NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 399

Multimodal Corridor and Capacity Analysis Manual

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This report presents the results of research carried out under NCHRP Project 8-31, *Long-Term Availability of Multimodal Corridor Capacity*. The report is presented as a manual on multimodal corridor and capacity analysis. Because transportation-system and corridor capacity for freight and passengers is critical for meeting current and future transportation demand, this manual will provide much needed assistance to a wide range of practitioners, particularly those engaged in performance analysis, capacity management, needs studies, systems planning, and corridor development planning—including major investment studies. It provides information regarding capacity analysis approaches for highways, rail, pipelines, and waterways and presents available options for enhancing corridor capacity and performance through various strategies such as new capacity development, freeing up unused capacity, or control of travel demand. Evaluation methods for these options are included. State and MPO planning practitioners, as well as others dealing with corridor and systemwide multimodal transportation development, will find this manual to be a valuable resource.

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Report 399

Multimodal Corridor and Capacity Analysis Manual

CAMBRIDGE SYSTEMATICS, INC.
Washington, DC

with

Transmode Consultants
Asil Gezen
ICF Kaiser Engineers, Inc.

Subject Areas

Planning and Administration
Highway Operations, Capacity
and Traffic Control
Aviation
Rail
Freight Transportation
Marine Transportation

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

Note: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

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FOREWORD

By Staff
Transportation Research Board

This report presents the results of research carried out under NCHRP Project 8-31, *Long-Term Availability of Multimodal Corridor Capacity.* The report is presented as a manual on multimodal corridor and capacity analysis. Because transportation-system and corridor capacity for freight and passengers is critical for meeting current and future transportation demand, this manual will provide much needed assistance to a wide range of practitioners, particularly those engaged in performance analysis, capacity management, needs studies, systems planning, and corridor development planning—including major investment studies. It provides information regarding capacity analysis approaches for highways, rail, pipelines, and waterways and presents available options for enhancing corridor capacity and performance through various strategies such as new capacity development, freeing up unused capacity, or control of travel demand. Evaluation methods for these options are included. State and MPO planning practitioners, as well as others dealing with corridor and systemwide multimodal transportation development, will find this manual to be a valuable resource.

Federal transportation policy, as embodied in the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), has significantly changed transportation planning requirements and expectations at the national, state, metropolitan, and local governmental levels. One major element of ISTEA having profound implications for decision makers is the requirement to integrate planning and resource commitments, for both passenger and freight transportation, in the development and coordination of the most appropriate modes tailored to serve the particular local conditions. Economic, social, and life-style changes are resulting in continued explosive growth in passenger and freight transportation demand. At the same time, federal and state environmental policies and regulations mandate that transportation systems development contribute more to achieving air quality and water quality standards through strategies designed to limit travel demand. These requirements make new capacity improvements difficult to select, especially in areas where air quality or other environmental problems exist.

There is broad recognition of the need for comprehensive multimodal approaches to passenger and freight capacity issues. These approaches should assist planners and decision makers in making the most efficient use of existing capacity, in managing demand in order to protect existing and future capacity, and in choosing the most effective blend of new capacity strategies that can meet travel demand, while protecting the environment. In order to achieve these objectives, it is necessary to evaluate completed and ongoing studies and the data that are available on multimodal corridor capacity; an analytical methodology must be established. The scope and severity of current and future capacity problems and the constraints on expansion in multimodal corridors need to be evaluated and recommended strategies for preserving long-term capacity need to be identified.

Under NCHRP Project 8-31, *Long-Term Availability of Multimodal Corridor Capacity,* Cambridge Systematics, Inc., carried out the research and preparation of the manual in

cooperation with Transmode Consultants, a Division of Science Applications International Corporation, and ICF Kaiser Engineers, Inc. The project was initiated under a contract with the Urban Institute in Washington, D.C. Midway through the project, the Principal Investigator moved to Cambridge Systematics, Inc. In order to maintain continuity and schedule progress, and to take full advantage of the expertise built up in the early phase of the project, the Urban Institute agreed to withdraw as the prime contractor and a new contract was executed with Cambridge Systematics, Inc.

