes due to traffic accidents, and are considered as random variables. The joint distribution of random arc capacities can be experimentally obtained or theoretically specified. Capacity reliability explicitly considers the uncertainties associated with link capacities by treating roadway capacities as continuous quantities subject to routine degradation due to physical and operational factors. Readers may note that when the roadway capacities are assumed to take only discrete binary values (zero for total failure and one for operating at ideal capacity), then capacity reliability includes connectivity reliability as a special case. Also, since link travel times are a function of link flows and capacities, any measure of network capacity reliability must also involve some measure of network travel time reliability. Chen et al. (2001) further developed the capacity reliability analysis by providing a comprehensive assessment methodology and extensive numerical results.

C.1.3.2 Synthesis of Travel Time and Capacity Reliability
Travel time reliability and capacity reliability are considered as two useful measures of the performance of a transportation network. Individual travelers are more concerned about the travel time reliability, because it directly affects their route choice decisions; while traffic managers or planners are more interested in the adequacy of the transportation network, which can be evaluated using capacity reliability. The PI of this CAREER proposal has done considerable research in capacity reliability and travel time reliability individually, but not together as a combined reliability measure. Since the determination of both reliability measures requires accounting for the route choice behavior, it would be intriguing to investigate their relationship and how these two inter-dependent reliability measures could be synthesized into a comprehensive performance measure (see Figure 1). For instance, given travel demands between all O-D pairs (i.e., travelers) and travel cost functions for each link of the network (i.e., transportation network subjects to recurrent and non-recurrent capacity disturbances), travel time or level of service will be different at different travel demand thresholds due to different degrees of flow variation and congestion. Similarly the maximum network capacity will also vary at different required levels of service or travel time thresholds. Thus while a single measure of either travel time or capacity reliability might not be sufficient, their combination may prove to be useful as a comprehensive performance measure for a transportation network that can be used for robust network planning and design.

C.1.4 Design Aspect
C.1.4.1 Network Improvement and Design
The design of any new road network or the upgrading of any existing road network requires understanding the uncertainties involved and their impact on the performance reliability of a road network. Only then could one compare the cost effectiveness between alternative options of road network design and improvement strategies. Let \( g(C) = g(C_1, C_2, \ldots, C_d) \) be a given performance index where \( C_1, C_2, \ldots, C_d \) are the random link capacities, the variance can be estimated from the variances of the respective random variables and the covariance between pairs of variables using first-order approximations:

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\[
\sigma_s^2 = \sum_{a \in A} \left( \frac{\partial g}{\partial C_a} \right)^2 \sigma_{C_a}^2 + \sum_{a \in A} \sum_{b \in A} \frac{\partial g}{\partial C_a} \frac{\partial g}{\partial C_b} \sigma_{C_a} \sigma_{C_b} r_{C_aC_b},
\]

and

\[
\frac{\partial g}{\partial C_a} = \sum_{b \in A} \frac{\partial g}{\partial v_b} \frac{\partial v_b}{\partial C_a}, \forall a \in A,
\]

where \( r_{C_aC_b} \) is the coefficient of the correlation between \( C_a \) and \( C_b \), \( \sigma_{C_a}^2 \) denotes the variance of \( C_a \), \( \partial v_b / \partial C_a \) is obtained by sensitivity analysis of equilibrium flows (see Tobin and Friesz, 1988; Yang, 1997; Bell and Friesz, 1997 for detailed derivation). The estimated variance together with the mean value of the relevant performance index is essential to ascertain its reliability when using the first-order reliability approach with an appropriate assumption of its probability distribution (Ang and Tang, 1990).

The sensitivity information combined with the variances of \( C_a \) and \( g(C) \) can be used to identify the most critical components that affect the system performance. This is important because a weak component with a higher probability of degradation may not necessarily be the critical component, a critical component must be one that is both important and weak (Du and Nicholson, 1997). This can be ascertained by \( \partial \sigma_s / \partial \sigma_{C_a} = (\partial g / \partial C_a)^2 \sigma_{C_a} / \sigma_s, \forall a \in A \), if the correlation term is ignored. The critical component so identified should be the prime candidate for strengthening rather than those that merely weak. Therefore, a priority scheme for repairing degraded or degradable roadways can be set up to efficiently improve the network reliability under limited resources.

