AMPLIFIED WORK PLAN

For the

STRATEGIC HIGHWAY RESEARCH PROGRAM 2
(SHRP2)

Project C05
Understanding the Contributions of Operations, Technology, and Design to Meeting Highway Capacity Needs

February 2008

From

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in association with

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University of Utah
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Write Rhetoric

Amplified Research Plan

4.1 INTRODUCTION

Kittelson & Associates, Inc (KAI), in association with the Institute for Transportation Research and Education (ITRE), the University of Utah, and Ruhr-University Bochum, is pleased to submit this research proposal in response to SHRP2 Project C05: *Understanding the Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs.*

This project recognizes the imperative to maximize the value and capabilities of our existing transportation infrastructure, and to do so in the context of a collaborative decision-making process that allows agencies and jurisdictions to make prudent decisions for investing scarce resources. The following sections provide an overview that is meant to put the discussion of individual task activities into proper context.

4.1.1 Some Historical Perspective

As noted in the RFP, SHRP2 is a targeted, short-term research program aimed at addressing the challenges of moving people and goods efficiently and safely. Within the overarching aims of the SHRP2 program, the Capacity Focus Area aims to develop approaches, methods, and practices for integrating environmental, economic, and community requirements into the analysis, planning, and design of capacity-based highway investment strategies.

There are significant parallels between the SHRP2 program occurring today and the policy-level activities of the 1930s and 1940s that marked the advent of preparations for an interstate highway system. At that time, very little was known about such fundamental issues as car-following characteristics and the capacity of a multilane highway. Yet, the emerging notion of a system of roadways dedicated to mobility and connecting all of the states caused this nation's transportation policy makers to recognize the imperative need for a consistent definition of capacity, as well as for uniform methods of analysis and reporting:

> *"…[What is needed is] a concerted, intelligently directed effort to determine the effectiveness of the highway in performing one of its most important functions, that of permitting the safe and expeditious movement of traffic."*[1]

Accordingly, the 1944 document entitled, "*Interregional Highways: A Message from the President of the United States,*" established the need for uniformity, opened the door to establishing a national highway system, and caused the Highway Research Board (the forerunner of the Transportation Research Board) to coordinate these activities. Thus was born the Highway Capacity Committee and the first edition of the *Highway Capacity Manual*, which was produced in 1950. This manual became an important tool in the development of the Interstate Highway System.

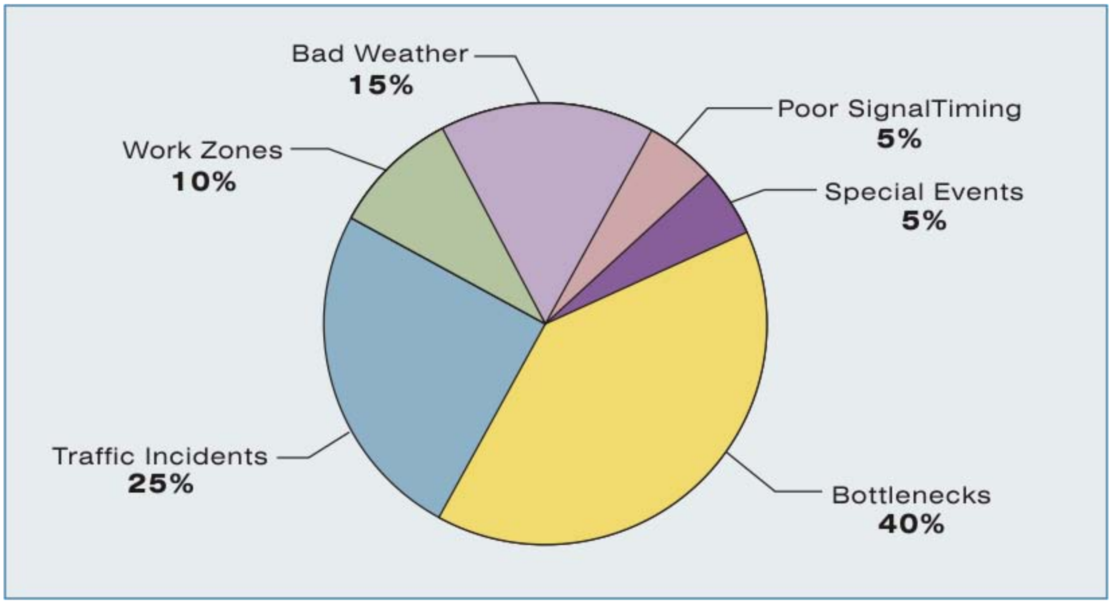
Today's economic successes and quality of life are, to some significant degree, a direct outcome of these earlier investments. And, as useful as they have been and continue to be, the singular and exclusive use of analytic tools derived from these investments is no longer the way to move forward or even keep pace with our nation's needs. The economic successes we now enjoy as a result of past investments have brought with them a much more complex and integrated urban environment that requires many more factors to be considered than in the past—environmental, economic, social, maintenance, and safety as well as the inherent tradeoffs between mobility and accessibility.

A substantial amount of effort has been invested into setting the groundwork for a system-based approach for investment decision making within the past decade. For example, the National Cooperative Highway Research Program (NCHRP) has explored the effectiveness of various operational improvements in a number of recent projects, many of which involved members of the KAI Research Team; these have included an evaluation of the effects of Right Turn Lanes (NCHRP 3-72), a comprehensive assessment of roundabout applications in the United States (NCHRP 3-65), an analysis of freeway weaving sections (NCHRP 3-75), the effectiveness of low-cost improvements in the vicinity of freeway bottlenecks (NCHRP 3-83), strategies for integrated operation of freeway/arterial corridors (NCHRP 3-81), maximizing freeway throughput under threat of breakdown flow (NCHRP 3-87), and others As well, two distinct Federal Highway Administration programs offer the potential to provide significant input into this project, including the Integrated Corridor Management (ICM) program and the Vehicle Infrastructure Initiative (VII). The ICM effort seeks to take advantage of unused capacity in transportation corridors by managing assets comprehensively as opposed to the fragmented approach taken today. The VII program promises more specific improvements to harnessing technology for safety and capacity benefits.

In this context, the SHRP2 program is the next major milestone in the evolution of transportation thought and practice. With the products of the SHRP2 program, transportation practitioners will think in terms of the transportation *system* rather than of the individual intersections, facilities, and modes that make it up. The development of a framework for collaborative decision making (SHRP2 Project C01) is a flagship effort in this regard, and its success depends on input from this particular project as well as several others within the SHRP2 program. Ultimately, a collaborative and multidimensional approach to managing, enhancing, and investing in the highway transportation system will lead transportation professionals to new levels of efficiency and productivity that could not otherwise be achieved.

Exhibit 4-1 below summarizes FHWA findings on the current root causes of congestion [2]. This project is an important piece of the overall SHRP2 program in that it will provide practical and implementable tools for evaluating the ability of various combinations of operational, technological, and design strategies to enhance network-wide traffic performance by addressing these sources of congestion.

Exhibit 4-1 Sources of Congestion



4.1.2 Research Objective

The request for proposals (RFP) for SHRP2 Project C05 has the following stated objectives:

> *The objectives of Project C05 are to: (1) quantify the capacity benefits, individually and in combination, of operations, design, and technology improvements at the network level for both new and existing facilities; (2) provide transportation planners with the information and tools to analyze operational improvements as an alternative to traditional construction (e.g., determine what operational improvements will give the same capacity gain as an additional lane); (3) develop guidelines for sustained service rates to be used in planning networks for limited access highways and urban arterials.*

These objectives need to be achieved in absolute terms, of course, but also in a pragmatic way if the results of Project C05 are expected to have a significant impact on real-world planning and decision making or on the performance of real transportation systems. This means that the tools and methodology developed must be sufficiently accurate, reliable, and consistent to meet decision-making needs. Beyond this, however, there are some practical and even logistical tasks that must also be complete: the input requirements must rely on data that is readily accessible to the prototypical user, the tools themselves must be easy to access and apply, the application methodology should be straightforward and intuitive, and the interpretation of output results should be clear and unambiguous. These are not trivial requirements because the nature of the issues being addressed is actually quite complex. They are important to address and the research approach must anticipate and respond to these outcomes.

4.1.2.1 Guiding Principles

To succeed in meeting the study objectives, the project team will be guided by the following set of principles:

1. The methods and tools developed in this project will enable the capacity-enhancing assessment of design, operational, and vehicle technology improvement measures when applied in isolation, or in any *feasible* combination.

2. Link or node capacity is a random variable that depends on driver behavior as well as design attributes and operational features, particularly under congested conditions (for details see section 4.2.7). Sustained service rates are also viewed in this context. This principle applies to both freeway and arterial networks.

3. Travel demand varies over time in a somewhat predictable fashion, but is subject to random variations from day to day and hour to hour. Randomness in both demand and capacity implies that the occurrence of breakdowns is also probabilistic in nature. This principle applies to both freeway and arterial networks.

4. There is an upper bound on the physical network capacity that can be gained from the application of the proposed design, operational, and vehicle technology tools. This research will therefore seek to adapt a system-optimization approach to characterize that upper bound and guide the search of management strategies to improve the network capacity.

5. The capacity gains from local improvements, effective as they may be, can be constrained by the inability of other portions of the network to handle the increased local throughout. Thus, while local assessment of capacity gains is necessary, it is certainly not by itself sufficient. Network-wide implications of local improvements will be assessed as well.

6. A "continuum" set of tools will be necessary to assess the proposed strategies, ranging from sophisticated, simulation/assignment model-driven methods, to simplified yet consistent methods that are applicable at the planning stage (e.g. spreadsheet; look-up tables; regression, etc.). This approach is analogous to the operational and planning procedures currently found in the HCM.

7. Performance measures that can be effectively applied and monitored in practical real-world settings will be selected at the link, node, sub-network, and network levels.

4.1.2.2 Project Deliverables

The research team will produce methodologies, tools, reports, and application guides for use by practitioners and researchers. The following bullet items describe the outcomes and project deliverables that are envisioned as part of this study effort.

- **A compendium of capacity enhancement strategies.** The strategies, as outlined in the RFP and extended by the team, along with the range of outcomes, will feed into the integrated decision process developed in the SHRP II Capacity Project C01.
- **Emerging technologies for increasing corridor capacity**. These technologies will be scanned using library research that informs a nominal group process through which team members will interact to identify promising technologies and to forecast their approximate date of availability and effectiveness. This can be done using an asynchronous Delphi-type process by e-mail or through a website. The most promising of these emerging options—in terms of readiness and effectiveness—will be incorporated into the compendium of actions. Ranges of effectiveness will be estimated based on available information and analogies.
- **Methods for estimating the combined effect of multiple strategies**. This is critical because, typically, multiple operational strategies will be implemented in a target corridor or network. The established methodologies for estimating the combined effects of multiple crash countermeasures provide an example for this effort.
- **Tools for estimating the capacity increments expected from (multiple, simultaneous) strategies in a particular corridor setting**. These tools must produce location-specific forecasts that will be applied, along with cost and impact information, in the collaborative systems analysis and choice processes in transportation investment decisions. The forecast results—logically in the form of maximum throughput flows (sustained service volumes)—should be in the form of *ranges* of expected flows (or capacity increments) and probabilities. Generally these tools should come from current and emerging practice.
- **Validation of both individual and combined operational strategies.** This will be done with a small number of validation tests, in which field measures from already-implemented operational improvements are compared with forecasts from the tools developed in this project. Validation will get underway soon enough to make changes in tools and procedures based on validation results.
- **Methods for selecting combinations of operational strategies to apply in specific settings**. This approach could be ruled-based, where options are classified or scored in terms of (1) compatibility or conflict among options; (2) relative effectiveness at increasing service volumes; (3) substitutability; (4) suitability for the setting.
- **Key institutional issues to be resolved to implement coordinated operational improvements in multi-jurisdictional settings**. This effort will focus on coordination with the contractor for project L06, Institutional Architectures for Implementing Operational Strategies. The emphasis here will be on ensuring that the L06 contractor addresses institutional coordination issues of importance to C05.
- **Example applications of the knowledge base and procedures developed in this project**. Such examples will be a part of the final product, and will vary in their level of sophistication.

- **Guidelines for application of the information and tools**. The results are envisioned to be a turnkey package that is readily integrated in planning, evaluation, and capacity-addition decision-making processes.

4.1.3 Overview of Team Qualifications

The research team members are uniquely qualified for this project and have joined together because of their proven track record in the areas of applied transportation research, development of guidebooks and reference manuals, practical application, implementation, interpretation of operations and planning analysis methodologies, and awareness of/involvement in international activities associated with defining system capacity and maximizing the effectiveness of a transportation network. The team brought together for this project includes the principal authors of the 2000 HCM, as well as the authors of the Highway Capacity Committee's 2006 Best Paper Award entitled, *Randomness of Capacity – Idea and Application* [3]. The research team has a proven track record of conducting applied research in areas that are relevant to this project, with the more notable examples listed here:

- Production of the 2000 *Highway Capacity Manual*
- Participation in NCHRP Project 3-83, *Low Cost Improvements to Recurring Freeway Bottlenecks*
- Preparation of the FHWA document entitled, *Design of Urban Streets*
- Development of the FREEVAL program, which implements the HCM2000 Freeway Facilities Procedure including multi-period analyses and oversaturated conditions
- Production of the FHWA guidebook entitled, *Signalized Intersections: An Informational Guide*
- Application of DYNASMART-P for assessing ATIS Effectiveness on a sub-network in the Research Triangle Region in North Carolina
- Production of NCHRP 3-65, *Applying Modern Roundabouts in the United States*
- Development of the FHWA *Signal Timing Manual* (estimated completion in January 2008)

In addition, the members of the team have led or been key contributors in other related research projects including:

- NCHRP 3-75, Freeway Weaving
- NCHRP 3-79, Urban Street Operations
- NCHRP 3-70, Multimodal Arterial LOS
- False Capacity for Lane Drops (FHWA/NC/03/007)
- Using Advanced Vehicle Monitoring to Extend System Capacity Along North Carolina Freeways (FHWA/NC/97/001)
- *Highway Capacity Manual* Revisions of Chapters 9 and 11 (DTFH61-92-C-00071)

- DYNASMART-P Integrated Corridor Management Benefit Analysis
- NCHRP 3-82, Default Values for Highway Capacity and Quality of Service Analysis
- TCRP G-6: *A Guidebook for Developing a Transit Performance-Measurement System*

4.1.3.1 Principal Investigator

Wayne Kittelson will serve as the Principal Investigator for the project. Wayne is the founding principal of Kittelson & Associates, Inc. and has for over 30 years directed and participated in a wide variety of projects related to traffic engineering, transportation planning, highway design, and transportation research. He has been actively involved in a wide range of NCHRP, TCRP, and FHWA-sponsored applied research projects dealing with the development of guides and methods for the planning, design, and operational analysis of all types of transportation facilities. He has been active within the HCQS Committee for more than 20 years.

4.1.3.2 Principal Researchers

The following individuals will serve as Principal Researchers on the project taking leadership roles in the development of the methodology and production of the deliverables.

Brandon Nevers will lead the validation tasks and will provide support for the development of the conceptual framework and methodology for estimating sustained service rates. He is co-author of FHWA's *Signalized Intersections: Informational Guide*. Mr. Nevers has worked extensively with microscopic and macroscopic traffic operations models for intersection, arterial, and freeway networks in practical applications for public and private entities. Mr. Nevers teaches short-courses on traffic flow fundamentals and highway capacity. He is a member of the Signalized Intersection Subcommittee of the Transportation Research Board's Highway Capacity and Quality of Service Committee, the Institute of Transportation Engineers, and the Urban Land Institute. .

Bill Reilly, a senior principal with Kittelson & Associates, Inc., will provide leadership for tasks 4 and 7. Mr. Reilly has broad experience in transportation research, in the development of user guides, and with the performance of safety, capacity, traffic operations, and transportation planning projects for all levels of government. With over 40 years experience, he has produced a number of user documents for the transportation profession, including the 600-page *Design of Urban Streets* for FHWA and, more recently, the 1,080-page *Highway Capacity Manual 2000*. He recently served as principal author for the first edition of the Pima County [Arizona] *Roadway Design Manual*. Bill has developed professional seminars in the areas of highway design, highway capacity, and traffic operations, and has lectured extensively in the United States and abroad. He has been active with the HCQS Committee for more than 30 years and was recently recognized by the Committee as an emeritus member.

Nagui Rouphail, PhD, will play a leadership role in managing the technical aspects of tasks 1, 2, and 3. He is responsible for developing and updating the conceptual framework for the project. He will work with KAI to provide information and write-ups for the task and project reports. Dr.

Rouphail will also coordinate with Dr. Xuesong Zhou at the University of Utah to implement the Dynamic Traffic Assignment (DTA) and simulation models for assessing the impact of improvement strategies.