The resulting manual provides a framework and procedures for analyzing and evaluating the nature, extent, and severity of capacity problems in transportation corridors. A typology, designed to characterize the conditions, problems, options, and constraints found in multimodal corridors, is presented and applied in four case studies. The manual also contains a review and analysis of capacity determination procedures for various modes, as well as level of service and performance measures. Options to increase or enhance the capacity and level of service of different types of corridors and their components are discussed in detail. The manual concludes by providing procedures for evaluating supply-side and demand-side management options for maintaining capacity.

CONTENTS

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This research was performed under NCHRP Project 8-31, *Long-Term Availability of Multimodal Corridor Capacity*, by Cambridge Systematics, Inc., the prime contractor for the study. The original contractor for the project was the Urban Institute in Washington, DC. Transmode Consultants, a Division of Science Applications International Corporation, and ICF Kaiser Engineers, Inc. were subcontractors.

William A. Hyman, Principal with Cambridge Systematics, Inc., and former Director of Transportation Studies at the Urban Institute, was the Principal Investigator. Paul O. Roberts, President of Transmode Consultants, was the Co-Principal Investigator. Roemer M. Alfelor, Associate with Cambridge Systematics, Inc. and former Research Associate with the Urban Institute, was the Principal Researcher. Technical contributors include Asil Gezen, Anne Yablonski of Transmode Consultants, Marc Sorenson and Gregory Rossel of ICF Kaiser Engineers and Behnam Pourbabai of Management Science Consultants of America.

Deep appreciation is expressed to Professor Lester Hoel of the University of Virginia, Dane Ismart of Federal Highway Administration, and Professor Louis Pignataro of the New Jersey Institute of Technology, who reviewed an early draft of this manual.

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Finally, we would like to thank the NCHRP panel members for guiding us in this very challenging research work.

CHAPTER 1

SUMMARY

Lack of sufficient capacity to meet current and future travel demands is seen as a major obstacle to both passenger and freight movements in many transportation corridors throughout the United States. Indeed, there are serious concerns about preserving adequate corridor capacity to meet future increases in travel demand. Many major highways are congested and operate at or below acceptable service levels during most hours of the day. Traditional approaches to corridor preservation, including those for urban and intercity transportation corridors, have proven to be inadequate. Land acquisition has encountered severe stumbling blocks due to the high costs of land in urban areas, environmental regulations, physical barriers, and political and community opposition.

The objective of NCHRP Project 8-31, *Long-Term Availability of Multimodal Corridor Capacity*, is to characterize the nature, type, and extent of existing and potential capacity problems in many important corridors in the country. There is a need to measure the maximum possible throughput in these corridors in terms of person and freight movements, not just vehicle movements. While some corridors may have reached their capacities in terms of maximum vehicle throughput, there could still be excess capacities in terms of potential person and goods movement. For example, statistics on average highway vehicle occupancy rates indicate that there is an extraordinary amount of excess capacity even on the most crowded highways. Compared with vehicle capacity measured in passenger-car equivalents, heavily traveled highways currently have nearly four times their current capacity when measured as potential passenger throughput. Options to increase current physical capacities, utilize excess or unused capacities, or reduce travel demands need to be identified and evaluated.

This *Multimodal Corridor and Capacity Analysis Manual* provides a comprehensive framework for dealing with capacity analysis, performance determination, needs and options identification, and alternatives evaluation for various elements comprising transportation corridors. It includes a typology of corridors that can help transportation analysts develop a specific approach for analysis. Four multimodal transportation corridors are used as examples to illustrate the procedures for establishing the scope of corridor analysis and to characterize the fundamental problem. Capacity analysis and determination methods for various transportation modes including highways, rail, air, pipeline, and waterways are discussed and supplemented with examples. A multimodal approach to capacity analysis is presented using the existing methods for individual modes, and specific measures of performance and level of service that are applicable to transportation corridors are identified. The *Multimodal Corridor and Capacity Analysis Manual* also provides a rather extensive summary and description of options that are available to enhance corridor capacity and performance either by providing additional capacity, freeing up unused capacity, or reducing travel demands. Methods to evaluate these options, including illustrative examples, help complete the manual.

Transportation planners and analysts are encouraged to use the rich and valuable information contained in this manual in dealing with multimodal transportation corridors.