Furthermore, the identification of the most critical components that affect network performance can be incorporated into a reliability-constrained continuous network design problem to consider optimal expansion of roadway capacities that satisfy the requirements of both travel time and capacity reliabilities of a road network under a budget constraint (Bell and Yang, 1998). One possible formulation is to maximize the network reserve capacity subject to meeting a pre-specified service standard (e.g. mean travel time) with a certain reliability requirement (e.g. the probability of the mean travel time not exceeding a pre-specified service level).

C.1.4.2 The Role of Information and Learning in Travel Decisions

A major factor in the determination and improvement of reliability is a good understanding and representation of the complex interactions between travel behavior and network performance (see Figure 1). Part of these complex interactions is due to travelers reacting autonomously to network conditions in an uncertain environment. This reaction (i.e., travel decision) is further complicated by the feedback effect due to information and learning of the network conditions. To address this feedback from the decisions taken by travelers to the factors behind their decision-making, the route choice analysis presented in Section C.1.2.2 is extended to include learning from day-to-day experience. Hence the day-to-day learning analysis would involve trip scheduling choice as well as route choice under information. The types of information would include expected travel times and possibly travel time variances for both pre-trip and en-route travel decisions. Pre-trip information allows travelers to choose better departure schedules for their selected route, while en-route information allows travelers to adapt the remaining portion of their trip if unfavorable traffic conditions were encountered in their current route. By combining day-to-day departure...
time choice and route choice, travelers minimize both the costs of commuting time and the costs associated with schedules delay, especially late arrival.

A substantial number of studies have been conducted to model travelers' day-to-day learning process (e.g., Horowitz, 1984; Ben-Akiva et al., 1991; Mahmassani and Stephan, 1991; Iida et al., 1992; Koutsopoulos and Xu, 1993; Vaughn et al., 1993; Hu and Mahmassani, 1995; Emmerink, 1997; Jha et al., 1998; Jou and Mahmassani, 1998; Polak and Hazelton, 1998; Liu and Mahmassani, 1999; Adler, 2001). However, many of these studies do not address the issue of traveler learning under the context of uncertain travel times and travel time reliability. Our approach here is to extend the definition of travel time reliability, which is defined as the probability that a trip between an O-D pair can be completed within a certain period of time, to include trip scheduling effect as part of a learning process with and without the provision of information.

C.1.5 Algorithm Development and Implementation Aspect

In addition to the modeling, evaluation, and design aspects of the integrated transportation network reliability analysis framework mentioned above, the development of algorithms and implementation are crucial to making the framework described in this CAREER proposal operational and successful. To address such a complex framework would naturally require a suite of algorithms and procedures. This research will develop the following procedures and algorithms that are necessary to analyze the reliability of an integrated transportation system:

- Risk-based traffic assignment algorithms
- Random variate generation procedure
- Network reserve capacity algorithm
- Sensitivity and uncertainty analysis procedure
- Stochastic simulation procedure
- Stochastic network design algorithm

The PI has done extensive research in traffic assignment algorithms for both additive and non-additive traffic equilibrium problems. Non-additive here means that the path cost in the traffic equilibrium problem is not a direct sum of the link costs (see Gabriel and Bernstein, 1997 for real-life applications of the non-additive traffic equilibrium problem). For the additive problem, the PI has implemented and performed computational study on the following algorithms: Frank-Wolfe (LeBlanc et al., 1975), PARTAN (LeBlanc et al., 1985; Florian et al., 1987; Arezki and Van Vliet, 1990), restricted simplicial decomposition (Hearn et al., 1985), disaggregate simplicial decomposition (Larsson and Patriksson, 1992), Gauss-Seidel Frank-Wolfe algorithm (Chen et al., 2001; Chen, 2001), and gradient projection (Jayakrishnan et al., 1994, Chen and Jayakrishnan, 1998, Chen and Lee, 1999). A comprehensive computational study on the additive traffic assignment algorithms listed above can be found in Chen et al. (2000). For the non-additive problem, the PI has developed the following algorithms: gradient-based algorithm for route-specific cost traffic equilibrium problem (Lo and Chen, 2000a), a sequential quadratic programming algorithm (Lo and Chen, 2000b), a self-adaptive projection and contraction algorithm (Chen et al., 2001), and an algorithm for the elastic, bi-criteria traffic equilibrium problem with nonlinear path costs (Chen et al., 2000). With such an extensive suite of traffic assignment algorithms available to the PI, he will choose the most appropriate algorithms to adapt for solving the risk-taking route choice models.