Xuesong Zhou, PhD, will play a leadership role in the evaluation, selection, application, and refinement of simulation models. Dr. Zhou is currently an Assistant Professor in the Department of Civil and Environmental Engineering at the University of Utah. Prior to joining the University of Utah, he served as a Traffic Data Architect and Senior Software Engineer at Dash Navigation, Inc. Dr. Zhou's research interests include modeling and simulation of dynamic traffic systems, estimation and prediction of network traffic states using advanced sensing technologies, and routing, scheduling, and collaborating decision making in multimodal transportation systems. He has unique technical expertise and extensive experience in the development and application of simulation-based dynamic traffic assignment systems for evaluating advanced ITS strategies. He has been assisting the FHWA to develop and provide technical support for a large-scale simulation-based DTA system, namely DYNASMART, for 7 years, which is one of FHWA's 24 priority, market-ready technologies and innovations.

Werner Brilon, PhD, will play a leadership role in the development of the methodological background of the study. Werner is a professor and head of the Transportation and Traffic Engineering Institute in the faculty of civil engineering at the Ruhr-University in Bochum, Germany. He has been involved in a large number of research projects for federal agencies in Germany including unsignalized intersection capacity, capacity for rural highways and freeways, microsimulation, and road safety. Recently, and together with his coworkers, he has developed innovative statistical models to describe freeway-traffic breakdown phenomena. Werner helped develop capacity guidelines for the German Federal DOT and for state departments of transportation in Germany. He is chairman of the Coordination Committee and Traffic Infrastructure Design (supervising all of the committees for highway design) in the FGSV, which is the German counterpart to TRB. He is also a former member of TRB's Committee AHB40 on Highway Capacity and Quality of Service.

4.1.3.3 Senior Researchers

The project team brings an enormous depth of seasoned research professionals who provide the team with the ability to address any research needs that may arise as part of this project and, equally importantly, provide the ability to accomplish the work within a very short period of time. Most of these individuals have been active members of the HCQS Committee for many years. While no specific assignments have been made at this time, the research team has access to the following individuals:

Kittelson & Associates, Inc.

Peter Koonce
Brian Ray
Lee Rodegerdts
Jim Schoen
Mark Vandehey
John Zegeer

ITRE
Dr. George List
Dr. Billy M. Williams

Ruhr-University Bochum
Justin Geistefeldt
Jochen Harding

4.1.3.4 Research and Support Staff

Numerous additional research engineers, graphic artists, and technical editors are part of each organization and can be called upon as needed during the research and production elements of Phases II and III of the project.

4.2 RESEARCH ISSUES

As the research team prepared to write this proposal, a number of important issues were identified that will most certainly need to be addressed in the successful completion of Project C05. Many of these issues will have to be either resolved or underway with good direction by the end of the first phase of the project. A summary of what the research team believes to be the most important issues that require either resolution or awareness follows.

4.2.1 Issue 1 – Awareness of the Schedule

Awareness and maintenance of the schedule for this project is important because of its contributing role to other related SHRP2 projects such as C01 and even non-capacity projects such as L02, L03, and L06. While the RFP indicates this is a 24-month project, it contains the following time-critical milestones:

- Submit an Interim Report and complete the first five tasks within the initial six months of the project;
- Complete Phase II within a 12 month period, including developing analytical tools in support of the measurement/assessment methodologies; and
- Deliver the Final Report, including user guidance materials and final versions of all tools and methodologies, by February 2010.

This research plan assumes the project begins February 1, 2008. We recognize that this may be an aggressive start date based on historical experience, but we also think it is both important and possible. Continued full funding of the SHRP2 program depends, at least to some extent, on the ability of early projects to demonstrate the value received as well as the potential benefits that remain. The results of this project can have important practical and near-term impacts on transportation investment decisions made every year, so time is of the essence.

Exhibit 4-2 presents an overview of the proposed project schedule.

Exhibit 4-2 Overview of Project Schedule

4.2.2 Issue 2 – Management and Coordination

Good communication is intrinsic to the success of any project. In most SHRP projects, this is typically achieved through monthly and quarterly progress reports from the Contractor, review comments provided by TCC members on both progress reports and interim documents, and possibly one or two face-to-face meetings between the TCC members and the Contractor at key milestone points in the project timeline. Internal communication links are also very important for project team members to stay connected with one another and to take maximum advantage of each other’s capabilities to contribute creative ideas and suggestions in all phases of this project. Toward this end, we will be using a project website as well as a very flexible and powerful telephone and videoconferencing system to strengthen communication and coordination.

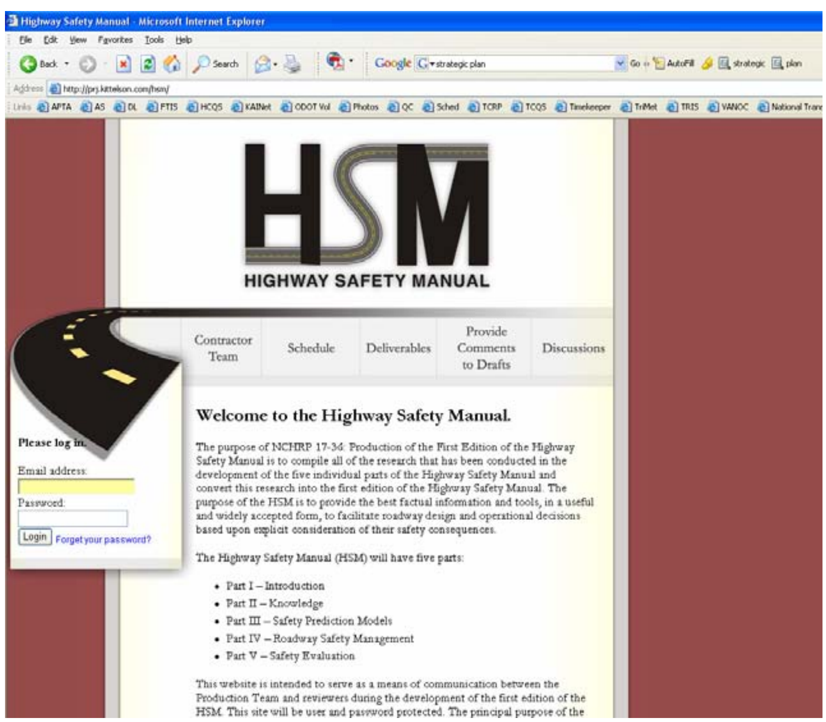
Videoconferencing: In addition to monthly and quarterly progress reports, response to review comments, and occasional face-to-face meetings, our project team will take advantage of videoconferencing technology to maintain stronger and more frequent interactions between team members. KAI owns and operates a video and audio conferencing bridge that is capable of accommodating up to 40 videoconference connections and 40 audio connections (more detailed information on this system is included in *Section 8*: *Equipment and Facilities*).

With the KAI videoconference system, project team members can connect with each other individually or as a group, they can do so whenever they need to without incurring special charges, and they can do so by either video or audio, according to their particular needs at the time. Exhibit 4-3 illustrates the system in the context of a videoconference conducted recently among people in several KAI offices. When combined with timely face-to-face meetings, we believe this system will help tremendously to create a seamless and integrated team capable of taking full advantage of each individual’s strengths and expertise.

Exhibit 4-3 KAI Video Conferencing System

Project Website: The final component to help with communication and coordination will be a dedicated website for the project. The project website will provide general information regarding the project purpose, objective, schedule, among other things. A password-protected section of the site will also be used to disseminate key project deliverables among project team members and/or the Technical Coordinating Committee (TCC) and SHRP2 staff, and will help to manage the receipt of comments from the various reviewers. Exhibit 4-4 shows an example of a similar website KAI developed to use for NCHRP 17-36 *(Production of the First Edition of the Highway Safety Manual).*

Exhibit 4-4 Sample Project Website



In summary, the capabilities provided by this equipment and technology will greatly increase the frequency, quality, and effectiveness of communications among project team members while simultaneously keeping associated costs to a minimum. These capabilities will also help both TCC members and SHRP2 staff to stay informed about project activities and to make key scope-related decisions in a timely manner. That is not to say that we expect TCC members or SHRP2 staff to become regular participants in project activities—that is still the responsibility and domain of the project team. Even so, their ability to gain access to project materials and even stay connected with one another will be enhanced through these elements.

4.2.3 Issue 3 - Target Audience, Purpose, and Objective

It is clear that the audience for this project is diverse in many respects. Groups who will benefit from a better understanding of the contributions of operations, technology, and design to meet highway capacity needs include:

- *Decision-makers*, who will use the analysis results to make public investment decisions;
- *Traffic engineers and transportation planners*, who will use the methodology developed in this project to plan and evaluate alternative operational improvement strategies;
- *Civil engineers*, who may use the methodology to evaluate the adequacy of their highway design;
- *Researchers and educators*, who will use the methodology to advance their research, to improve their understanding of traffic phenomena, and to train future transportation professionals; and
- *ITS designers*, who are interested in exploring the benefits of current and future ITS technologies.

Each group will have its own particular perspective, informational requirements, and desired method of interface, all of which will need to be adequately addressed by the products of this effort if the group members are to gain the value that this project intends to and can offer. Along this line, the RFP identifies three primary objectives to be achieved:

1. Quantify the capacity benefits, individually and in combination, of operations, design, and technology improvements at the network level for both new and existing facilities;

2. Provide the information and tools to analyze operational improvements as an alternative to traditional construction; and

3. Develop guidelines for sustained service rates to be used in planning networks for limited-access highways and urban arterials.

The research team believes it is critical to resolve the needs of each audience group and to determine what we can realistically give them. Tasks 7 (Quantify Strategy Impacts), 8 (Develop Strategy Selection Procedures), and 9 (Guidance for Planning-level Implementation) of the research plan describe how the team plans to address this important issue.

4.2.4 Issue 4 – Key Analysis Issues

Project C05 must provide input to the collaborative decision making process so that operational enhancements in the congested corridor can be compared on an equal footing with major capital expansion projects (e.g., lane additions). In broad terms, this means delivering information on the performance, impacts, and costs of operational changes that is comparable to the kinds of information used to describe major capital investment projects. Performance here can be interpreted to mean changes—increases—in sustained service rate. Other dimensions of importance include crash rates and travel-time reliability. In contrast to capital projects such as lane additions, operational actions are likely to involve multiple actions within a corridor, e.g., signal coordination, turning lanes, parking restrictions, and/or variable speed limits. This will require methods for estimating the combined or integrated effects of multiple, coordinated, but sometimes disparate actions.

Corridor-network analysis should be examined from the perspective of network capacity, an undefined (or poorly defined) concept. A knowledge base and supporting tools are needed to analyze and support decisions about actions to increase capacity in *corridors* that can be described as sub-regional. Effort should be devoted to developing an operational definition of corridor capacity—a concept alluded to in the RFP that needs to be addressed explicitly.

A key objective of this research effort is to find ways to utilize the full capacity in a corridor, including both limited-access roadways and arterial streets. Typically, experienced and informed drivers will make the most of capacity available on roads of all types in their corridor of travel. ITS can be used to detect both incidents and available capacity on this corridor network so that drivers can be informed and diverted to take advantage of improved levels of service, whether temporary (incident driven) or recurring. In complicated cases it will be difficult or impossible to intuit effects on capacity caused by changes in operations or micro-design characteristics. This suggests the need for network-level analyses.

The relevant corridor network will not normally include every street in the corridor, for some are likely to be too sensitive to support traffic diversions. The overall approach should recognize this, and the deliverables should include a procedural guide that defines the relevant corridor network and its attributes, including road segments to be protected from traffic diversions.

Determining the effectiveness of operational interventions from the corridor-network perspective requires the use of a traffic assignment model to account for changes in driver path choice. This will be needed for both the research and applications, and will provide a basis for estimating changes in corridor capacity (sustained service volumes). An accurate picture of capacity (and change in capacity) will come from understanding how travelers are likely to use the network, which calls for a user equilibrium (UE) assignment model.[1]

Dynamic traffic assignment should be considered to reflect variations in demand and flow patterns over time. These tools are essential for evaluating real-time ITS technologies. Several DTA algorithms have been developed, and their use is becoming more common. DTA

[1] A system equilibrium (SE) model might also be utilized to design a corridor flow plan, after which control strategies may be created (part of the implementation) to make the SE pattern a reality.

algorithms typically rely on micro-simulation, which is another tool that is particularly well-suited for analyzing operational contributions to capacity.

Could local data reveal an alternative to some advanced micro-assignment techniques? Can the network be "force fed" to estimate corridor (sub-regional) capacity? This seems possible (kind of a *foie gras* approach), but users are going to be most interested in the relevant capacity of their corridor, not just a perspective on theoretical capacity.

To ensure the practicality of the results of this project, it will be important to address data requirements to support user applications. This includes defining data specifications, sources, default values (where applicable), and ways to adapt and/or synthesize data to meet user needs. The data requirements for corridor modeling, and particularly for DTA applications, are substantial: there is a need to know (time based) O-D flows, at least in the immediate vicinity of the corridor in question.

4.2.5 Issue 5 – Technological Advances

How can we assure that we have a comprehensive vision of relevant technological changes likely to occur over the next 10 years? Is a ten-year vision long enough? How do we assure that we cover international experience and innovations, rather than only domestic ones?

In the context of these questions, the transportation (highway) network might be viewed as a massively-distributed, large-scale production system whose objective is to achieve the safe, effective, efficient, and per-promised movement of people and goods in time and space (and condition). The challenge is to gain maximum productivity from the system while meeting these (promised) performance targets, especially travel (arrival) times.

From a capacity standpoint, this means using all (needed) available "slots" in time and space to move entities (vehicles) through the system. It is a massive-scale scheduling problem. And, it involves maximizing throughput for each facility by minimizing turbulence. It is analogous in some regards to air traffic control.

Technology is instrumental in ensuring success and optimization. Anything that enhances the smoothness of the interplay between vehicles reduces "wasted" slots and maximizes the upper bound on throughput for any given facility. Examples include in-vehicle driving assistance systems and vehicle-to-vehicle communication systems, as addressed by FHWA's Vehicle Infrastructure Integration (VII) initiative. Major advances in the United States are needed, but international experience can be drawn upon to supplement current knowledge gaps.

The second major issue is localized scheduling—coordinating the use of shared resources among conflicting activities, at critical junctures. In plainer terminology, this means optimally timing signals to avoid the waste of precious green time; or, controlling ramp meters to maximize flow within the freeway network. This technology is further advanced than the vehicle technology, but the "frontier of diminishing returns" is still far away. A major leap forward would be vehicle-to-control-device communications systems (e.g., for signal control or ramp metering). With digital short-range communications technologies, for example, it is possible for each vehicle to announce its arrival in the vicinity of a signal. Each vehicle could also indicate what turning movements it wants (needs) to make, and perhaps other possibilities (leading to alternate paths), and the time at which it wants to be serviced. (The vehicle might also identify its lateness so the signal is more sensitive to meeting its needs if it is really late.) The signal should be able to devise a switching strategy that responds to system and local-level objectives for performance (e.g., minimizing the incremental lateness imposed on the vehicle most delayed while ensuring no spillback occurs, plus the usual average delay measures). Only fledgling versions of this technology exist today. Ten years is probably too short for full development let alone deployment in the United States.

A third issue is routing, coupled with departure-time choice. Decisions of this type maximize the effective use of scarce capacity by avoiding network saturation. Secondary paths are exploited so that unnecessary conflicts in path choices are avoided. Like filing flight plans, this can be viewed as the process whereby vehicles dialog with the network control system to identify network trajectories that deliver acceptable arrival times. These negotiations might only pertain to critical conflict points. They might be only user-based, with in-vehicle devices scheming routes that maximize the likelihood that on-time arrivals are achieved. They might also be aided and abetted by congestion pricing in a real- or quasi-real-time market place in which virtual money or real dollars are spent by users to gain access to varying qualities of service. In a “Buck Rogers”–like case, throughput is maximized because wasted capacity “slots” are minimized; the use of scarce vehicle processing resources is optimally assigned. Interestingly, this technology is the closest to large-scale market penetration in the US. Not the interactive, price-based kind, nor the filing-of-flight-plans type, but the conveyance of real-time information about network status and congestion to users who then use route-choice-decision assistants to determine how best to scheme the system for their needs.

The technology for visualizing vehicle trajectories in real-time now exists. Automatic Vehicle Identification (AVI), and more importantly Automatic Vehicle Location (AVL) technologies address this need. While there are issues of market penetration and deployment, the technology now exists, which was not true even 5 years ago. The nature of AVL technology will continue to evolve rapidly and probably fastest in Japan and Europe. AVI technology will also evolve with the cost of tags declining, interoperability improving, and the cost of tag readers and deployment becoming a non-issue (e.g., tags in license plates and wireless, solar-powered tag readers already exist). Point detectors will also advance, especially wireless, self-powered devices that can be installed anywhere in the pavement. In summary, the fundamental technology exists, but guidance is needed to focus on how, when, and with what the technology is applied.

The technology for seeing the state of the network is less advanced. This hampers the ability of operators to take advantage of available capacity because the estimates of available capacity are formed without data. Pavement sensors are needed to measure pavement condition (e.g., ice, snow, rain), signal visibility, and fog, among others, so that true expected / achievable capacities can be estimated. Major advances are needed in this area.

Finally, technology that allows vehicles to see/sense the operating plan for the network is almost completely undeveloped. This is technology that would allow vehicles to receive the real-time evolving plans for signal control, ramp metering, and network pricing so that routing decisions can be responsive to onset-of-green decisions.