CHAPTER 2

INTRODUCTION AND RESEARCH APPROACH

2.1 RESEARCH PROBLEM STATEMENT

As the demands to move people and goods from place to place continue to increase, it is predicted that highway traffic volumes will double by the year 2020. There are grave concerns that this will lead to future congestion and traffic delays caused by inadequate highway capacity, which will substantially influence freight transportation. High-quality freight service is increasingly important to the nation's shippers, and the inability to maintain fast, reliable service can inhibit economic development and the international competitiveness of the nation.

In the past, growth in highway traffic has been managed by constructing new roadways or by expanding existing ones. Transportation agencies are now more frequently facing situations, particularly in urban areas, where it is impractical or impossible to increase highway capacity because of physical barriers, environmental impacts and regulations, community opposition (i.e., the "not in my backyard" phenomenon), or extraordinary cost. For example, apart from certain intrinsic legal difficulties of traditional corridor preservation, including the unconstitutionality of reserving private property for future transportation use without adequate compensation, this approach of preservation of land for roads has proven to be inadequate.

Yet, there is a considerable amount of excess capacity even on the most crowded highways. The average automobile occupancy rate was only 1.1 person per car in 1990, down from 1.2 in 1980 and 1.3 in the 1970s. Compared with vehicle capacity measured in passenger-car equivalents, heavily traveled highways currently have nearly four times their current capacity when measured as potential passenger throughput. Indeed there are some maverick transportation professionals who argue there is no congestion at all. Instead, travel time, which motorists and truckers experience as delay, is being used to ration the scarce availability of highway facilities in lieu of rational prices for travel and transport.

Because of the inability to increase highway capacity to match growth in demand, it has become increasingly important to view capacity problems in a multimodal transportation corridor context. Options for increasing capacity must not be limited to major highways in the corridor but must also include parallel roads and rail, transit, water, and other modes where available.

The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) promotes innovative approaches necessary to improve effective capacity. This watershed legislation encourages multimodal and intermodal solutions to transportation problems including those pertaining to corridor congestion. ISTEA fosters research, development, and demonstrations concerning advanced technologies such as magnetic levitation trains (Maglev) and intelligent transportation systems (ITS), plus other transportation systems management (TSM) and transportation demand management (TDM) strategies like congestion pricing.

Other key provisions of ISTEA include greater flexibility in the use of funds for modes other than highways, a congestion management and air quality program that requires application of transportation control measures (TCM) to reduce vehicle miles traveled (VMT), and new requirements for statewide and metropolitan planning that promote nontraditional approaches to providing transportation including bicycling. ISTEA originally required the implementation of a variety of infrastructure management systems including ones for managing congestion and intermodal transfer facilities, but these management systems have become nonmandatory. This NCHRP Project on *Long-Term Availability of Multimodal Corridor Capacity* is very much in tune with the policy objectives of the ISTEA.

2.2 OBJECTIVES

The objectives of this research are to evaluate the scope and severity of current and future capacity problems and constraints on transportation corridors and to recommend strategies to ensure the long-term availability of multimodal corridor capacity. Part of the project is to develop a manual for performing multimodal corridor and capacity analysis.

This *Multimodal Corridor and Capacity Analysis Manual* addresses the problems identified in the research problem statement above by providing a comprehensive approach to corridor capacity analysis for passenger and freight movements, different modes of transportation, and line-haul and transfer/intermodal facilities. It aims to provide analytical methods that can be used for statewide and metropolitan multimodal planning, major investment studies, and other types of project impact estimation. It places capacity analysis in the

context of both the supply and demand for transportation and emphasizes the movement of people and goods, not merely vehicles. The methods provided here are, in most cases, simple and require the least amount of data possible, in recognition of the fact that most transportation and planning agencies have highly limited funds and staff to support planning and data collection. The quantitative methods described here can be carried out on a calculator or by writing a simple computer spreadsheet program.

This manual is also intended to complement the widely used *Highway Capacity Manual* (HCM) and other capacity analysis methods developed for individual modes. However, unlike the HCM, which has undergone four revisions since its first edition came out in 1950, this is only the first edition of the *Multimodal Corridor and Capacity Analysis Manual*. It naturally contains the shortcomings of most initial undertakings of a similar scope and complexity. In trying to be comprehensive, many details remain unaddressed. Capacity concepts have been set out and applied in many cases to specific examples, but results frequently are only first-order approximations and depend upon assumptions that are reasonable in most but not all instances. In many cases, the research that is needed to refine the analytical methods has yet to occur. More precise results will later be obtained that are validated in empirical studies. Notwithstanding these limitations, this manual should prove to be a valuable aid to transportation professionals seeking to address transportation capacity problems in a multimodal/intermodal context.