In addition to the development of a suite of traffic assignment algorithms, the PI has developed a set of procedures for a comprehensive assessment of network capacity reliability (Chen et al., 2000).
These procedures include a random variate generation procedure for generating random values of input components (e.g. link capacities) according to pre-specified distribution properties (e.g. mean, variance, and correlation), a sensitivity-based algorithm for solving the bi-level network reserve capacity problem, sensitivity and uncertainty analysis for quantifying the variability of the performance measure, which can offer important insights to identify the relative contribution of each input component to the overall uncertainty of the output, and a stochastic simulation procedure that integrates the procedures listed above into a comprehensive framework for assessing the performance of a degradable road network.

The network design problem has long been recognized to be one of the most difficult and challenging problems in transportation. It has emerged as an important research topic, because the demand for travel on the roads is growing at a rate faster than urban transport systems can ever hope to accommodate while resources available for expanding the system capacity remain limited. For a comprehensive survey on the modeling and algorithm development on the network design problem over the past two decades, see Boyce (1984), Magnanti and Wong (1984), Friesz (1985), and Yang and Bell (1998). Traditionally, this problem has been posed as a deterministic problem where all relevant inputs are known with certainty. This research extends the network design problem to consider uncertainties and their impact on designing a reliable and cost-effective road network. Using the simulation-optimization procedure recently developed by the PI to solve the Build-Operate-Transfer (BOT) network design problem with demand uncertainty (Chen et al., 2001), the PI plans to further enhance it by using a genetic algorithm combined with variance reduction techniques to solve the stochastic network design problem.

C.1.6 Summary of Relevant Research Accomplished by the Principal Investigator

Introduction of Capacity Reliability as a New Performance Measure (Chen et al., 1999): A capacity reliability for transportation networks was introduced using the concept of network reserve capacity. This method of estimating maximum network capacity differs from the conventional maximum flow model in which route choice behavior is explicitly considered. To model everyday situations, capacity of a link is treated as a random variable to allow for different levels of degradation. This reliability measure provides a probabilistic way to assess the existing network capacity, which could be used to improve the planning, design, and operation of transportation networks.

Examination of the Effect of Route Choice Models on Estimating Capacity Reliability (Chen et al., 2000): An important component of the capacity reliability of a road network is the route choice model used to describe the drivers’ behavior and the resulting link-flow pattern. In this study, we compare three different route choice models (one deterministic and two stochastic models) and examine the effect of using each of these models on estimating network capacity reliability.

Development of a Capacity Reliability Assessment Methodology (Chen et al., In press): This research extends the capacity reliability analysis by providing a comprehensive methodology, which combines reliability and uncertainty analysis, network equilibrium models, sensitivity analysis of equilibrium network flow and expected performance measure, as well as Monte Carlo methods, to assess the performance of a degradable road network.

Considering Risk-Taking Behavior in Travel Time Reliability (Chen and Recker, 2001): Given the significance of travel time uncertainty in route choice, this study examines a number of realistic route choice models to capture how travelers make tradeoff decisions between a route that is longer but has reliable travel time versus another route that is shorter but has unreliable...
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travel time according to their risk-taking behaviors. In particular, we examine the effect of considering risk-taking behavior in a route choice model and its impact on the estimation of travel time reliability of a road network under an uncertain environment.

Travel Time Reliability with Risk-Sensitive Travelers (Chen et al., 2001): This study continues the fundamental research in risk-taking route choice models and its effect on travel time reliability. The risk-taking route choice models examined here focus on individuals’ risk perceptions and preferences in making route choice decisions based on the tradeoff between expected travel time and travel time variability. The goal is to examine what the aggregate impact of changes in variability might be on network assignment and how individual travelers with different degrees of risk sensitivity respond to the changes caused by supply and demand variations.