The previous paragraphs demonstrate the wide range of technologies currently available or foreseeable. They also highlight these technologies are in various states of readiness for large-scale deployment. The research team believes that transportation professionals will benefit most from an efficient research approach focusing on technologies that are realistically available and implementable to them within the next 5-10 years. Therefore, some ordering of technologies identified during the course of this project may be appropriate, perhaps according to the following categories:

- Technologies unlikely to be available in anything other than test-bed environments within the next 5-10 years. The research team will still want to be aware of these so that methods and tools developed as part of this project anticipate their eventual emergence. However, the strategy selection guidebook and procedures resulting from this project will also assume that practitioners do not have access to these particular technologies for the time being.
- Technologies likely to be available in sophisticated and large metropolitan areas within the next 5-10 years, but probably not elsewhere.
- Technologies likely to be generally available throughout the country within the next 5-10 years.

4.2.6 Issue 6 - Conceptual Framework Approach

The conceptual framework will present and integrate the team's understanding of the various, and sometime disparate elements of the project into a system approach. It explains the methodology in a manner that is (a) consistent with the project's goals and objectives, and (b) applicable to a variety of network characteristics under study. The framework is also dynamic in the sense that it will be continuously updated as new knowledge is gained or new data acquired that require the plan to be modified. Many different conceptual frameworks could serve as the basis for this research effort. While the research team remains open to alternatives, the following sections of this Issue Discussion present the initial team thinking on the conceptual approach that is currently envisioned.

4.2.6.1 Proposed Framework

A high-level representation of the proposed conceptual framework is illustrated in Exhibit 4-5. It includes three principal components: inputs, strategies, and outputs that mutually interact through processes or models. The blocks on the left represent the minimum set of input requirements to carry out a baseline analysis of the network under current or "*prevailing conditions.*" They include a baseline, time-dependent OD-matrix or a method to estimate the O-D matrix if it is not readily available, the topology of the network (link, nodes, and connectivity for both freeway and arterial networks) and a baseline operational plan that describes the current traffic control functionality on both freeway and arterial sub-networks. The blocks on the right of the exhibit represent the toolbox of strategies (such as those listed on page 2 of the RFP).

Strategies are categorized into two groups: those that primarily affect the network travel demand patterns in time and space, and those that primarily affect the network supply features. This designation is only preliminary, and will be revised in the course of the study. It should be noted that while the framework supports the consideration of all classes of strategies, it not the intent of the research team to assess all possible strategy combinations as that number can be become quite unwieldy, and may not be necessary.

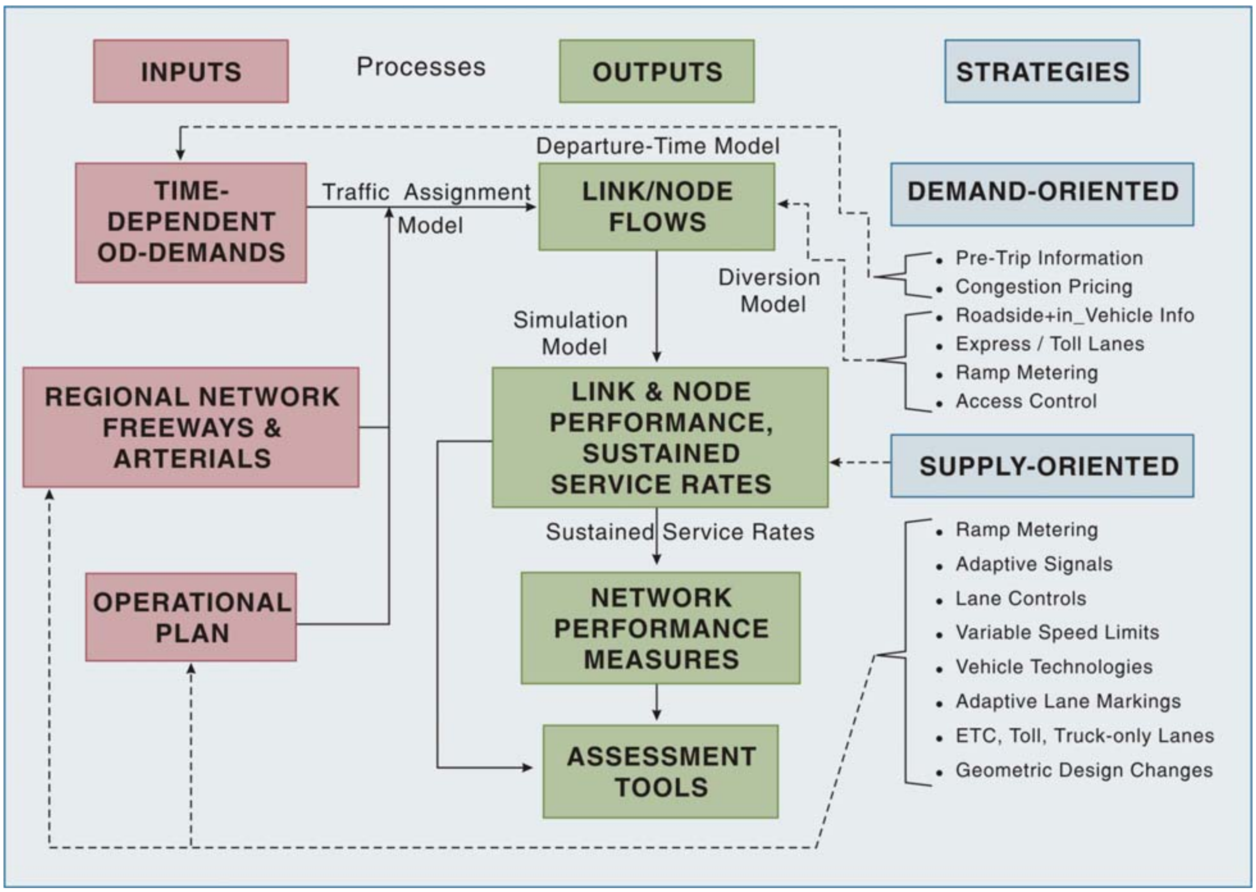
Therefore, the project team will focus its efforts on those strategies that are likely to be field-implemented within the next 5-10 years, and/or on those strategies over which the transportation network manager can exercise some type of control. This latter limitation pertains mostly to the vehicle technology strategy group. For example, we will consider the effects of autonomous vehicle navigation and guidance systems (including AVL/GPS) as these are increasingly prevalent in the US auto fleet, particularly in urban areas. However, the team at this time may not be able to fully quantify the effects of some vehicle technology elements such as collision avoidance systems since (a) their current and projected market share is rather slim, and (b) their capabilities cannot currently be exploited by the network traffic manager to gain capacity. It is reasonable to assume that vehicles equipped with such systems can likely sustain higher flow rates (due to the ability of maintaining shorter headways). However, without further information on their deployment, operational characteristics, and effectiveness in improving network capacity at less-than-full market penetration, the team can only provide the means to incorporate them into the analysis system at some future date (through some type of plug-and-play capability), but may not be able to definitively quantify their benefits in the course of the project. The same rationale applies to other technologies such as adaptive cruise control and vehicle-to-vehicle communications. We will work collaboratively within the team and with the SHRP2 TCC to further our understanding on how to best represent those “down the road” technologies in our approach.

The center blocks in Exhibit 4-5 represent the methodology outputs at different spatial and temporal levels. They include flows on links and nodes; performance at the link and node levels, including the likelihood of breakdown if flows are above sustainable thresholds; and the aggregation of performance to the network level to assess network-wide impacts. Both local and network performance will be utilized in the development of a continuum of assessment tools.

The processes in the Exhibit represent operators that convert inputs or strategies into outputs. For example, the baseline network performance can be evaluated using the input and output blocks where the processes are indicated by the solid lines (only). Such analyses will require the use of traffic assignment and simulation models to determine the prevailing network status, including links and nodes that are likely to operate in breakdown conditions. It should be noted that because both demand and capacity are considered random variables, so will the resulting link, node, and network performance. In other words, the method will generate a range of operating conditions for a fixed set of inputs and strategies. The proposed method will also identify the maximum network capacity, assuming optimal utilization of the system, and will use it as a benchmark to assess the effectiveness of capacity enhancement strategies, as alluded to in the Issue 4 discussion.

The implementation of one or more packages of operational, design, or vehicle technology strategies will alter the nature of the original set of inputs and outputs (indicated in Exhibit 4-5 by the dashed lines). Where these changes occur will depend, in part, on the nature of the application. For example, one can surmise that having access to and acting upon pre-trip information (in the form of dynamic congestion maps or time-dependent route plans available at home or at work) could alter the demand profile in the OD-matrix, by shifting trips in time to avoid congestion, therefore flattening the peak . On the other hand, en-route information received via VMS or in-vehicle information systems is more likely to result in some diversion from pre-planned routes, thus affecting the prevailing link flows. A smart strategy would recommend such diversions to maintain sustainable service rates on critical network links. Ramp metering is categorized as both a demand- and supply-oriented strategy since it affects both the link flows that appear at a potential bottleneck and the likelihood of breakdown. In general, however, supply-oriented strategies will tend to impact the topology of the network (e.g. narrow lanes, more lanes, shoulder use, etc.), the base operational plan (e.g. signal control, variable speed limits, lane controls, etc.) or both.

Exhibit 4-5 Conceptual Framework



4.2.6.2. Performance Measures

An important element of any framework is the specification of the traffic performance measures that will be used to assess capacity gains at both the local or network levels. A variety of measures will be considered in this project. A sampling of promising measures is shown in Exhibit 4-6, and these will serve as the starting point for identifying the most appropriate measures and their attributes early on in the project. It is evident from this that two performance measures, namely sustained flow rates and breakdown probability, will be on the final list.

Exhibit 4-6 Potential Measures of Effectiveness

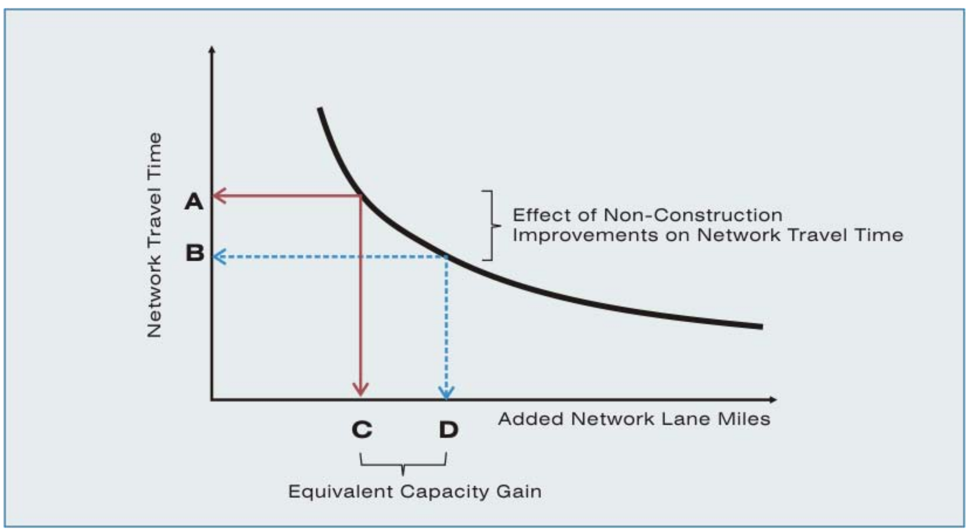
Performance Measure	Freeway, Arterial, Both	Coverage (Link/Node/ Network)	User Understanding	Ease of Aggregation to Network	Ease of Measurement	Sensitive to Operational Improvements	Sensitive to Design Improvements	Sensitive to Vehicle Technology
Capacity	Both	Link, Node	High	Difficult	Reasonable	Yes	Yes	No
Sustained Flow Rate	Both	Link, Node	Low	Difficult	Difficult	Yes	Yes	Sometime
Delay	Mostly Arterials	All levels	High	Reasonable	Reasonable for Arterials	Yes	Yes	Yes
VMT	Both	Network	Medium	Simple	Difficult	Could be counterintuitive	Could be counterintuitive	Could be counterintuitive
VHT	Both	Network	Medium	Simple	Reasonable	Yes	Yes	Yes
Speed	Both	All levels	High	Reasonable	Simple	Yes	Yes	Yes
%Links in Breakdown	Mostly Freeways	Network	Medium	Simple	Difficult	Yes	Yes	Sometime
% Cycle Failures	Mostly Arterials	Node	Medium	Difficult	Reasonable	Yes	Yes	No
Average Travel Time	Both	All levels	High	Simple	Reasonable	Yes	Yes	Yes
Queue Length	Both	Link, Node	High	Difficult	Difficult	Yes	Yes	Sometime
Network Throughput	Both	Network	Low	Simple	Difficult	Yes	Yes	Yes
TTI-Index	Both	Network	Low	Simple	Difficult	Yes	Yes	Unclear
Average Trip Length	Both	Link, Network	High	Simple	Difficult	Could be counterintuitive	Could be counterintuitive	Could be counterintuitive

4.2.6.3 Capacity-Equivalent Concept – An Alternative Approach

In relation to the choice of performance measures to determine capacity gains, it may be useful, as an alternative to determining the theoretical network capacity, to generate a capacity-performance relationship that can indirectly determine the "equivalent" capacity gains from design, operational-, and technology-based improvement strategies.

Exhibit 4-7 below illustrates one possible way to do this through a hypothetical relationship between lane-miles added onto a network and performance, measured in terms of total network travel time. It might be possible to develop such a relationship from a variety of travel demand, HCM, or simulation models for a given network case study, because lane miles represent the traditional way of increasing network capacity. Of course this relationship does not take into account the effect of latent demand on performance, nor is it necessarily continuous. As illustrated in Exhibit 4-7, for a set of non-construction improvements that result in reducing the network travel time from, say, A to B, those improvement would be equivalent to have added D minus C lane miles, or increased the network capacity by (D-C)/C percent. While this is not the team's preferred approach, it is one option that might be considered if the theoretical capacity approach falters.

Exhibit 4-7 Equivalent Capacity Gain Concept



4.2.7 Issue 7 – Sustained Service Rates

Recent research indicates that highway capacity shows all properties of a random variable [3, 4, 5, 6, 7]. The capacity of a highway facility is the result of driver behavior and, therefore, varies as driver population (types of vehicles, motivation or trip purposes, experiences, familiarity with the freeway section and/or with the traffic operation at the specific time) varies. In addition, highway capacity is also a matter of systematic variability due to accidents, incidents, weather, and work zones, among other things. This systematic variability is the reason for most of the congestion delay on freeways. The amount of this delay increases with increasing demand. However, only in a limited part of the network does demand exceed the normal capacity of the infrastructure so that it becomes the main contributor to delay.

Considering the randomness of highway capacity, then, consideration should be given to whether it is reasonable to define the sustained service rate as a fixed (deterministic) threshold. In fact, it might be more appropriate to consider this threshold to be variable. Variability will, at least, exist between different sections of the network (even under identical geometric conditions). Variability will also exist on one section over time. If we consider capacity to be a random variable, it could be useful to define the sustained service rate as a probability of a traffic breakdown for the given traffic demand as discussed later in Task 3 (Develop Conceptual Study Framework); see in particular Section 4.3.3.1.

Particularly for freeways, a method to estimate the distribution function of breakdown capacities based on loop-detector data was derived by Brilon et al. [4]. This method can be applied using simulation (Monte Carlo–Method) in order to quantify the effects of any network improvements or traffic management measures. With this approach, improvements in the road network can be evaluated based on parameters like the reduction in the sum of delays over a year or the duration of congestion during a year.

Conventional approaches for highway capacity analysis only allow operational, design, and technological improvements to be assessed based on average capacities (i.e. the expectancy value of the capacity distribution function). Thus, the variance of the capacity distribution function, which can also have a significant impact on delays, is not taken into account. For German freeways, it was found that the main impact of variable speed limits is a reduction of the capacity variance. By considering capacity as a random variable, this effect can be determined and included in the assessment of traffic flow quality.

4.2.8 Issue 8 – Available Simulation Tools

The goal of this project is to quantify sustained service rates on a facility level and to understand the corridor and network capacity gains achievable by different operational, design, and vehicle-technology strategies. An accurate and reliable quantification of the network throughput requires the integrated system-level perspective to be adopted, which calls for advanced transportation analysis tools to estimate network conditions and to analyze network performance. An important question to be answered in this study is: what assignment/simulation tools can be considered as (perhaps modified to be) the primary evaluation tool? Accordingly, a decision support methodology needs to be further developed to (1) take advantage of the full potential of Advanced Traveler Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS) strategies to improve operational and design aspects that consequently affected travel time, reliability, and predictability of travel in the network, and to (2) quantify the marginal value of individual and combined management strategies in terms of improving regional/network capacity.

One simple theoretical approach to quantify network-wide capacity is to solve the max-flow min-cut optimization problem, which aims to find the maximum possible flow that can be routed from an origin node to a destination node, given capacity constraints on each link. The maximum network-flow capacity can be calculated by finding the minimum value among all simple cut-sets, and this approach has been successfully applied to calculate the upper bound on commodity flows in communications networks and a variety of resource-scheduling applications.