C.1.7 Summary of Research Activities in This CAREER Proposal

Improved Network Reserve Capacity Model: While the concept of network reserve capacity has provided a feasible approach to determine the transportation network capacity with a route choice, it is restricted to a common multiplier for all O-D pairs. This assumes that every O-D pair will have a uniform growth or decline in its O-D demand pattern. Relaxing this limitation can yield information regarding the spatial distribution of the demand pattern to reflect non-uniform growth, which can be very useful in zonal land-use development plans. An approach based on a combined trip distribution and assignment model will be adopted to allow the maximum flow to be scaled by individual O-D pairs reflecting the non-uniform growth of the spatial demand pattern (see Yang et al. (2000) for details).

Enhanced Risk-Taking Route Choice Model: The SN-SUE model described in Section C.1.2.2 is for a single-class, risk-taking route choice model based on a pre-specified disutility function to model a specific risk preference (e.g. risk averse) for all travelers in the population. In reality, different travelers with the same characteristics facing the same choice situation may respond differently according to various degrees of risk aversion to travel time uncertainty. This is important in studying route choice behavior at the individuals level since it is not possible to directly observe all factors involved in how travelers make tradeoff decisions between expected travel time and travel time variability in actual choice situations. Thus, it is necessary to account for different sources of heterogeneity in route choice models. Using the random-coefficients logit model (Ben-Akiva et al., 1993; Train, 1997; Bhat, 1998a, 1998b), the degrees of risk aversion can be captured by taste variation across individuals resulting in differences in their responses to route-specific attributes and in differences in their preferences to various choices.

Integration of Travel Time and Capacity Reliability: While travel time reliability and capacity reliability are considered to be two useful measures describing the performance of a transportation network, their combination may prove to be useful as a comprehensive performance measure for a transportation network that can be used for robust network planning and design.

Stochastic Network Design Problem: The current practice of roadway network design does not consider reliability analysis (Yang and Bell, 1998). The reason is the lack of suitable reliability and uncertainty analysis for road networks. The design of a new road network or the upgrading of existing roadways would require a good understanding of the uncertainties involved and their impact on the reliability performance of a road network. Thus, it is important to study the reliability of road networks such that cost-effective design or modification can be implemented to improve its level of performance. One possible formulation is to maximize the network reserve...
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capacity subject to meeting a pre-specified service standard (e.g. mean travel time) with a certain reliability requirement (e.g. the probability of the mean travel time not exceeding a pre-specified service level).

Analysis of Travel Time and Arrival Schedule Reliability: This study provides a day-to-day learning analysis of the reliability of commuting time and trip scheduling under the provision of information. Travelers' accumulated travel experience and pre-trip and in-vehicle information are considered two major factors in making their day-to-day departure time and route choice decision. The analysis extends the definition of travel time reliability to include arrival schedule reliability through learning from day-to-day travel experience.

C.1.8 Impact of the Proposed Research
The economy of a nation or region depends heavily upon an efficient and reliable transportation system to provide accessibility and promote the safe and efficient movement of people and goods. Moreover, a reliable transportation system is essential for maintenance and repair of other lifeline systems. Thus, the importance of guaranteeing an acceptable level of transportation service cannot be overemphasized. The contribution of this CAREER is the development of a comprehensive transportation network reliability analysis framework that integrates modeling, evaluation, and design in a single framework to better understand the complex interactions between travelers and the transportation system. Results from this research are anticipated to be useful in capacity planning, roadway improvement projects, congestion control, and other relevant work, thus enhancing both travel time and capacity reliabilities of the transportation system. It may also have the potential of providing a valuable tool to design road networks that are resistant to disturbances.

C.1.9 Scholarly Dissemination
Results of this research will be disseminated through publications in scholarly journals and presentations at both international and national conferences. Presentations are anticipated for the international symposium on network reliability analysis to be held annually at different countries, and national conferences including Transportation Research Board, Institute for Operations Research and Management Sciences, and Optimization Days. Technical reports resulting from the CAREER award will also be made available through the PI's website to interested parties as new findings and results are generated.

C.1.10 International Participation in Transportation Network Reliability Analysis
Since 1998 after obtaining the PhD degree from the University of California at Irvine, the PI has been actively involved in transportation network reliability analysis research. He has participated in the past two international workshops on transport network reliability. In the First International Transport Network Reliability Workshop held at Hong Kong in December 1998, the PI and his co-authors introduced capacity reliability as a new performance measure to analyze transportation networks. His work was well received by well-known international researchers from Australia, Canada, Hong Kong, Japan, and United Kingdom, and he was invited to publish in a special issue of the Journal of Advanced Transportation. Subsequently, the PI was invited to present his work on risk-taking behavior in travel time reliability at the Third International Workshop on Transport Network Reliability held at Matsuyama, Japan in August 2000. His unique research on capacity reliability and risk-taking route choice models has earned him another invitation from Dr. van Zuylen, professor at Delft University of Technology, The Netherlands, to present at the First International Symposium on Network Reliability Analysis to

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be held at Kyoto University, Japan in August 2001. The PI plans to continue actively participating and being more involved in organizing international workshops and conferences on transportation network reliability.

C.2 EDUCATION PLAN

The Department of Civil and Environmental Engineering at Utah State University (USU) offers BS, MS, and PhD degrees in five academic divisions: Water, Environmental, Geotechnical, Structural, and Transportation Engineering. Among these disciplines in Civil Engineering, the transportation program is the smallest division with only two faculty members managing both the undergraduate and graduate programs. The PI was hired in the Fall of 1999 to enhance the undergraduate program and to develop and lead a research and graduate teaching program in transportation systems analysis. The enhancement of the undergraduate program primarily focuses on providing “hands-on” computer experience to better prepare students for careers in the transportation industry. The development of a Transportation Engineering Graduate program is to advance the understanding of transportation systems through teaching and research activities using theory, state-of-the-art computer tools, and best practices in planning, design, operation, and management. These two tasks are inline with the missions of the College of Engineering at USU. That is, “to educate our students by providing hands-on, team experiences which prepare them for engineering/technology careers of the 21st century and to research and develop technologies, products, and processes” (www.engineering.usu.edu). The education plan will describe what the PI has done in the past two years since he was hired, and what the PI plans to do in the next five years with the support from the NSF CAREER award.

C.2.1 Enhancement of Current USU Courses

In the undergraduate transportation program at USU, we offer four courses to prepare our students for careers in the transportation field. These four courses are:

CEE 3210 Introduction to Transportation Engineering
CEE 5220 Traffic Engineering
CEE 5230 Geometric Design for Highways
CEE 5240 Urban and Regional Transportation Planning

Of the above courses, The PI has taught CEE 5240 (Fall, 1999 and 2000), CEE 5220 (Spring, 2000), and CEE 3210 (Spring, 2001). In each course, the PI has attempted to instill students to the field of transportation by providing “hands-on” experience through using the latest transportation software packages. These courses introduce transportation modeling tools via small problems and case study applications. Techniques that are used to model, plan, and design the transportation systems are emphasized in these courses. In general, these courses comprise of lectures, computer labs, homework assignments, and unannounced quizzes. The lectures focus on the fundamental theory and principles underlying the current design practices; the computer labs are aimed to turn theory taught in lectures into applied practice through “hands-on” computer exercises. Because most undergraduate engineering students are active learners (Felder and Silverman, 1988), the computer labs play an important role in enhancing their educational experience. Similar ideas have also been implemented in the senior design class at USU to create a unique, interactive teaming experience for senior students before they graduate. Homework assignments provide opportunities for students to practice and work on problems that lead to better understanding of the concepts taught in lectures, and unannounced in-class quizzes ensure students keep up-to-date with the lectures and also encourage them to ask questions about unclear concepts. The PI applied
the unannounced quizzes in CEE 3210 during the Spring 2001 semester and found that it is a useful tool to encourage active learning. This is probably because quizzes, especially unannounced, are tied to the students' excitement over things affecting their grade. Besides learning the important technical skills in transportation, the PI also encourages collaborative/cooperative learning (Bruffee, 1993; Reis, 1997) in CEE 5220 and CEE 5240. Students work together in small groups to study, discuss, and collectively work on a semester-long project. Collaborative/cooperative learning focuses on learner-centered teaching, involves all students as active learners, and uses peer group to enhance performance and learning (Cooper et al., 1990). The PI plans to continue using "hands-on" computer exercises, unannounced quizzes, and other teaching innovations in future undergraduate courses.