It has been widely recognized that the above general-purpose optimization method cannot consider complex traffic-flow dynamics in a time-varying and complex traffic network. This is because the traffic congestion evolution, such as queue build-up, spillback and dissipation, and the concept of probabilistic service rates, highlighted in this project, cannot be accurately represented by well-defined analytic cost functions and constraints (e.g. the Bureau of Public Road functions). The system complexity, as a result of the spatial and temporal interactions of travelers, precludes the analytical derivation of network capacity in a large-scale metropolitan area. Nevertheless, the above optimization approach still sheds light on and motivates the assignment/simulation-based *system-optimization* approach that will be presented in this research. That is, we first seek to use the system-optimal assignment solution to characterize the upper bound on the physical network capacity, Next, we use the resulting ideal network flow pattern to guide the search of traffic-information and demand-management strategies to gain the realistic maximum capacity.

Dynamic Traffic Assignment (DTA) modeling tools uniquely address the need to evaluate network performance under time-varying demand and supply conditions created by various ATIS and ATMS strategies. To describe the propagation and dissipation of system congestion, a variety of DTA approaches have been proposed and developed to model route choices of passenger cars with fixed departure times. As shown below, a wide range of network analysis tools are currently available to assess the impacts of ITS technologies and different traffic operations and control strategies.

- DYNASMART-P, developed at UT at Austin, UMD, and Northwestern University by Mahmassani et al.
- DYNAMIT, developed at MIT by Ben-Akiva et al.
- IDAS, developed by Cambridge Systematics, Inc.
- Integration, developed by M. Van Aerde & Assoc.
- VISSIM, developed by PTV AG
- Paramics, developed by Quadstone Paramics
- SCRITS, initially developed for FHWA by SAIC
- EMME/3, developed by INRO

In general, IDAS can evaluate different ATIS options, and it can produce useful benefit/cost ratio and net benefit reports. However, IDAS does not model traveler response to ATIS (e.g., route diversion, or departure time shift) and its capability is similar to spreadsheet models (such as SCRITS). DYNAMIT and Integration, on the other hand, are suitable for simulating network traffic dynamics, but their capabilities in modeling different traveler information classes and time-dependent pricing strategies are still fairly limited. As two widely-used commercial micro-simulation systems, VISSIM and Paramics provide good traffic-flow modeling capabilities at a corridor level, but currently they can only simulate relatively small networks. In addition, their heuristics-based dynamic traffic assignment procedures do not necessarily lead to theoretically rigorous network-wide user equilibrium, and the resulting flow patterns are not fully optimized with respect to individual user utilities.

With its current ability to model buildup and dissipation of traffic congestion on a large-scale network, DYNASMART-P is considered a good candidate for assessing the capacity impacts of various types of traveler information (historical, pre-trip, en-route information, VMS), ramp metering, and road-pricing strategies. The FHWA is currently promoting the use of DYNASMART-P for region-wide transportation operations planning to (1) address operational issues in the transportation planning process and to (2) develop and evaluate traffic management and control strategies, particularly in the ITS context. More importantly, DYNASMART-P provides a unique *system-optimization* capability, which can be used to quantify the *maximum* network-flow rate under different traffic conditions. The benchmark set by system-optimal assignment will be used to assess the effectiveness of capacity enhancement strategies and to further provide useful guidance on how to design management strategies that will optimize the network route flow pattern.

It is also important to recognize that using a single model to evaluate traffic-network capacity may not be sufficient to meet different needs in both operational and planning applications. For example, dynamic assignment tools require accurate time-dependent Origin-Destination demand matrices as a fundamental input, and the complex traffic-flow and route-choice models should be carefully calibrated to provide reliable assessment results. The research team aims to provide a range of tools, from a simulation-based methodology for operational analysis to spreadsheet/regression tools for planning applications. The intent of the latter to offer a rapid analysis framework that can estimate/approximate the magnitude and probabilistic upper bound of the network capacity at peak hours. The team plans to seamlessly integrate the above models at the different modeling and analysis phases, namely data collection, model calibration, assignment/simulation, and model validation, to provide unbiased and comprehensive analysis results.

To offer a next-generation planning model for network capacity evaluation, the team plans to further enhance DYNASMART-P in the aspects listed here to meet the unique needs of this project.

1. **Traffic flow model calibration**: Because DYNASMART-P is a mesoscopic model, the maximum service rate for each link is given as an external input parameter. Its link-based traffic flow model needs to be carefully calibrated with field data to capture the impact of detailed geometric-design changes.

2. **Link and network reliability measures**: In general, the travel-time variability can be contributed to by a number of factors, such as day-to-day demand fluctuations, special events, and capacity reductions due to severe weather, work zones, or incidents. As a deterministic assignment/simulation model, DYNASMART-P needs to be enhanced to model probabilistic occurrences of breakdown, incorporate randomness in the demand and service rate pattern, and finally produce link-specific and network-wide reliability/variability measures.

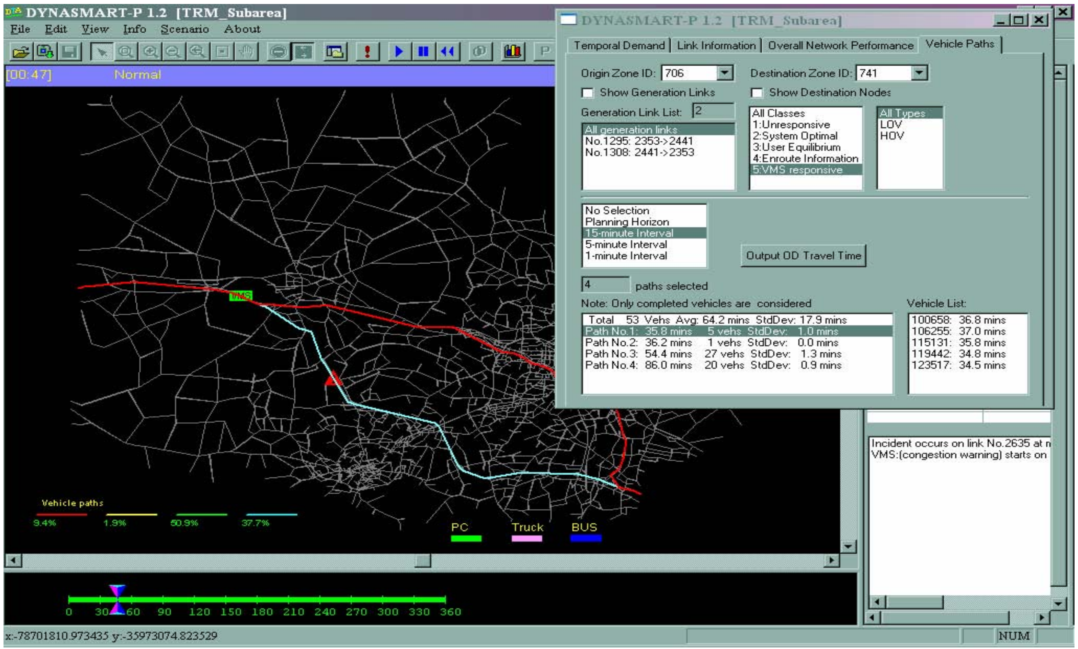
3. Departure time redistribution for network capacity improvement: Currently, DYNASMART-P only models fixed departure times, while advanced demand-management policies such as flexible working hours, time-dependent link pricing, and pre-trip traveler information allow the spatial and temporal demand and supply to be balanced. To evaluate the above strategies, additional utilities are required to redistribute departure-time patterns in the network-capacity optimization process.

4. Sub-area analysis and assignment/simulation system integration: To provide in-depth analysis results related to geometric design and signal timing factors in a sub-area network, assignment results from DYNASMART-P on a large-scale network should be post-processed to generate the Origin-Destination demand and path-flow input for the sub-area analysis. In this analysis, microscopic simulation models such as VISSIM can be further used to consider the impact of detailed flow management and control strategies.

In this effort to develop and extend the model, we will work with data from a number of real, large-scale traffic networks in the network capacity assessment of this project. The following (partial) list shows some of the network data sets currently available in DYNASMART-P format and accessible to the research team.

- CHART corridor network between Washington, DC and Baltimore, MD
- Southern California Association of Governments (SCAG) regional network, CA
- Research Triangle corridor network, NC
- Southeast Michigan Council of Governments (SEMCOG) network, MI
- Portland metropolitan network, OR
- Miami metropolitan network, FL
- Salt Lake City metropolitan network, UT
- Twin Cities metropolitan network, MN

Exhibit 4-8 Possible VMS Diversion Scenario in Research Triangle Corridor Network, NC, Modeled in DYNASMART-P



As one example of these available data sets, Research Triangle corridor links Research Triangle Park with the cities of Durham, Cary, Chapel Hill, and Raleigh, North Carolina. The total estimated population for this region in 2002 was 1,149,114 persons. Exhibit 4-8 shows a VMS diversion scenario modeled in DYNASMART-P for an incident-management application. The network-and-demand matrix used in DYNASMART-P is imported from the existing planning databases and a new round of Triangle Travel Surveys, conducted in 2006. These surveys sampled over 5,000 households in the Greater Triangle Region. The survey samples provide a very rich behavioral data set that can be used to estimate and calibrate the fundamental mode- and route-choice models. The estimated traveler-choice model can be further incorporated into this study to identify future route flow/departure shift trends and, accordingly, to improve the accuracy and validity of the network capacity models.

4.2.9 Issue 9 – Data Collection Issues

There are several factors inherent in the scope and timing of this project that present challenges for the data collection/assembly effort. First, the research of SHRP2 is to be completed in a limited, but achievable time frame. This means that Task 6 (Phase II) must be accomplished in a 6- to 7-month time period. Second, the data to be obtained or collected will have to address network conditions ("network" implies corridors, systems, freeways, and arterials) comprising more than one access-controlled highway and/or arterial. Finally, the data must reflect a combination of operations-, design-, and technology-improvement types applicable to the network capacity enhancements.

In response to the challenges described above, the research team is prepared to use a variety of data sources, including, but not limited to:

- New (relatively) field data collected for capacity-related research projects performed since 1998 (e.g., NCHRP 3-75, Weaving, and NCHRP 3-79, Urban Arterials).
- Data from micro-simulation and other models developed since 1998 for capacity research.
- Data considered well documented and found in printed/web form that reflects network performance measures and the capacity impacts of independent variables (operations, design, technology) both individually and in combination (e.g., FHWA compendium on ITS impacts will be an important source).
- Capacity impacts (e.g., adjustment factors in HCM 2000) of independent variables from HCM 2000 and recent updated chapters.
- Data from this research (field, micro-simulation).
- Data on the operational and design impacts of capacity improvements and related elasticities such as found in NCHRP Report 5-35, *Predicting Air Quality Effects of Traffic-Flow Improvements*.
- NGSIM (Next Generation Simulation) vehicle trajectories datasets on freeway and arterial facilities.

To address the issue of a relatively short time frame (6- to 7-months) for the data collection task, the research team will ensure that the work of Tasks 1 through 4 is documented in a manner that will allow of the team to rapidly identify the existing databases required. Contact persons and cooperative agencies will be determined as part of the Task 4 work.

The second data issue relates to how the capacity of a network is defined. It is true that "network capacity" is not a well-defined term in the HCM 2000. Rather, performance measures such as system or network delay (in person-hours of travel) are used to establish the service provided. In Task 3 of the research, the research team will develop a framework for considering the sustained service rate for the network as a whole. Finally, the research team will address the issue of combining independent variables using estimates of the impact on network capacity and service rates, based on the impacts of individual factors and accounting for possible interactions among the variables.

4.2.10 Issue 10 – Validation

As important as it is to develop a procedure for estimating the performance of capacity-management strategies, it is equally important to provide a means to establish the soundness and reasonableness of its results. Validation protects against errors in the methodology and is needed to build credibility for wide-spread application.

Validation requires field data to determine the relevance and accuracy of prediction models. The use of field data is particularly important given that many of the products of this research effort will likely be developed from microsimulation and travel-demand models. While simple in concept, there are several complex and difficult issues associated with validation.

First is the availability of field data. Collecting new field data is time intensive and likely beyond the scope of this research project. Historical data sets can be obtained from previous research efforts and traffic data archives maintained by transportation agencies. However, there is no guarantee that the historical data reflect the conditions that are desired for testing. Additionally, the data sets may not contain all of the variables needed for the prediction methods that will be developed as part of this project.

Second is the difficulty of isolating the effects of one particular strategy or set of strategies against the many other factors that affect capacity. Before/after testing is commonly applied to quantify the effects of a particular treatment. However, individual treatments are oftentimes implemented as part of a larger project where other geometric conditions are being affected. Other conditions, such as new development and changing land-use patterns, further complicate the ability to isolate the effects of a treatment through before/after testing.

Third is quantifying and validating the cumulative effects of capacity treatments. The relationships among various capacity-enhancing strategies are not well known. Different models exist for predicting the cumulative effects for a particular condition. As an example, the saturation-flow-rate model that is applied in the HCM2000 uses a multiplicative equation for estimating the saturation-flow effects of impedances at signalized intersections. This provides a "portable" model that can be customized to local conditions. Other methods include an additive approach where the effects of a condition are estimated individually and summed, and look-up tables that reflect the combined conditions observed from field data and/or simulation modeling.

Fourth is validating the capacity prediction methodologies against varying traffic conditions, particularly high-volume conditions. The concept of *sustained service rate* acknowledges that capacity is variable and relates to the probability of a breakdown occurring within a given timeframe. The degree of confidence in a result is related to the sample size of field data. Large amounts of data are needed to adequately address the variability of capacity on a facility.

Our approach for validating results and addressing the issues identified above is further explored in Task 10 of the Research Plan.

4.2.11 Issue 11 – Integration with Long-Term Planning Needs

The products of this research effort are likely to be particularly valuable to near-term and longer-term planning efforts, which ultimately become the basis for many important investment decisions. These planning efforts can and do occur across the full spectrum of analytical sophistication, from simple rules of thumb and look-up tables to microscopic simulation models, dynamic traffic assignment, and beyond.

Any and all of these estimating methodologies can effectively inform the investment decision-making process, provided that a) the question being addressed is commensurate with the attainable level of accuracy, b) the analysis tool requires input data that are reasonably and readily met, and c) the analyst is reasonably protected from misapplication of the analysis method and/or misinterpretation of the analysis results. Unfortunately, these conditions do not always coexist. As an example, consider the HCM 2000, which includes planning-level look-up tables for service volumes on every facility type. The tables were built upon a very specific set of assumptions and default values, and each table contains a caveat indicating it is being presented for illustrative purposes only. Nevertheless, experience has shown that these tables are often inappropriately used as-is in a variety of planning-level applications, even though the built-in assumptions and default values may not match actual conditions at all. At the other extreme, the results obtainable from sophisticated microscopic-stochastic simulation models might be just as unreliable if they use a large number of standard but unjustified default values, if inputs are unrealistic or inappropriate, if multiple runs are not averaged, or if the analyst is not a regular user or is unclear on how to interpret the results.

These dangers can be overcome, or at least minimized, but this requires care and thought in the preparation and presentation of the various planning tools. For example, the application of simple look-up tables contained in HCM 2000 might be more reliable if they were replaced with either a step-by-step procedure for building customized tables from a few key user-supplied input parameters, or with expert system software that does this automatically from user responses to a few questions. Additionally, users would most likely benefit from seeing the results in probabilistic terms (for example, a high/low range or the probability of achieving a particular result) because this would reinforce the variable and dynamic nature of capacity both at a point and within a system.

We expect the Phase I products of SHRP2 Project C01 to provide valuable insights and direction into the most effective means for incorporating the results of this effort into planning studies. The real-world case studies included therein will reveal the amount and detail of data readily available to planners and decision makers, the range of circumstances under which the analyses are conducted, and the types of tools and levels of analytic sophistication that are most typically accessible. We recognize that an overall framework for collaborative decision-making is being prepared in SHRP2 Project C01, and that the results of this project must integrate into that effort. Even so, this project can provide guidance on incorporating the effects of capacity-enhancing strategies into planning-level studies that will be instrumental in developing the overall decision-making framework plan in SHRP2 Project C01.

4.3 RESEARCH APPROACH

The research plan outlined in this proposal has been developed to achieve the project's stated goals and objectives. The proposal plan will be carried out within the time frame and budget allocations for this project. Detailed descriptions of each work task are included in the sections that follow.

4.3.0 Task 0 – Prepare Amplified Research Plan

Within 15 days following the project's contract start date, the research team will submit an Amplified Research Plan to SHRP2 staff. The Amplified Research Plan will include an updated Research Approach reflecting panel comments on the proposal, project schedule, budget and hours by task.

4.3.1 Task 1 – Identify Technological Changes

Identify technological changes that may affect traffic operations within the next 10 years. Technologies include items like adaptive cruise control, collision avoidance, information dissemination, and telecommunications—Dedicated Short Range Communications (DSRC), and mobile ad-hoc networks/zero infrastructure ITS. How can the technologies be implemented or taken advantage of to increase sustained service rates?

Task Objective: Identify promising technologies for improving the sustained service rates of transportation facilities and that have potential for wide-spread application in the next ten years.