C.2.2 Graduate Transportation Curriculum Development and Teaching

As mentioned above, the PI's role in the graduate program is to develop and lead a research and teaching program focusing on systems modeling and applied operations research in transportation applications. As an engineering faculty, we (his colleagues at USU and the PI) believe that systems modeling skills are essential to our students in the transportation curriculum for success in practice in the 21st century. Traditionally systems courses are in the realm of Industrial Engineering, Systems Engineering, or Operations Research departments. Since USU does not have such departments, it is crucial that this plan delivers the necessary systems modeling skills to our students.

During the next five years of the CAREER award, the PI will develop and refine five new courses to be added to the graduate transportation program. These are:

- Transportation Network Analysis
- Transportation Logistics
- Travel Demand and Supply Analysis
- Traffic Operations Analysis
- Special Topics: Stochastic Modeling and Simulation

Since joining the faculty at USU in the Fall of 1999, the PI has developed and taught preliminary versions of two of these courses: Transportation Network Analysis (Spring, 2000) and Transportation Logistics (Fall, 2000). In these two courses, some basic tools in systems modeling - linear programming, nonlinear programming, integer programming, network programming, optimization techniques, probability concepts, queuing models, and simulation - are taught with applications in network analysis and logistics. Still under refinement, these two courses will be complemented by travel demand and supply analysis, traffic operations analysis, and a special topics course in stochastic modeling and simulation. In each of the new courses, some systems concepts will be introduced along with appropriate transportation applications for that course. Whenever possible, the PI will incorporate results obtained from this CAREER award into class projects (e.g., route choice models in the Transportation Network Analysis, network improvement and design in the Travel Demand and Supply analysis, and travel time and schedule arrival reliability in Special Topics: Stochastic Modeling and Simulation) to enhance students' educational experience by exposing them to real transportation research problems.

C.2.3 Transportation Research Seminar Development

In addition to the standard teaching load of undergraduate and graduate courses each year, the PI plans to develop a monthly graduate seminar providing an informal forum for our students to discuss a wide range of topics related to transportation issues that do not necessarily fit into the
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course curriculum. Initially the graduate seminar will focus on using journal articles to introduce the state-of-the-art methodological techniques and approaches as well as cutting-edge research in transportation to our graduate students in an informal, brown-bag lunch format. As the transportation graduate program expands (currently there are eight graduate students in our program), the PI plans to establish joint seminars with other groups on campus with similar research interests in solving real-life problems using systems analysis and artificial intelligent computing techniques (e.g., Professors Kevin Moore and Randy Haupt in the Electrical and Computer Engineering Department and Professor Heng-Da Chang in the Computer Science Department). One advantage of these meetings is that students will have the opportunity to learn about different advanced techniques in systems optimization from experts of different disciplines. This will significantly foster more critical thinking in students (as well as teachers) to develop their own research methodology.

C.2.4 Undergraduate Research Opportunities
The PI's first experience in transportation research was in the summer of 1991. He received the Summer Undergraduate Research Fellowship (SURF) sponsored by the Institute of Transportation Studies at the University of California at Irvine. The SURF program provided invaluable experience to the PI not only in research but also in teaching as well. This impetus motivated the PI to pursue an academic career: first to continue graduate study pursuing his MS and PhD degrees at UC Irvine, then to receive a postdoctoral fellowship at the Hong Kong University of Science and Technology to engage in research on capacity reliability analysis for transportation networks, and eventually to take a tenure-track position in the Department of Civil and Environmental Engineering at Utah State University. Thus, the PI firmly believes in the importance of exposing students to research opportunities at the undergraduate level. The PI plans to provide similar research opportunities to promising undergraduate students using funds from the CAREER award and additional support from the department. This can substantially further the students' learning process and significantly enhance their educational experience. Another opportunity for undergraduate research is the Senior Design Project at USU. A well-crafted research project from the CAREER proposal will also provide an opportunity for the students to test newly learned skills with real world problems.

C.2.5 Teaching Assessment
Effective teaching depends on both the choice and delivery of course materials. Accurate tools of teaching assessment should reflect both aspects to ensure the successful implementation of the teaching activities listed above. Described here are several useful assessment tools:

(1) Peer Review and Evaluation: The evaluation is made by three faculty members in the promotion and tenure committee. It consists of course materials review, classroom visits, student interviews, and faculty review. The teacher/course evaluations made by faculty members are a very useful resource in helping junior faculty to improve their teaching.

(2) Student Evaluation of Teaching: Evaluation made by the students, particularly the written portion, can significantly direct teaching improvements and will be given serious attention.

(3) Minute Paper: A simple classroom assessment device for getting useful feedback from students during the semester. Students write answers to one or two questions for a minute each. According to Light (1990), minute paper offers the following benefits: force students to stop and reflect on what they have learned, prompt students to pay closer attention and ask more questions, and offer teachers useful feedback that can be used to make adjustments while the semester is in progress.

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C.3 INTEGRATION OF RESEARCH AND TEACHING

Teaching and research are two great pillars of higher education. When integrated well, these two pillars are complementary supporting each other rather than competing (Boyer, 1990). Research fosters openness toward learning. By conducting research, teachers become ongoing learners that allow them to expand the knowledge base of effective teaching methods and to keep abreast of new information. As a junior faculty, the PI strives to achieve excellence in both pillars by integrating research and teaching. Described below are several ideas that the PI plans to implement during the period of the CAREER award.

- Bring new insights and results generated by this proposal into both undergraduate and graduate courses. For the undergraduate courses, research results will be presented as real-world problems using "hands-on" computer exercises to promote active learning. For the graduate courses, research results will be used as class projects to teach important concepts in systems modeling of transportation applications.

- Include both undergraduate and graduate students in the research plan outlined in this proposal. As mentioned above, the PI firmly believes in the importance of exposing students to research opportunities at the undergraduate level. He plans to include at least two promising undergraduate students using funds from the CAREER award, and will work closely with them to improve their learning and research skills, to increase their self-esteem, to enhance their educational experience, and to encourage them to pursue graduate studies. Currently the research program the PI has developed in transportation network reliability analysis has involved two graduate students in the past year and will include at least that many during the 2001-2002 academic year. Mr. Zhaowang Ji (second year PhD student) works on risk-taking behavior in travel time reliability, and Ms. Panatda Kasikitwiwat (second year PhD student) works on enhanced capacity reliability models. The PI expects this research group to grow to four PhD students and two to three MS students.

- Recruit and retain historically under-represented students into the undergraduate research and graduate program in transportation. Currently USU Engineering has 165 women, nearly 11% of the total enrollment (USU Engineer, 2000). As commented by Dean Bishop, "Our track record for including women and minorities is improving, but we still have a long way to go."
D. REFERENCES CITED


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Yang, H. and Bell, M.G.H. (1998a) A Capacity Paradox in network design and how to avoid it. Transportation Research 32A, 539-545.

Yang, H. and Bell, M.G.H. (1998b) Models and algorithms for road network design: A review and some new developments. Transport Reviews 18, 257-278.

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E. BIOGRAPHICAL SKETCH

Anthony Chen
Department of Civil and Environmental Engineering
Utah State University
Logan, UT 84322-4110
Phone: (435) 797-7109
Fax: (435) 797-1185
Email: achen@cc.usu.edu

EDUCATION
BS (Magna Cum Laude)  Civil Engineering, University of California at Irvine, 1992
MS  Civil Engineering, University of California at Irvine, 1994
PhD  Civil Engineering, University of California at Irvine, 1997

EXPERIENCE
Assistant Professor, Department of Civil and Environmental Engineering, Utah State University, Aug. 1999 - present
Postdoctoral Researcher, Institute of Transportation Studies, University of California at Irvine, Jan. 1999 – July 1999
Research Associate, Department of Civil Engineering, Hong Kong University of Science and Technology, Jan. 1998 – Dec. 1998
Research Assistant, Department of Civil Engineering, University of California at Irvine, 1992 – 1997