The purpose of this task is to identify the technological changes that are likely to affect traffic operations within the next 10 years. The options include ideas like adaptive cruise control, collision avoidance, information dissemination, and telecommunications—Dedicated Short Range Communications (DSRC), and mobile ad-hoc networks. The question to be answered is: how can these technologies be implemented to capitalize on the increases in sustained service rates that they provide? The steps in completing the task will be:

- canvas the published literature, the web, and other sources to update the Research Team's sense of the advancing technological frontier;
- assess the likelihood that these technologies will affect sustainable capacity values;
- document these technologies and their anticipated capacity effects;
- highlight how the technology can be used in combination with other technologies or strategies to maximize its benefit;
- identify barriers for implementation, particularly from the standpoint of transportation managers; and
- assess technologies not likely to be deployed until after 10 years that hold significant promise.

The technologies identify through the research will be grouped in one of three categories as outlined in Section 4.2.5: (1) technologies that will only exist in test-bed environments in the next ten years; (2) technologies that are likely to only see implementation in progressive metropolitan regions in the next ten years; and (3) technologies that are likely to have wide-spread implementation in the next ten years.

Task Deliverable: The research team will prepare Working Paper #1 that summarizes the identified technologies along with a matrix summary evaluation. The working paper will highlight the issues and opportunities associated with each technology, the appropriate applications/context for each technology, and keys for successful implementation. The working paper will be incorporated in a quarterly progress report and the Phase I report.

4.3.2 Task 2 – Inventory Existing Strategies and Tactics

Prepare a summary of what is already known about the potential of different strategies and tactics for achieving improvements in sustained service rates.

Task Objective: Identify current operational, design, and technology strategies that are applied in practice to increase the utilization of network capacity. Describe the strategies, the context in which they are applied, and their documented effectiveness.

This task involves preparing a summary of what is already known about the potential of different strategies and tactics to achieve improvements in sustained service rates. These ideas will form the basis of the rest of the project. The strategies and tactics will include methods to deploy technologies that can enhance sustainable service rates and mechanisms to observe those service rates. The steps involved will be: canvas the published literature, the web, and other sources to determine what strategies and tactics have been employed by researchers and practitioners; utilize the expertise of the Research Team to determine which strategies and tactics are most likely to be productive and implementable by various agencies across the US; and prepare a report documenting these findings.

While many strategies have been studied as part of previous research efforts, there lacks a single document that addresses the wide range of potential capacity-enhancing strategies for both freeway and arterial networks. This effort will synthesize the known characteristics and effects of various strategies as documented in published research reports, much of which is coordinated by Federal Highway Administration's Freeway Management and Arterial Management programs.

Additionally, the research team will reach out to select transportation agencies to identify first-hand experiences and insights regarding the practical effects of operational strategies that have been implemented in the field.

Exhibit 4-9 provides a sample of known strategies for improving capacity categorized by network type and strategy type.

Exhibit 4-9 Summary Strategies to Improve System Capacity

	Operational	Design	Technology
Arterial	Signal retiming Signal coordination Adaptive signal control	Roundabouts Right turn lane Auxiliary lanes Access Management	Dynamic Lane Assignment Intersection Collision Warning
Freeway	Ramp meter deployment Incident management HOV Operations Lane management Pricing	Auxiliary passing lanes Weaving sections Use of shoulders Narrow lanes	Forward Collision Warning Road Departure Warning Adaptive Cruise Control
Both	Special Event Management Variable Speed Limits Enforcement		ATIS In vehicle driver information

Task Deliverable: The research team will prepare Working Paper #2 that documents the strategies, their appropriate use and application, operational effects, and implementation challenges. The technical memorandum will be incorporated in a quarterly progress report and the Phase I report.

4.3.3 Task 3 – Develop Conceptual Study Framework

Develop a conceptual framework for the study. Recognizing the shortcomings of conventional definitions of capacity for the operation of and planning for congested facilities and networks, develop a conceptual framework for determining potential increases in sustained service rats attainable through improved operation, design, and technology. The conceptual framework should focus on limited-access highways and urban arterials and address:

- *The factors that affect sustained service rates,*
- *Performance measures,*
- *A way to set priorities based on incremental improvements in sustained service rate relative to cost,*
- *Appropriate sustained service rates for planning and incorporating them into the planning process,*
- *How improved service rates can be incorporated into next-generation planning models. (Look beyond static models and IDAS).*

Task objective: Develop a framework that can be applied to determine potential increases in sustained service rates that can be attained through operation, design, and technology strategies. The framework should be applicable to both limited-access highway and urban arterial networks.

A preliminary framework for this research was described in Section 4.2.6. The concept of using combinations of demand and supply oriented measures to increase network capacity and performance is embedded in the framework. This task will explore in more detail several aspects related to the framework, namely supply and demand factors that affect service rates, a discussion of performance measures, development of planning-level sustained service rates and methods for their incorporation into next-generation planning models. The prioritization scheme for selecting improvements is discussed in Task 8.

4.3.3.1 Factors That Impact Sustained Service Rates

The inability of traffic systems to consistently process high flow rates near the theoretical capacity (e.g. HCM) of links and nodes is rooted in variability. By that we mean variations in driver behavior in terms of speed, lane selection, acceleration capabilities and lane changes that cause disruptions to the stable flow of traffic. When compounded with short term surges in traffic demand, these variations often lead to flow breakdown. Once breakdown occurs, previous research has shown that flow rates on freeways drop considerably below their pre-breakdown levels (in the range of 3-15% upon queue formation), thus reducing the link throughput significantly [9, 10, 11]. Such events tend to occur more commonly at locations where there are flow disruptions, for example at freeway ramp terminals [12, 13], at signalized intersections, and under non-recurring conditions such as incidents, work zones, and inclement weather conditions. Among the factors that limit the ability of a road section or intersection to process sustained high flow rates are the following:

1. Short term demand surges when the prevailing flow is near the link or node capacity

2. Short term capacity drops due to excessive lane changing or weaving activity, especially when the demand flow rate is near the link or node capacity

3. Large speed gradients (expressed in mph/mile) over consecutive freeway segments

4. Inability of heavy vehicles to match a similar sustained flow rate to autos, particularly on steep grades and/ or from a stopped position at an intersection

5. Improper lane balance, or lane utilization, in which case a traffic signal processing rate in green is much lower than the rated saturation flow rate

6. Large disparities in driver population attributes (e.g. differences in desired headways for aggressive vs. conservative drivers; differences in lost time by attentive and distracted drivers), which will lead the system to operate in a sub-optimum manner.

7. Degree to which conflicting movements share the same right of way at the same time. For example, the presence of weaving vehicles at weaving sections, or shared through-left lanes on arterials, or permitted left turns at signals ultimately impact the service rate of the facility.

8. Roadside activity that influences the ability of the link or node to sustain high service rates. This is not much of an issue for freeways (save perhaps for the gawking effects of accidents or incidents), but much more for arterial traffic including parking maneuvers, bicyclists and pedestrians, etc.

9. Basic geometric attributes such as lane width, grade, and clear shoulder width.

To emphasize, it is the disparity or heterogeneity between elements (drivers, vehicles, vehicle paths, vehicle lane selection etc.) when combined with variations in demand and capacity under the prevailing geometric and control elements that are likely to lead to breakdown. Because many of these factors are stochastic in nature, their effects must be characterized mathematically as a probability of breakdown. In response to these factors, any intervention that contributes to increased uniformity in performance is likely to yield higher sustained flow rates. This concept often motivates traffic and transportation engineers to physically separate traffic streams that have varying performance. Examples include the use of exclusive left turn lanes on arterials, bus only-lanes, truck restrictions on freeways, truck lanes, lane controls on freeways, and a host of other treatments intended to segregate traffic elements that have different operating characteristics.

In this subtask, the above list will be refined, disaggregated into its individual components, and analyzed as to their individual and combined effect on sustained flow rates.

4.3.3.2 Performance Measures

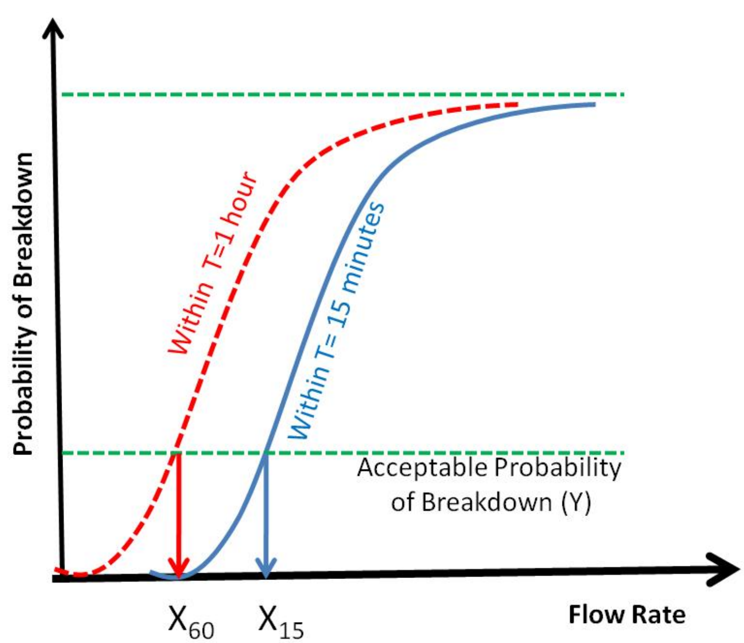
A preliminary list of potential performance measures was provided in Exhibit 4-6. It includes both local and network measures. In this task, the research team will evaluate each of the proposed measures using a variety of criteria and make a selection on which to use for the purpose of local and network wide evaluation. Some discussion is provided in this section on the definition and conceptual construction of sustained flow rates, the key performance measure in this study.

We define a sustained flow rate (X_s) as the maximum flow rate that can pass without interruption through a link, node or a series of links and nodes in a traffic system over a time period (T), such that the probability of breakdown (B) does not exceed (Y). Mathematically, this is defined as:

$$P(B_T \mid X_S) \leq Y$$

Conceptually, one would need to develop the probability of breakdown as a function of flow rate, with the threshold X_s associated with an acceptable risk of breakdown specified by the user. The determination of the value T requires more thought, since as T increases, the system's ability to sustain the same flow without breakdown is likely to decrease. Possible values to consider are one hour, consistent with a typical planning horizon, or 15 minutes, consistent with HCM analyses. Credible value of Y are in the range of 1% to 20%. In most cases, however these thresholds should be selected based on local experience and practice. In Germany, for example, conventional 1-hour capacities were found to correspond to a 20-30% probability of breakdown. The tradeoff between time to breakdown and sustained flow rate is illustrated below in Exhibit 4-10 and explained next.

Exhibit 4-10 Defining Sustained Flow Rates From Breakdown Probability



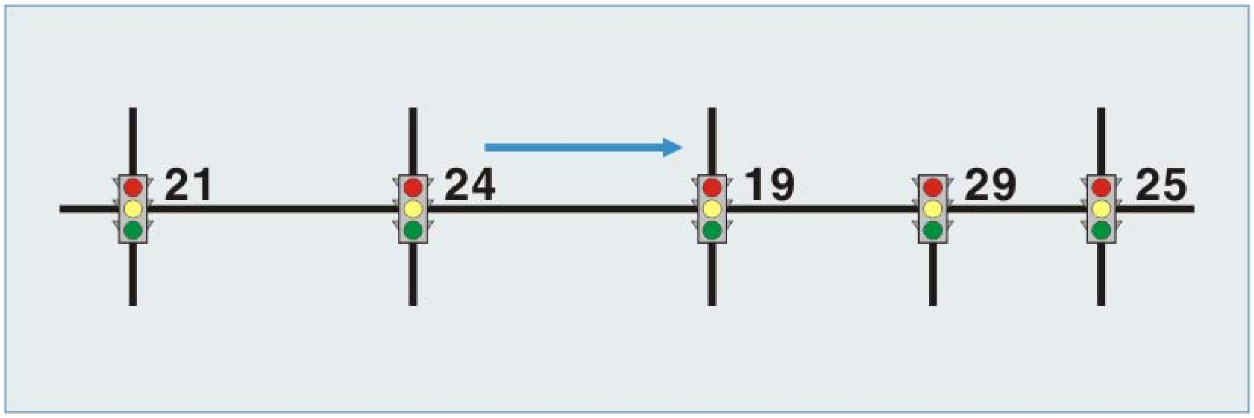
In the previous Exhibit, the flow rate that can be sustained for 15 minutes (X_{15}) before reaching the breakdown threshold Y is obviously larger than the flow rate that can be sustained over one hour (X_{60}). Values higher than X_{15} and X_{60} are obviously observed but tend to be associated with a higher likelihood of breakdown than the threshold Y. The research team will investigate whether to use a single or multiple periods, and will develop the appropriate breakdown curves associated with each period, if needed using datasets available to the study team.

The figure also leads to another important question: what is the definition of a breakdown? And how do we measure it? The answer will be different for the different type of facilities. Usually a freeway breakdown is defined in terms of sudden drops in the average speed that are sustained for a certain time period. For example, Chen et al. [11] used a 20 mph speed drop to proclaim breakdown; Caltrans District 3 congestion maps define a congested segment as one with speeds lower than 35 mph over 15 minutes (equivalent to a 25 mph speed drops given the 60 mph prevailing free flow speed). While breakdown thresholds tend to be site specific, they vary narrowly from 19-25 mph below the free flow speed in most cases. Thus a possible third dimension of sustained flow rates is the severity (or duration) of the breakdown associated with their occurrence. The project team will use existing datasets available to the team to further study and calibrate those relationships.

For signalized arterials, the objective is to maintain sustained high flow rates during the green phase, and low arrival rates during the red phase. This is what good signal timing and coordination programs attempt to achieve. Breakdown occurs when the queues fail to clear in the green phase (termed a cycle failure), or when vehicles cannot enter a downstream link due to the presence of queues (demand starvation). These observations are motivated by two possible events: the saturation flow rate during a cycle—which is a random variable—is below that which was assumed in timing the signal, or the demand during a cycle exceeds what was designed in the signal plan. The confluence of those two events in one cycle will tend to increase the likelihood of this cycle to fail to clear the queue, and in the event of limited queuing space to starve demand from the upstream signals.

To illustrate the concept a simple arterial example is presented in Exhibit 4-11. It shows a directional linear arterial with several signalized intersections having different rated through movement *cycle capacities*. The engineer is interested in finding out what sustained (through) flow rate can this arterial handle. On first blush, the critical intersection is examined and the *maximum* flow rate that can pass through the system would be 19 vehicles/cycle. However, due to randomness in demand and saturation flow rate, it is likely that this rate may not sustainable at the critical intersection, and that perhaps a lower arrival rate of 16-17 vehicles/cycle (d/c ~ 0.85-0.90) would ensure sustainability without cycle failures at all intersections. Another interesting observation would be the effect of an operational improvement at the critical intersection, which would increase its through movement rated capacity to say 23 vehicles/cycle. In this case, the sustained service rate would no longer be governed by that intersection, but by the furthest upstream intersection, which now controls, or meters the flow rate through the system. Applying the same rationale as before, the sustained rate would now increase to about 18-19 vehicles/cycle, far below what the improvement at the (old) critical intersection was intended to provide. The same approach is very applicable to the operations of congested freeways facilities, in that it takes into account the effect of hidden bottlenecks that may be activated when a main bottleneck is treated [14, 15]. Looking at the system-wide effects of sustained flow rates will be a key feature of the KAI approach in assessing the effects of local operational, geometric and technological improvements.

Exhibit 4-11 Illustrative example of sustained arterial flow rates



The remainder of this subtask will focus on selecting local and network performance measures that are consistent with the stated sustainability definition at the local and network levels, and to canvass the literature on additional measures not considered in this proposal.

4.3.3.3 Developing Appropriate Sustained Service Rates for Planning Applications

At the operational level, the research team will have developed breakdown probability curves associated with various flow rates on arterial and freeway networks, and with various improvement strategies. Default values for acceptable rates of failures will be selected based on team consensus in coordination with the panel. This will result in quantifying planning level service rates that can replace those currently in use in travel demand models. Alternatives will include look-up tables and regression models to estimate the service rates in a simple manner for incorporation into the planning process. This approach is further described in Task 9 (Develop Planning-level Guidance).

4.3.3.4 Incorporating Improved Service Rates Into Next-Generation Planning Models

The next generation planning models will integrate the effects of operational, design and technology improvement into network performance and evaluation. The research team, with its significant strength and experience in modeling and simulation has opted, initially, to use the DYNASMART-P platform as the vehicle to implement the proposed framework. The rationale is simple: it is the only dynamic model that is capable of incorporating both traditional supply-oriented improvements as well as behavioral models tied to path changes due to the presence of traveler information. Additional details on the rationale for using DYNSMART-P were provided in section 4.2.8. However, for the purpose of this study, the following enhancements and additions to this tool will be needed (among other things):

- Model probabilistic occurrences of breakdown;
- Incorporate randomness into the arrival and service rate patterns;

- Estimate and redistribute time-dependent O-D demand patterns; and
- Generate performance reports (at the node, link, subarea, and network levels) that are consistent with the required measures to be established in this task.

Task Deliverable: The research team will prepare Working Paper #3 that describes the proposed conceptual framework for the study. The technical memorandum will be included in a quarterly progress report and the Phase I Report.

4.3.4 Task 4 - Develop Measurement Methodology

Develop a methodology for measuring sustained service rate and assessing the capacity improvements achievable from operations, design, and technology packages. Identify the role of simulation and modeling in the methodology. Identify the data resources you plan to use in the methodology, assess their adequacy for the purpose, and specify enhancements needed to carry out the methodology.

Task Objective: The objective for this task comprises three areas of research. First, the cornerstone of the overall project and of Task 4 is to devise a method for estimating sustained service rates (SSR) and possible improvements in those rates which can be achieved through operations, design, and technology. The other two areas for research are to identify the role of the simulation and modeling in the method and the data resources to be used.

4.3.4.1 Estimating Sustained Service Rate

From the RFP, sustained service rate (SSR) is defined as “the highest flow rate that can be sustained over a peak demand period with a low probability of breakdown.” As developed in Task 3 (study framework) the SSR will depend on the probability of breakdown and the operating agency’s assessment of what level of risk of breakdown is acceptable on a given segment.

In this task, the research team will identify the method(s) that can be used to estimate (or field measure) the SSR under congested conditions. A key for doing this will be to understand the need for setting a level of risk (of breakdown) that is acceptable for a given freeway segment or urban arterial. Standard or default values of service rates will be generated in Task 3 by the team for inclusion in the final report.

4.3.4.2 Assessing Capacity Improvements

The universe of project strategies that can be considered for improving the SSR is very large. This becomes even more apparent when one considers that combinations of project types are to be considered. To achieve a general idea as to how the improvement strategies listed in the RFP might impact the performance of freeways or arterials, Exhibits 4-12 and 4-13 are included. For each improvement strategy or project type, a qualitative estimate is given of the impact on reducing probability of breakdown and on increasing sustained service rate.

Exhibit 4-12 Illustrated Summary of Improvement Impacts (Part I)

Capacity Improvement Factor	Qualitative Assessment of Impact 1=Low, 5=High	FREEWAYS		ARTERIALS		Source or Data Likely Available to Show Impact
		Increased Capacity	Decreased Probability of Breakdown	Increased Capacity	Decreased Probability of Breakdown	
1. Traveler Info. (pre-trip)	2		●		●	Yes: ITS, FHWA
2. Traveler Info. (trip, roadside)	3		●		●	Yes: ITS, FHWA, State DOTs
3. Traveler Info. (in vehicle)	2		●		●	Yes: ITS, FHWA, State DOTs
4. Variable Speed Limits	2	●	●		●	Yes: ITS, Europe, State DOTs
5. Ramp Metering	4		●	N/A		Yes: FHWA, State DOTs
6. Express Lanes	3			●	●	Yes: ITS, FHWA, Cities
7. Network Optimized Adaptive Signals	3		●			Yes: ITS, FHWA, State DOTs
8. Electronic Toll Collection	3		●	N/A		Yes: ITE, State DOTs
9. Reversible Lanes	4	●	●	N/A	●	Yes: FHWA, Cities
10. Lane Controls	2		●		●	Yes: ITS, Cities
11. Use of Shoulder Lanes	4	●		●		Yes: FHWA, State DOTs
12. Use of Narrow Lanes (more lanes)	4	●		●		Yes: State DOTs, FHWA

Exhibit 4-13 Illustrated Summary of Improvement Impacts (Part II)

Capacity Improvement Factor	Qualitative Assessment of Impact 1=Low, 5=High	FREEWAYS		ARTERIALS		Source or Data Likely Available to Show Impact
Geometric Design		Increased Capacity	Decreased Probability of Breakdown	Increased Capacity	Decreased Probability of Breakdown	
13. Improve Bottlenecks	2	●	●	●	●	Yes: NCHRP, State DOTs
14. Improve Weaving Areas	3	●	●	●	●	Yes: NCHRP, FHWA
15. Provide Turn Lanes	2		●		●	Yes: Various
16. Improve Intersections	2		●		●	Yes: Various
17. Access Controls on Arterials	4				●	Yes: NCHRP, FHWA, State DOTs
Technology						
18. Navigation Aids	2		●		●	Possibly
19. Radar/Adaptive Cruise Control	1	—	—	—	—	Possibly
20. Collision Avoidance	2		●		●	Possibly
21. Vehicle to Vehicle Communications	1	—	—	—	—	Possibly
22. Probe Value of GPS-Equipped Vehicles	2		●		●	Yes: FHWA, State DOTs

4.3.4.3 Identify Role of Simulation and Modeling

The use of simulation and other models will be important for producing measures of performance for various improvement strategies and for validation of the proposed method. Transportation planning models will be an important element in the overall method since the vehicle path re-assignment in a network will be one impact of reaching breakdown condition at one or more locations in a network. The following models are a small sample of those that will be considered for application.

- DYNASMART
- DYNAMIT
- IDAS
- Integration
- VISSIM
- Paramics

Models found in the HCM 2000 will also play an important role in estimating the capacity and SSR levels for freeways and arterials.

Based on the conceptual study framework presented in Task 3, this task also aims to ensure that the analytical, simulation, and assignment models adapted in this study can fully meet the following requirements:

1. Utilize existing data sources to provide reliable regional O-D demand and stochastic link capacity input;

2. Adequately and realistically model the existing and emerging operational, technological and design strategies documented in Task 2;

3. Provide accurate estimates of network capacity and marginal capacity gains of different strategies; and

4. Construct a seamlessly integrated model system that can produce link-specific and network-wide reliability/variability measures.

The research team will identify the candidate models, assess their capabilities, document differences, and evaluate their utility in producing the performance measures and using the appropriate input variables for this research.

4.3.4.4. Identify Data Resources

There are two levels of data resources that will be identified by the research team. First, existing resources that can be used to assist in the development of the methodology will be identified. These resources include the following:

- Databases from operating jurisdictions (for performance characteristics)
- Databases from other recent research (NCHRP, FHWA)
- Databases from MPO's and other planning organizations
- Databases from international work (e.g., Germany)
- Other data sets from consulting groups

These identified databases will also be used in Task 12, Validation.

A list of representative existing data sets that will be considered for use in this research is identified below. A number of large-scale traffic network data sets in DYNASMRT-P format have been described in Section 4.2.8. Note that many other data sets will be identified during the project and will also be considered as candidates.

- NCHRP 3-75, Weaving
- NCHRP 3-79, Urban Street Operations
- NCHRP 3-70, Multimodal Arterial LOS
- False Capacity for Lane Drops

- Using Advanced Vehicle Monitoring to Extend System Capacity Along North Carolina Freeways
- London Motorway Data
- NGSIM trajectory data
- Downtown Chicago Video Data

Task Deliverable: The research team will prepare Working Paper #4 which will document the proposed methodology for estimating capacity, the role of simulation/travel forecast modeling, and data sources for model development. The working paper will be incorporated into a quarterly progress report and the Phase I Report.

4.3.5 Task 5 – Prepare Interim Report

Prepare an Interim Report. If necessary, include a revised work plan and budget based on the results of Phase I. Do not proceed with Phase II until the interim report is approved.

Task Objective: The objective of this task is to summarize the key findings from Phase I of the research effort and provide an updated work plan, budget, schedule for Phase II if necessary.

The Interim Report will include a compilation of the issues, working papers and comments received for each of the preceding tasks. It will also provide a summary of feedback and direction received from the TCC and SHRP2 staff during the course of their review. The interim report will clearly document a work plan, budget and schedule for Phase II of the project. No work will be initiated on any task associated with Phases II and III until the Interim Report has been approved.

Task Deliverable: The deliverable of this task will be the Interim Report, which will be submitted within five months after the start of the project.

TCC Responsibility: Review and provide comments on the project Interim Report. It is anticipated that comments will be received from the TCC in writing and these comments will be integrated, as appropriate, into the final content of the Interim Report and subsequent task activities.

4.3.6 Task 6 – Obtain and/or Collect Data

Obtain and/or collect data as called for in the methodology.

Task Objective: The task objective is to carry out a data collection program, including assembly of existing databases, that conforms with the data requirements established in Task 4. The following subtasks will be undertaken to satisfy this objective.

4.3.6.1 Assemble Existing Data

In this subtask, the research team will assemble, from KAI projects and other sources, all data sets identified in Task 4, as applicable. It is not possible, at this early date, to firmly establish the details of the data sets that will be assembled and used. However, the project team expects to make use of three basic types of data and according to the approximate proportions as follows:

- Newly-collected field data (50%)
- Simulation results (25%)
- Synthesis of recently-completed and relevant data collection activities (25%)

Much preparatory work will be completed as a result of the previous task activities, which will also guide the work of this particular subtask. For example, the qualitative assessment of the potential impact of various capacity improvement factors conducted in Task 4 will be especially important in defining how and where to focus these data collection activities. Exhibits 4-12 and 4-13 identify the project team's preliminary assessment of the potential impact of various capacity improvement factors on a scale from 1 (low) through 5 (high). The project team expects to rely exclusively on synthesized data sources for evaluating any capacity improvement factor rated at or below 2 on this scale. Factors rated at 3 may use any of the three data sources identified above, and factors rated at or above 4 will most likely use multiple data sources and data types. Newly-collected field data will be focused exclusively toward factors rated at or above 4.

New field data collection activities will be focused toward sites with the following characteristics:

a) sites that have been used in previous data collection efforts for related/relevant purposes, thereby allowing the project team to build upon previously-completed work;

b) previous data collection efforts associated with projects for which the research team is already familiar, thereby allowing the research team to minimize learning-curve costs; and

previous data collection efforts that were recently completed, thereby allowing the project team to build upon it with minimal problems and discontinuities.

A review of the completeness of the data will be made. Also, the utility of the data for method development and for validation will be assessed.

4.3.6.2 Produce Simulation

As indicated in Task 4, some amount of simulation modeling is likely to be required. This subtask will exercise the simulation and other models that will produce the specified data.

4.3.6.3 Quality Control and Summary

The entire database developed in this subtask will be reviewed for its utility and quality and any significant gaps will be filled. The data will be prepared in electronic format for subsequent use.

Task deliverable: The research team will prepare Working Paper #5 which will include a description of each data source, the sample size, date/time that the data were collected, and a sample table or image to highlight the data types (speed, volume, density, etc.). The Working Paper will be submitted in the applicable quarterly report and Phase II report.

4.3.7 Task 7 – Quantify Strategy Impacts

Quantify the improvement in sustained service rate that can be expected from the strategies, individually and in combinations most likely to be of interest to practitioners. Perform network level assessment using the methodology proposed.

Task objective: Using the framework and methodology from Phase I, estimate the effect of select strategies on sustained service rates, individually and in combination, for freeway and arterial facilities.

The conceptual framework developed in Task 3 along with the sustained service flow rate measurement and assessment methodology developed in Task 4 will be implemented using a carefully selected collection of simulation and analytical tools (see section 4.2.8). The impacts, absolute and relative, of the technology changes, strategies, and tactics identified in tasks 1 and 2 will be quantified. The data obtained and collected in Task 5 will provide the observational foundation for this effort.

Although tool selection will be finalized during the execution of tasks 3 and 4, the research team envisions that DYNASMART-P or a simulation tool with similar features will provide the primary integrative role in the evaluation and quantification methodology. Key functional requirements for this integrative role include the capability to interface with regional planning models as well as the capability to support more detailed subarea analysis as needed for project specific decision support. A tool such as DYNASMART-P will also effectively support the network level assessment that is a fundamental requirement of this task.

The identified strategies will be first evaluated individually. Following this initial evaluation, impacts will be quantified for a robust subset of feasible combinations of strategies focused on packages that are, in the words of the request for proposals, “most likely to be of interest to practitioners.” The strategy impact quantification task will provide a prototype decision support toolbox based on the capacity impact assessment framework as well as general strategy assessments that will form the basis for the sketch level selection tool developed in Task 8. In other words, the toolbox developed and used in this task will be intentionally designed for full featured decision support. However, the key capacity impact findings from this task will be encapsulated in a streamlined procedure in the following task. The streamlined procedure will be tailored for decision makers who need or desire a simpler support tool.

Task Deliverable: The research team will prepare Working Paper #6 which will document the improvement achieved in sustained service rate for each analyzed strategy and set of strategies. The working paper will be included in a quarterly progress report and the Phase II interim report.

4.3.8 Task 8 - Develop Strategy Selection Procedures

Using the results of Task 7, develop, build upon, or adapt a tool(s) for the selection of appropriate strategies to achieve near-term improvements in sustained service rate at both the local and network level under various conditions.

Task Objective: Provide tools and guidance to practitioners for selecting appropriate strategies for increasing the capacity and sustained service rate of local and network facilities.

In practice, the selection of an operational strategy or set of strategies is dependent upon multiple factors that go beyond operational effects. Elements such as public/political perception and support, cost, and maintenance/enforcement/education requirements all play a roll in an agency's decision to implement a particular strategy. However, the purpose of this task is to focus on the operational benefits that can be achieved for a particular strategy or set of strategies and provide guidance to practitioners for estimating the operational benefits of a strategy at a local and network level. Practitioners will use this information to identify the most promising strategies for improving capacity and sustained service rates for their facility.

For each strategy and set of strategies we will provide a description of the applicable context of the strategy, a description of its operational effects as it relates to traffic flow fundamentals, the required input parameters for analysis, tools for estimating the operational effects, and performance measures that should be used to evaluate the strategy at the local and network level. This effort will incorporate the quantified capacity benefits of strategies as determined as part of Task 7. The result will be a "menu" of strategy options presented in either written narrative form, in a matrix, and/or incorporated in a decision-making software tool.

Additionally, we will explore the use of mathematical programming tools to identify those improvements that achieve the desired performance at a minimum cost. One possibility is the use of chance programming techniques, a class of stochastic programming methods [16] in which one seeks to minimize an objective function of improvement costs, subject to budgetary constraints (by improvement type if needed), and upper bound constraints on the probability of breakdown throughout the network. By increasing (relaxing) the budget in small increments, a new set of improvements can be identified that produce the next set of cost-effective projects. In essence this approach could provide an implementation schedule as well as an improvement list. If the problem is well specified, then this approach may provide an optimum selection of bundles of strategies that have network-wide benefits at acceptable costs. We will also explore other less esoteric approaches in which a compatibility matrix between project improvement options is developed. In this case, the research team will propose the most appropriate bundle of improvements for a given budget, and estimate the impact of each bundle using simulation or other tools. Other approaches which rely on users' (i.e. system managers) surveys to identify how priorities are set could also be integrated in either the mathematical or empirical approach.

Additional questions that are important for the user to consider will be incorporated in the strategy selection methodology, such as:

- Does the selected strategy address the bottleneck or capacity constraint on the system?

- Will the strategy cause the bottleneck or capacity constraint to shift to a different location? If so, what is the net capacity benefit, or the reduction in probability of breakdown?
- Does the strategy adversely impact operations of the system at a local or network level?
- What are the capacity effects, if any, of the strategy during off-peak periods or periods of non-recurring congestion?
- Are there associated benefits or disbenefits for the natural or built environments related to the selected strategy?
- Are there associated safety benefits or impacts, particularly related to driver expectations?
- What is required in terms of education, enforcement, and maintenance to achieve the full benefits of the strategy?
- What is the operational design life of the strategy?
- What cost is required for planning and design engineering, implementation/construction, and maintenance?

Task Deliverable: As part of this task, a guidebook will be prepared (either in electronic or web-based form) and documented in Working Paper #7 that describes the selection tools and how to apply them. We anticipate including examples in the form of case studies for three network types: a freeway-only network, an arterial-only network, and a combination freeway-arterial network. The case studies for the guidebook will be revised/updated with the results from Task 12 *Validation.* The guidebook will be submitted in a quarterly progress report and the Phase II report. Depending on the outcome of this task, spreadsheet and software tools could also be produced for application by the end-users.

4.3.9 Task 9 -- Develop Guidance for Planning-Level Implementation

Develop guidance for incorporating the sustained service rates achievable from operations, design, and technology into alternatives analysis, corridor planning, and long-range planning.

Task Objective: The objective of this task is to provide mechanisms for planners, analysts, and decision makers to estimate the cumulative effects of one or more capacity-enhancing strategies on point, facility, and/or system-wide performance characteristics. This task draws information from preceding tasks as well as other ongoing SHRP2 projects. The following substasks will be undertaken to satisfy this objective:

- Subtask 9.1. Inventory Results of Other Ongoing SHRP2 Projects.
- Subtask 9.2. Correlate Strategy Selection Procedures
- Subtask 9.3. Develop Guidance and Associated Tools

Each of these subtasks is described in more detail in the following paragraphs.

4.3.9.1 Inventory Results of Other Ongoing SHRP2 Projects

In this subtask, published and/or reportable outcomes associated with other external projects will be reviewed and inventoried for the purpose of identifying relevant characteristics of near- and long-term planning studies. Particular attention will be paid to SHRP2 Projects C01 and C02, but other relevant work conducted by FHWA, state DOT's, and universities will also be investigated to ensure maximum integration and interface with existing/planned tools, processes, and strategies. The results of this effort will be a three-dimensional matrix that summarizes these inventory results according to:

- The amount and detail of data readily available to typical planning analyses;
- The range of circumstances/conditions under which typical planning-level analyses are conducted; and
- The types of tools and analytic sophistication most typically accessible to these planning-level investigations.