PROFESSIONAL AFFILIATIONS
Committee Member, Transportation Network Modeling, Transportation Research Board
Committee Member, Route Choice and Spatial Behavior, Transportation Research Board
Member, Institute for Operations Research and Management Sciences
Reviewer for the following journals: Transportation Research C, ASCE Journal of Transportation Engineering, Transportation Research Record, Journal of Advanced Transportation, Journal of EASTS

HONORS AND AWARDS
Summer Undergraduate Research Fellowship (SURF), UC Irvine, 1991
University of California Transportation Center Fellowship, UC Irvine, 1992-1997
Postdoctoral Fellowship, Hong Kong University of Science and Technology, 1998

RELATED PUBLICATIONS


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SELECTED OTHER PUBLICATIONS


RESEARCH PROJECTS
Principal Investigator, Prioritizing Degraded/Degradable Roadways for Repairs Using Network Reliability Concept, sponsored by University New Faculty Grant, 7/00 – 6/01, $11,400.

Principal Investigator (with Heng-Da Cheng), Video-Based Vehicle Classification for Utah’s Intelligent Transportation Systems, sponsored by Community/University Research Initiative Grant, 7/01 – 6/02, $32,000.


COLLABORATORS & OTHER AFFILIATIONS
(i) Collaborators
Dr. Will Recker, University of California at Irvine
Dr. Heng-Da Cheng, Utah State University
Dr. Michael Zhang, University of California at Davis
Mr. Doyt Bolling, Technology Transfer Center, Utah State University

(ii) Dissertation Advisors
Dr. R. Jayakrishnan, Dr. Will Recker, Dr. Wei K. Tsai, and Dr. Michael McNally, University of California at Irvine

(iii) Advisees (Total Number: 5)
Piya Chootinan (PhD), Zhaowang Ji (PhD), Panatda Kasikitwiwat (PhD), Ken Smith (MS), Wen Zhang (MS)

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This budget reflects the Utah State University accounting procedures and indirect cost for a standard NSF grant.

Direct Labor: Funds are requested for the PI's summer salary (one month per year for 5 years) and two graduate students per year at a rate of $2400 per month (9 academic months 50% time and 3 summer months 75% time) for 5 years. The graduate student funds will support 3 to 4 MS/PhD thesis over the 5-year period of the CAREER award. A $3000 stipend per year for 5 years is requested for an undergraduate student.

Fringe Benefits: Fringe benefits are requested in accordance with the Utah State University guidelines.

Travel: The travel budget is for the PI and his students assigned to this project to attend and present results at domestic conferences ($1500 per year), and for the PI to participate in international workshops/conferences on transportation network reliability analysis ($2500 per year).

Materials and supplies: about $1000 per year for administrative and operational expenses

Publication costs/documentation/dissemination: $500 per year.

Computer services: $600 per year for computer ethernet connection and support.

Indirect costs: Indirect costs are requested at rate of 39% according to the Utah State University policy.
FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use "Other" to describe the facilities at any other performance sites listed and at sites for field studies. USE additional pages as necessary.

Laboratory: Transportation Systems Laboratory
Located in Rooms 163 and 127 in the Engineering Lab Building within the Civil & Environmental Engineering Department.

Clinical:

Animal:

Computer: Equipment: Four Pentium III PCs capable of performing most of the proposed computational work. Computers are connected to the CEE Dept. LAN and plotters, color printers, and scanners.

Office: Anthony Chen has assigned office space in close proximity to the Transportation Systems Laboratory with computers connected via the CEE Dept. LAN.

Other: Library: Up to date transportation library with all NAS holdings as well as several major transportation journals.

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate identifying the location and pertinent capabilities of each.

Listed above under computer.

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual arrangements with other organizations.

USU's Science and Technology Library has many technical journals and texts pertinent to the proposed project. Additionally, the library's inter-library loan office provides excellent support and rapid service.

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DEPARTMENTAL ENDORSEMENT

I have read and I endorse this career development plan. I attest that the PI's career-development plan is supported by and integrated into the educational and research goals of the department and the institution. I personally commit to the support and professional development of the PI.

Loren R. Anderson, Professor & Head
Department of Civil and Environmental Engineering
Utah State University
Tel.: (435) 797-2938
Fax: (435) 797-1185
Email: loren@cc.usu.edu