4.3.9.2 Correlate Strategy Selection Procedures

In this subtask, the strategy selection procedures developed in Task 8 will be matched with the input, output, and analytic skills requirements associated with each of the cells contained in the categorized inventory prepared in Subtask 9.1. The objective of this matching process will be to keep the input, output, and analytic skills requirements to the minimum level necessary that also achieves acceptable accuracy and results detail for each cell of the matrix inventory. It is currently anticipated that 3-4 different levels of strategy selection procedures will be developed in Task 8, possibly including rules-of-thumb; table look-up; macroscopic; and/or microscopic methodologies. However, this will be adjusted according to the actual work associated with Task 8, the results of which will be incorporated into this subtask.

4.3.9.3 Develop Guidance and Associated Tools

In this final subtask activity, spreadsheet- based systems and procedures will be developed for guiding planning-level analysts to appropriate estimates of the capacity-enhancing potential associated with various technological, operational, and design strategies. Spreadsheets are simple to use and apply, and because of this it is believed they represent a very effective tool for this purpose.

In some cases, the result may actually be a redirection of the analyst to a more sophisticated analysis tool when conditions warrant.

The final product of this Task will be one or more spreadsheet tools, and accompany documentation, for applying the strategy-selection procedures developed in Task 8 within alternatives analysis, corridor planning, and long-range planning evaluation and decision-making environments.

Task Deliverable: The final product of this task will be one or more spreadsheet tools, and accompany documentation (Working Paper #8), for applying the strategy-selection procedures developed in Task 8 within alternatives analysis, corridor planning, and long-range planning evaluation and decision-making environments. The report will be submitted in a quarterly progress report and the Phase II report.

4.3.10 Task 10 - Develop Validation Procedure

Propose a validation method.

Task Objective: The objective of this task is to provide a methodology to validate estimates of capacity-enhancing treatments and to use the results to refine the capacity estimation techniques. The following subtasks will be undertaken to satisfy this objective:

- Subtask 10.1. Prepare a list of traffic data requirements
- Subtask 10.2. Determine appropriate statistical tests
- Subtask 10.3. Contact agencies and conduct search of historical traffic data sets
- Subtask 10.4. Develop guidelines for analyzing and interpreting validation results
- Subtask 10.5. Document the validation methodology

This task will provide the framework and guidance for carrying out the validation in Task 12. Our approach will rely on the use of archived/historical data for specific case studies. This could include data collected as part of other research projects and studies, and automated data collection systems that are managed by transportation agencies. The timeframe and budget of the project limits the ability to collect new data, and we believe the resources available for this project are better spent on research and development of prediction methodologies and guidance regarding treatment selection.

The relevance of the validation methodology extends beyond this project to future research efforts and applications by the user community. There will be a continuing need for researchers and practitioners to update and validate capacity performance of a facility as additional data are available and new strategies and technologies emerge. The validation methodology should provide the framework and basis for subsequent data collection and analysis efforts related to this research topic.

Each of the subtasks for developing a validation procedure is described in more detail in the following paragraphs.

4.3.10.1 Prepare a List of Traffic Data Requirements

Using the results of Task 4 *Methodology* and Task 7 *Quantify Improvements*, the research team will identify the traffic data that are needed for validation. Namely, the input data required for the analysis methodology and the performance measures that the methodology produces. The validation efforts will likely focus on the local level (link and node performance) given the challenges of collecting/obtaining data for system-wide measures.

For each data type, we will document the range of traffic conditions desired for validation (e.g., time periods for analysis, range of volumes, number of lanes, facility type, etc.). We anticipate that the validation will be performed for the peak hour of analysis to be consistent with the time period used in planning applications. Additionally, we envision that three facility types will be included in the validation: one freeway-only network, one arterial-only network, and one that has a combination of both freeway and arterial roadways.

The results of this subtask will be used in the search of historical and archived data sets in Subtask 10.3.

4.3.10.2 Determine Appropriate Statistical Tests

Based on the type of validation that is being performed, we will identify the statistical tests that can be applied to interpret the “goodness of fit” between model predictions and observed field data. The type of statistical test that is ultimately applied will depend on multiple factors including the type of data being collected and the intent of the comparison.

Two statistical tests that can be applied for validating the results of empirical models are the Root Mean Squared Error (RMSE) test and the Mean Absolute Percentage Error (MAPE) test. The RMSE test calculates the expected value of the square of the error (difference between observed and predicted values). The MAPE test calculates the accuracy of predicted values compared to the observed values as a percentage.

The equations for calculating the RMSE and MAPE error values follow.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \hat{x}_i\right)^2} \qquad MAPE = \left(\frac{1}{N}\sum_{i=1}^{N}\frac{\left|x_i - \hat{x}_i\right|}{x_i}\right)\cdot 100$$

where x_i = observed value of measure,

$\hat{x}_i$ = forecast value of measure, and

N = number of observations.

4.3.10.3 Conduct Search of Historical Traffic Data Sets

In this subtask, the research team will contact transportation agencies where operational strategies have been applied to determine if traffic data are available with and without the treatment in place. Previous research efforts such as NCHRP 3-79 and NGSIM will also be investigated to review data collection/validation procedures for similar efforts and to identify if traffic data are suitable for analysis and validation purposes as part of this project.

We will seek archived data sets with the following characteristics:

- Data sets contain both before and after data
- Multiple strategies can be evaluated from the data
- The network has been previously coded or can easily be converted into DYNASMART-P or a microsimulation program that will be used for operational analysis.

We will evaluate the data sets we obtain to determine if they meet the data requirements identified in Subtask 10.1. The results of this subtask will be used to determine which facilities to use in the validation testing in Task 12.

At this time the research team has access to, or is aware of, the following data sets that are candidates for the validation effort:

- London Motorway Data
- DYNASMART-P (described in Section 4.2.8)
- NGSIM trajectory data sets for Peachtree Street in Atlanta, Georgia; Lankershim Boulevard in Los Angeles, California; Interstate 80 in Emeryville, California; and U.S. 101 in Universal City, California.
- Video data records of signalized arterials in downtown Chicago, Illinois maintained by ITRE/NCSU
- Archival PEMS data from Caltrans for Southern California freeway networks

In addition, we have contacts with the following select transportation agencies that maintain archived data:

- Oregon Department of Transportation
- Washington Department of Transportation
- Minnesota Department of Transportation
- California Department of Transportation
- Texas Department of Transportation
- Maryland State Highway Administration
- North Carolina Department of Transportation

The transportation agencies will be identified early in the project to determine if they have access to archived traffic data and performance measures and if those data are available for our use. This timing is necessary to ensure that data are available for analysis at the start of Task 12 (Phase III) of the project.

Agencies will also be identified contacted if they have recently implemented a relevant capacity strategy or plan to do so within the timeframe of the project. Where this is the case, we will inquire if the agency is willing to collect and provide traffic data before and after the implementation. We will also request that they provide documentation of findings regarding traffic conditions and performance to determine if other changing factors influence operations.

4.3.10.4 Develop Guidelines for Analyzing and Interpreting Validation Results

In this subtask, the research team will explore techniques for evaluating field data and comparing results to model predictions. Graphical techniques, tables, and analyses will be identified that allow for results to be interpreted in a clear, consistent, and effective manner.

Specific performance measures will be identified for individual strategies to be tested in Task 12. Guidance will be provided regarding the application of statistical tests identified in Subtask 10.2 and how results from statistical tests should be interpreted and applied. Additionally, guidance will be developed for refining the prediction methods to incorporate the field data, particularly where differences between the observed and predicted values vary.

The results of this subtask will be applied as part of Task 12 *Validation,* and will also be useful for subsequent research/validation that is performed on capacity treatments.

4.3.10.5 Document the Validation Methodology

A technical memorandum will be prepared to document the validation methodology including the data required for analysis, the statistical tests to apply, a comprehensive list of known data sets including archived data sources, and procedures/criteria for validating the model predictions against field data. The memorandum will also recommend the facilities and data sets (case studies) recommended for validation as part of Task 12.

Additionally, gaps in the available data sets will be documented. It is likely that data for lesser-applied technologies and strategies will be difficult to obtain. In these instances, guidance and alternative validation methods will be proposed that allow users to estimate the reasonableness of results despite a lack of field data.

As an outcome of this task, the Panel and Research Team will identify the specific facilities, treatments, and data sets that will be examined as part of Task 12 *Validation.*

Task Deliverable: The deliverable of this task will be Working Paper #9, which will document the validation methodology. The working paper will be submitted in a quarterly report and the Phase II Report.

4.3.11 Task 11 – Prepare Phase II Report

Prepare a Phase II Report for review and submit any tools developed.

Task Objective: The objective of this task is to produce a synthesis of the working papers, analysis results, tools, and user guidance prepared during the course of all Phase II activities. While many of the products associated with individual Phase II tasks will stand on their own, this Phase II Report is nevertheless important because it will serve to memorialize the activities, the processes, and the findings of the C05 project. In this regard, then, the Phase II report will not be just a restatement of products already produced in Tasks 6-10. Rather, it will articulate the "how" and "why" of key decisions made and key activities undertaken along the way so that the logic and rationale is not lost to future researchers and practitioners who aim to build upon the work completed in this effort.

Task Deliverable: The deliverable of this task will be the Phase II Report, which will be submitted within 17 months after the start of the project.

TCC Responsibility: Review and provide comments on the Phase II Report. It is anticipated that comments will be received from the TCC in writing and these comments will be integrated, as appropriate, into the final content of the Phase II Report and subsequent task activities.

4.3.12 Task 12 – Apply Validation Methodology

Apply the validation methodology developed as part of Task 10 to field data sets for selected facilities and case studies.

Task Objective: The objective of this task is to assess the appropriateness of the model predictions of sustained service rate and applicable performance measures used for decision making by comparing them to real-world data.

In this task, field data will be obtained for the selected transportation facilities as determined as part of Task 10 and compared to predictions using the methodology and quantified results developed as part of Tasks 4 and 7.

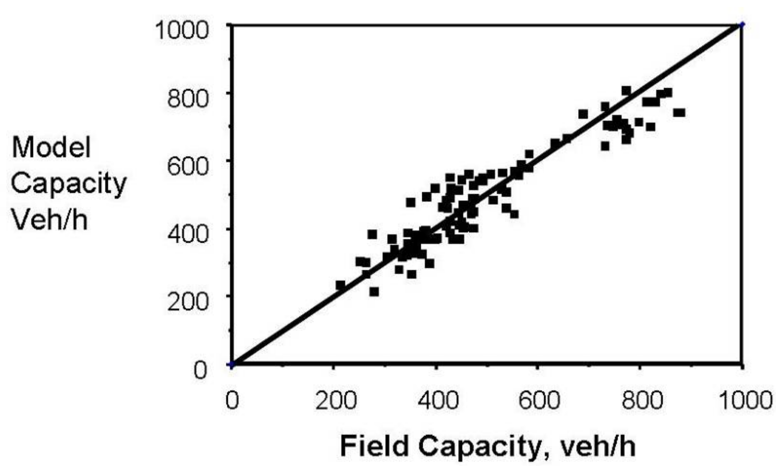
As described in Task 10, we anticipate that validation will be performed for three facility types: one freeway-only network, one arterial-only network, and one network with both freeway and arterial facilities.

The detail of the validation performed will depend on the amount of field data that are available and the treatment type/strategy being tested. At the most simplistic level, the transportation model (such as Dynasmart-P or Vissim) or empirical model that is applied to estimate the capacity effect of a strategy will be validated under baseline-only ("without treatment" or "before") conditions. Once the baseline model is calibrated to the *before* condition field data, various strategies will be tested in the model to estimate the effects on sustained service rates and other performance measures. The *before* condition validation would be the extent of the validation performed if *after* condition data are not available – either because it does not exist or is not directly comparable to the *before* field data.

At the most refined level, *before* and *after* field data will be obtained through data sets or archived systems. The data would, ideally, provide a basis for directly comparing the predicted effect of a capacity strategy or set of strategies with field data. For example, the freeway throughput for a given facility could be examined under a *before* condition without any treatments in place and for an *after* condition with multiple strategies such as ramp metering, elimination of weaving sections, etc. Using the guidance and criteria developed as part of Task 10, the comparison of *before* and *after* field data will provide evidence of the actual performance improvements resulting from a set of strategies for a given condition. The performance improvements observed from the field data - whether an increase throughput or sustained service rate, reduction in travel time, reduction in percent of break down, etc. – will then be directly compared with the model predictions to determine the degree of accuracy of the model prediction. As new field data are obtained and tested, the capacity prediction methods will be refined.

Exhibit 4-14 below shows how field data collected for two-way stop controlled intersections were compared to the capacities predicted from the HCM model.

Exhibit 4-14 Collected Field Data Compared to the HCM Model



Additionally, the validation task will examine the variability associated with capacity/sustained service rates and, where possible, provide confidence intervals for a given set of conditions.

A technical memorandum will be prepared for review by the research panel that documents the findings of this task and compares the results from the model predictions to the field data. Where appropriate, suggested modifications and enhancements to the prediction methodology will be incorporated.

Task Deliverable: The deliverable of this task will be Working Paper #10, which will document the results of the validation effort. The working paper will be submitted in a quarterly progress report and as part of the Draft Final Report.

4.3.13 Task 13 – Prepare Final Report

Prepare a Draft Final Report that incorporates the validation and updates. Following review, submit a Final Report and final tools.

Task Objective: The objective of this task is to prepare a draft final report that incorporates the validation findings from Task 12 into the Phase II report and submit to the review panel for review and comment. Upon receiving review comments, revise the report and submit a final version along with analysis tools.

- Subtask 13.1 Prepare draft final report
- Subtask 13.2 Submit draft report to the review panel
- Subtask 13.3 Participate in panel review meeting
- Subtask 13.4 Respond to comments
- Subtask 13.5 Submit final report

4.3.13.1 Prepare Draft Final Report

The research team will prepare a draft final report that combines the results from Task 12 *Validation* with the Phase II report. The draft report will address proposed changes to the methodology resulting from the validation task. The draft final report will also include software tools and analysis methodologies developed as part of this research effort.

4.3.13.2 Submit Draft Report to the Review Panel

A complete report including appendices and attachments will be provided to the panel members for review. The report will be available in electronic form (Word and PDF) and as a bounded hard copy. Panel review members will be provided a response form to follow that includes:

- Name of reviewer.
- Review date.
- Draft version and submittal date.

- Each comment line will have columns describing chapter number, page number, paragraph number, sentence or line number, and comment.

4.3.13.3 Participate in Panel Review Meeting

Upon completion of the review of the draft final report by the panel members, the research team will meet with the panel in person (with video conference available for those participants who are not able to attend in person) to go over comments, questions, and issues and to receive direction regarding the final report preparation and submittal. Review comments from the panel members will be submitted to the research team five working days prior to the panel meeting.

4.3.13.4 Prepare Response to Panel Comments

Following the panel meeting, we will prepare and distribute a written summary of meeting notes and respond to individual comments received in writing from panel members. The comments will be provided in electronic form to allow panel members to modify the notes using the “track changes” feature in Word.

4.3.13.5 Submit Final Report

A final version of the report will be prepared that incorporates comments received in writing from individual panel members and comments, questions, and issues raised during the panel review meeting. The report will be submitted to the panel members and will be available in both electronic (PDF) and hard copy form. Anticipated Research Results

The primary outcome of the research project will be a methodology for estimating sustained service rates and assessing the capacity improvement achievable from alternative and implementable operations, design, and technology strategies. Equally important, this project will also include guidance and practical tools for practitioners to use while incorporating these results into alternatives analyses, corridor planning, and long-range planning.

The documents and analysis tools that result from this project will be prepared in a user friendly format that meets the needs of the various user groups and can readily and effectively be used in typical work environments for purposes of application, interpretation, and implementation.

4.4 IMPLEMENTATION PLAN

4.4.1 Product Expected from the Research

As described above, the product of this project will be a methodology for estimating sustained service rates and assessing the capacity improvement achievable from alternative and implementable operations, design, and technology strategies. Equally important, this project will include guidance and practical tools for practitioners to use while incorporating these results into alternatives analyses, corridor planning, and long-range planning.

4.4.2 Audience or Market for the Product

As described earlier in the research plan, the audience for the practical guidance this project will produce is diverse in many respects. Groups who will benefit from a better understanding of the contributions of operations, technology, and design to meeting highway capacity needs include:

- *Traffic engineers and transportation planners*, who will use the methodology developed in this project to plan and evaluate alternative highway improvement strategies;
- *Civil engineers*, who may use the methodology to evaluate the adequacy of their highway design;
- *Researchers and teachers*, who will use the methodology in their research and for training future transportation professionals; and
- *Decision-makers*, who will use the analysis results to make public-investment decisions.

Each group will have its own particular perspective, informational requirements, and desired method of interface, all of which will need to be adequately addressed by the products of this effort if the group members are to gain the value that this project intends to and can offer.

4.4.3 Potential Impediments to Implementation

There are no major impediments to the implementation of this research effort. However, schedule adherence is important to consider as it relates to the ultimate success of the SHRP2 program, and the timely completion of this project will play an important role in the overall success of the SHRP2 capacity projects (notably, SHRP2 Project C01). For this project specifically, Exhibit 4-15 shows potential schedule-related risks, the likelihood of occurrence and the action we will take to avoid such issues.

Exhibit 4-15 Potential Research Project Risks and Actions to Avoid the Potential Issues

Potential Risk	Likelihood of Occurring	Action to Avoid
Project Schedule Slips	Moderate	The research team will pay particular attention to project schedule throughout the duration of the contract. Researchers and reviewers alike will be kept to strict deadlines for submittals. However, there are key issues in both Phase I and Phase II that will require resolution to keep the project on track.
On-going research is not completed in a timely manner or not accepted by the SHRP2 Oversight Committee	Low to Moderate	Project team members already have good communication linkages with the key team members on other related SHRP2 projects, and will stay in regular communication with them.

4.4.4 Institutions or Individuals Who Might Take Leadership

The TCC Committee, the Oversight Committee, and the SHRP2 staff are in a joint leadership position for overcoming the potential risks identified above. Strategic and prompt direction from these two groups will influence the successful completion of this project.

As has been its past practice, TRB will continue its overall responsibility for developing an implementation program that includes marketing activities, on-going updates, and development. Both FHWA and ITE have historically provided strong institutional support for the kinds of products that are anticipated from Project C05. These influential organizations will play a key role in establishing the use and accessibility of the products arising out of this project. As well, the C01 contractor is ideally situated to integrate the results of Project C05 into the collaborative decision-making process that is being developed. Finally, the results of this project are also likely to be of use to several of the SHRP2 reliability projects, including in particular L02 and L03; the contractors associated with each of these projects might also take a leadership role in integrating the results of Project C05 into the overarching SHRP2 objectives.

4.4.5 Activities Necessary for Implementation

First-order implementation of Project C05's work products will come about through its integration into the collaborative decision-making process being developed under SHRP2 Project C01. To the extent that software developers incorporate the project's analysis tools and methodology into their own products, a wide implementation will also be assured. Promulgation of the methodology and tools by review agencies such as FHWA (particularly in conjunction with the development and enhancement of its Traffic Analysis Tools procedures and guidelines), professional service organizations such as ITE, and teaching environments such as university curricula in transportation planning, will all accelerate the implementation of Project C05's work products.

4.4.6 Criteria for Judging Progress and Consequences of Implementation

Success of Project C05 will best be judged by obtaining feedback from the user community. It is recommended that the TCC, the Oversight Committee, and SHRP2 staff play a lead role in soliciting and summarizing user feedback. Conference sessions and/or focus group meetings conducted in conjunction with TRB's Annual Meeting could be a very useful way to both publicize the project products and obtain real-world feedback. SHRP2 staff members conduct regular field visits to participating agencies, and feedback and observations from these visits would also be an excellent way to judge real-world progress and consequences. Finally, ongoing communication and feedback from key institutions such as FHWA and ITE will be very valuable as well.

4.4.7 Applicability of Results to Highway Practice

By definition, this is a very practice-oriented project in that all of the tasks focus on developing tools, methodologies, and strategies to meet the needs of practitioners and decision makers. Getting more value out of the existing transportation infrastructure is one of the most important advances that this profession can take in positively affecting our communities' overall quality of life. By expanding and improving the available tools to include the latest research results as well as computational software and more examples, this project will exert a significant influence on alternatives analysis and decision-making by planners, designers, engineers, and administrators.

4.4.8 References

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Time Requirements

The research team believes that understanding of and commitment to the schedule is critical to the success of this project. Exhibit 9-1 provides an overall schedule flow diagram for the project. This Exhibit also identifies the points in time where project deliverables and reports are planned.

Table 10-1 Cost Breakdown by Task and Consulting Team
SHRP2 C05
Understanding the Contribution of Operations, Technology and Design to Meeting Highway Capacity Needs

KITTELSON & ASSOCIATES, INC.
TRANSPORTATION PLANNING/TRAFFIC ENGINEERING

Research Team	Staff	Role	Hourly Rate	% Time Over Contract (Ind/Total Time)	Hours By Task 0	1	2	3	4	5	6	7	8	9	10	11	12	13	Total Hours	Cost
Kittelson & Associates, Inc.	Wayne Kittelson	Principal Investigator	$ 70.00	14%	8	14	10	16	32	24	62	140	62	40	40	50	40	40	578	$40,460
	Brandon Nevers	Senior Researcher	$ 45.00	29%	20	20	20	30	30	30	130	150	100	120	100	130	200	150	1230	$55,350
	William Reilly	Senior Researcher	$ 60.00	6%					100	10		100	30			10		10	260	$15,600
	KAI Engineer	Researcher	$ 30.00	18%			10	20	20	20	60	100	100	100	30	30	200	60	750	$22,500
	Support	Graphics/Admin Support	$ 25.00	16%		8	8	8	8	30	20	80	80	100	40	100	100	100	682	$17,050
	Support	Technical Editing	$ 18.00	3%		4	4			4	4	20	20	20	5	10	20	10	121	$2,178
Kittelson & Associates, Inc. - Totals	WAGES				$1,460	$2,152	$2,172	$3,270	$10,390	$5,052	$12,562	$27,010	$16,000	$14,060	$9,200	$13,530	$20,060	$14,630		$153,138
	OVERHEAD (198.87%) *				$2,904	$4,280	$4,310	$6,503	$20,663	$10,047	$24,982	$55,605	$31,819	$27,961	$18,475	$26,907	$41,087	$29,095		$304,546
	PROFIT (7%)				$305	$450	$454	$684	$2,174	$1,057	$2,628	$5,639	$3,347	$2,941	$1,944	$2,831	$4,322	$3,061		$32,038
	Subtotal Labor Only				$4,669	$6,882	$6,946	$10,457	$33,226	$16,156	$40,172	$89,254	$51,167	$44,963	$29,709	$43,268	$66,069	$46,785		$489,721
ITRE	Nagui Rouphail	Principal Researcher	$195.00	14%	0	10	10	30	20	20	20	160	40	40	20	10	160	30	570	$111,150
	Research Engineer	Researcher	$51.00	93%	0	40	40	150	60	90	300	1200	500	350	150	130	600	260	3890	$198,390
	ITRE Subtotal				$0	$3,990	$3,990	$13,500	$7,980	$8,490	$19,200	$92,400	$33,300	$25,650	$11,550	$8,580	$61,800	$19,110	4460	$309,540
University of Utah	Xuesong Zhou	Principal Researcher	$102.00	9%				10	50	10	60	100	20	20	20	10	40	20	360	$36,720
	Graduate Student	Researcher	$31.00	43%				60	160		400	700	100		60		250		1700	$55,490
	Subtotal				$0	$0	$0	$3,500	$10,680	$1,020	$18,520	$31,900	$5,140	$2,040	$4,520	$1,020	$11,830	$2,040	2150	$92,210
Karlsruhe University	Werner Brilon	Principal Researcher	$180.00	4%		8	4	20	16	4	16	32	20	8	4	4	4	8	148	$26,640
	Research Engineer	Researcher	$80.00	5%		16	8	30	20	8	20	24	20	10	8	8	8	16	196	$15,680
	Subtotal				$0	$2,720	$1,360	$6,000	$4,480	$1,360	$4,480	$7,680	$5,200	$2,240	$1,360	$1,360	$1,360	$2,720	344	$42,320
Write Rhetoric	Danica Rhodes	Technical Editing	$40.00	10%		8	8			8	8	80	80	80	20	40	60	40	432	$17,280
	Subtotal				$0	$1,440	$1,440	$0	$0	$1,440	$1,440	$14,400	$14,400	$14,400	$3,600	$7,200	$10,800	$7,200	432	$17,280
Summary	KAI (hours)				28	46	52	74	190	118	276	590	392	380	215	330	560	370	3621	$489,721
	Consultants (hours and total labor)				0	82	70	320	366	140	824	2296	780	508	302	202	1122	374	7380	$461,350
	Total (dollars, not including expenses and travel)				$4,669	$15,032	$13,736	$33,457	$56,366	$28,466	$83,812	$235,634	$109,207	$89,293	$50,739	$61,428	$151,859	$77,855		$951,071

* The agreed-upon indirect cost rate of 198.87% will be fixed for the period of the contract as requested

	0	1	2	3	4	5	6	7	8	9	10	11	12	13		Total
Subcons. Exp	$0	$524	$428	$1,622	$1,212	$824	$2,314	$8,910	$3,246	$2,333	$1,154	$831	$5,485	$1,824		$30,707
KAI Expense	$168	$247	$250	$376	$1,194	$581	$1,444	$3,208	$1,839	$1,616	$1,068	$1,555	$2,374	$2,303		$18,222
																$1,000,000

KAI Direct Expenses		Units	Cost
Airline Tickets	$ 8,000.00	16	$ 500.00
Lodging	$ 6,400.00	32	$ 200.00
Per Diem	$ 3,200.00	32	$ 100.00
Total	$ 17,600.00		

Itemized Budget

10.1 SUMMARY

The Kittelson & Associates, Inc. project budget is summarized below in Exhibit 10-1. The total estimated costs are in accordance with the funds available as noted in the SHRP2 Project Statement.

Exhibit 10-1 Budget Summary by Category

Item		Cost
a.	KAI Salaries and Wages	$158,736
b.	Borrowed Personnel	$0
c.	Consultant Fees	$0
d.	Subcontracts	$474,777
e.	Capital Equipment	$0
f.	Materials and Services	$0
g.	Communications and Shipping	$0
h.	Travel	$17,600
i.	KAI Employee Benefit Plan Costs and Payroll Taxes	$0
j.	KAI Overhead	$315,678
k.	KAI Fixed Fee (7%)	$33,209
TOTAL COST PLUS FIXED FEE		**$1,000,000**

10.2. DETAILED ITEMS

10.2.1 KAI Salaries and Wages

Estimates of salaries and wages are tabulated in Exhibit 10-3 and are based on time to be devoted to the project by Kittelson & Associates, Inc. staff over the 48-month study period. These estimates are distributed by task. Estimates are provided in person-hours by key individual and support staff.

10.2.2 Borrowed Personnel

No borrowed personnel are anticipated for this project.

10.2.3 Consultant Fees

No outside consultant services are anticipated for this project.

10.2.4 Subcontracts

The Institute for Transportation Research and Education (ITRE), University of Utah, and Ruhr-University Bochum (RUB) will serve as subcontractors. The total estimated subcontract budget is based on time to be devoted to the project by these subcontractors over the 24-month study period.

10.2.5 Capital Equipment

No capital equipment expenditure is anticipated.

10.2.6 Materials and Services

Total costs for materials and services include minor printing charges. All draft documents will be submitted in electronic format.

10.2.7 Communications and Shipping

KAI's invoicing procedures normally bill communications and shipping charges as a per-hour communication fee. As this fee is not allowed by TRB, no communications or shipping charges are anticipated.

10.2.8 Travel

Anticipated project travel consists of four two-day team workshops over the 24-month duration of the project. As well, the Research Team expects to convene during TRB Annual Meetings. Since the key project team members normally attend the TRB Annual Meeting, no travel charges are anticipated for such attendance.

- *Air Travel (16 trips @ $500/trip)*
- *Lodging (32 nights @ $200/night)*
- *Per Diem (32 days @ $100/day)*

10.2.9 KAI Employee Benefit Plan Costs and Payroll Taxes

Employee benefits and taxes for Kittelson and Associates, Inc. employees are calculated as part of general overhead and are included in KAI's combined current overhead rates.

10.2.10 KAI Overhead

The overhead rate has been calculated according to the audited overheads of KAI.

10.2.11 KAI Fixed Fee

A fixed fee of 7% will be used with KAI labor costs. This level of fee is commensurate with the responsibilities anticipated and the degree of risk associated with serving as the prime contractor for this important research.

10.3 PRELIMINARY BUDGET ALLOCATION BY TASK

Exhibit 10-2 summarizes the preliminary allocation of budget by task.

Exhibit 10-2
Budget Summary by Task

Item	Cost
0. Amplified Research Plan	$6,947
1. State-of-the-Art Review and Inventory	$18,415
2. HCM Focus Group Meetings	$39,822
3. Explore Alternative Delivery Methods	$37,243
4. Recommendations on Purpose and Target Users	$57,367
5. Interim Report	$30,185
6. Supplemental Research	$281,068
7. Sample Problems and Computational Engines	$171,537
8. Prepare and Submit Draft HCM Chapters	$223,281
9. Prepare and Submit Final HCM	$90,508
10. Assist TRB During Publication	$43,627
TOTAL	**$1,000,000**

10.4 DETAILED LABOR ESTIMATE

Exhibit 10-3 presents labor hours by key staff individual and support staff category.

EXHIBIT 10-3
Detailed Labor Estimate by Task and Staff

Name	Role	% Time Over Contract (Ind/Total Time)	Hours By Task 0	1	2	3	4	5	6	7	8	9	10	11	12	13	Total Hours	Cost
Wayne Kittelson	Principal Investigator	14%	8	14	10	16	32	24	62	140	62	40	40	50	40	40	578	$40,460
Brandon Nevers	Senior Researcher	29%	20	20	20	30	30	30	130	150	100	120	100	130	200	150	1230	$55,350
William Reilly	Senior Researcher	6%					100	10		100	30			10		10	260	$15,600
KAI Engineer	Researcher	18%			10	20	20	20	60	100	100	100	30	30	200	60	750	$22,500
Support	Graphics/Admin Support	16%		8	8	8	8	30	20	80	80	100	40	100	100	100	682	$17,050
Support	Technical Editing	3%		4	4			4	4	20	20	20	5	10	20	10	121	$2,178
WAGES			$1,460	$2,152	$2,172	$3,270	$10,390	$5,052	$12,562	$27,910	$16,000	$14,060	$9,290	$13,530	$20,660	$14,630		$153,138
OVERHEAD (198.87%) *			$2,904	$4,280	$4,319	$6,503	$20,663	$10,047	$24,982	$55,505	$31,819	$27,961	$18,475	$26,907	$41,087	$29,095		$304,546
PROFIT (7%)			$305	$450	$454	$684	$2,174	$1,057	$2,628	$5,839	$3,347	$2,941	$1,944	$2,831	$4,322	$3,061		$32,038
Subtotal Labor Only			**$4,669**	**$6,882**	**$6,946**	**$10,457**	**$33,226**	**$16,156**	**$40,172**	**$89,254**	**$51,167**	**$44,963**	**$29,709**	**$43,268**	**$66,069**	**$46,785**		**$489,721**
Nagui Rouphail	Principal Researcher	14%	0	10	10	30	20	20	20	160	40	40	20	10	160	30	570	$111,150
Research Engineer	Researcher	93%	0	40	40	150	80	90	300	1200	500	350	150	130	600	260	3890	$198,390
ITRE Subtotal			**$0**	**$3,990**	**$3,990**	**$13,500**	**$7,980**	**$8,490**	**$19,200**	**$92,400**	**$33,300**	**$25,650**	**$11,550**	**$8,580**	**$61,800**	**$19,110**	**4460**	**$309,540**
Xuesong Zhou	Principal Researcher	9%				10	50	10	60	100	20	20	20	10	40	20	360	$36,720
Graduate Student	Researcher	43%				80	180		400	700	100		80		250		1790	$55,490
Subtotal			**$0**	**$0**	**$0**	**$3,500**	**$10,680**	**$1,020**	**$18,520**	**$31,900**	**$5,140**	**$2,040**	**$4,520**	**$1,020**	**$11,830**	**$2,040**	**2150**	**$92,210**
Werner Brilon	Principal Researcher	4%		8	4	20	16	4	16	32	20	8	4	4	4	8	148	$26,640
Research Engineer	Researcher	5%		16	8	30	20	8	20	24	20	10	8	8	8	16	196	$15,680
Subtotal			**$0**	**$2,720**	**$1,360**	**$6,000**	**$4,480**	**$1,360**	**$4,480**	**$7,680**	**$5,200**	**$2,240**	**$1,360**	**$1,360**	**$1,360**	**$2,720**	**344**	**$42,320**
Danica Rhodes	Technical Editing	10%		8	8			8	8	80	80	80	20	40	60	40	432	$17,280
Subtotal			**$0**	**$1,440**	**$1,440**	**$0**	**$0**	**$1,440**	**$1,440**	**$14,400**	**$14,400**	**$14,400**	**$3,600**	**$7,200**	**$10,800**	**$7,200**	**432**	**$17,280**
KAI (hours)			28	46	52	74	190	118	276	590	392	380	215	330	560	370	3621	$489,721
Consultants (hours and total labor)			0	82	70	320	366	140	824	2296	780	508	302	202	1122	374	7386	$461,350
Total (dollars, not including expenses and travel)			**$4,669**	**$15,032**	**$13,736**	**$33,457**	**$56,366**	**$28,466**	**$83,812**	**$235,634**	**$109,207**	**$89,293**	**$50,739**	**$61,428**	**$151,859**	**$77,855**		**$951,071**