2.3 RESEARCH APPROACH

In order to meet the objectives of the research including the development of the manual, a two-phase project approach was undertaken. The purposes and the tasks associated with each phase are described below.

Phase I

This phase consisted of two parts. The first part involved establishing the framework for analysis and developing the procedures necessary to perform multimodal corridor and capacity analysis. The other part entailed an evaluation of completed and ongoing studies and data on current and future multimodal corridor capacity. These were accomplished under the following tasks.

Task 1

Literature review including identification and development of definitions of terms appropriate for key issues in the study. Under this task existing procedures for evaluating capacity of various modes including highways, rail, airports, waterways, and other types of corridor facilities were reviewed and investigated. The manual contains discussions as well as examples pertaining to these methods. The manual also lists and defines many terminologies relevant to multimodal corridor and capacity analysis and differentiates between physical capacity determination and economic capacity determination.

Task 2

Identification, evaluation and summary of completed and ongoing studies of corridor problems, capacity preservation and expansion strategies, methods of corridor administration, and shipper, carrier, and traveler responses to congestion. The research included numerous major U.S. corridors, encompassing those that characterize the problem from national, regional, state, and local perspectives. Corridors included represent a variety of characteristics including urban and rural locations, freight and passenger emphasis, short-distance and long-haul traffic, and intercity and intracity linkages. The corridors selected also addressed alternative responses to congestion such as construction, intelligent vehicle highway systems (IVHS) applications, high-occupancy vehicle (HOV) strategies, transit improvements, and corridor management involving administrative or regulatory actions.

Task 3

With the results of Tasks 1 and 2, analysis methods were identified, evaluated, and modified for incorporation in this manual and used as the analytical framework for multimodal corridor and capacity analysis. Also, based on the findings of Task 1 and Task 2, a typology of transportation corridors was developed that described among others the nature, extent, and severity of traffic problems; the facility expansion constraints; and the feasible multimodal transportation alternatives. The transportation alternatives identified include options to enhance the capacity of the corridor, which have been classified as affecting either the transportation supply or demand. The manual contains two chapters for identifying and evaluating a variety of supply-side and demand-side options to improve corridor capacity and performance.

The typology is intended to help characterize a transportation corridor for which a capacity analysis is required and to frame the type of analysis that should be included in preliminary scoping studies that set the stage for more detailed capacity analysis.

Phase II

With the results of Phase I, scoping studies for four existing multimodal corridors, which are typical of many corridors found in the United States, were performed. These corridors are

1. New York metropolitan area river crossing in New York City,
2. Altamont corridor in Oakland, California,
3. North-south corridor in Seattle, Washington, and
4. East-west corridor in Madison, Wisconsin.

Each preliminary analysis applied the general approaches set out in the manual including characterization of the scope and severity of current and future capacity problems and the constraints on expansion in each of these multimodal corridors. The preliminary analyses also identified strategies for enhancing or preserving long-term capacity.

Although very limited in scope and in level of detail, the case studies can provide guidance and directions for more detailed and comprehensive multimodal corridor and capacity analyses utilizing the concepts and procedures developed in the manual.

2.4 ORGANIZATION OF THIS MANUAL

The chapters comprising the rest of this manual and their general objectives are as follows:

Chapter 3 - Basic Concepts of Multimodal Capacity Analysis

The objective of Chapter 3 is to define the concepts and terms used in corridor capacity analysis. It also provides a brief overview of capacity analysis and determination as it applies to various modes.

Chapter 4 - Corridor Identification and Problem Definition

The objective of Chapter 4 is to enable the analyst to characterize a transportation corridor in terms of physical features, transportation components, sources of congestion, travel patterns, composition of traffic, and general category of corridor problem. Four case study corridors are used as examples to illustrate the concepts.

Chapter 5 - Capacity Determination and Analysis

The objective of Chapter 5 is to explain the analytical procedures for estimating vehicular and carrier capacity as well as multimodal person and goods capacity.

Chapter 6 - Level of Service and Performance Measures

The objective of Chapter 6 is to identify various measures of link/node/corridor performance and explain how they are related to capacity (supply) and traffic volume (demand). Performance measures utilized include frequency of service, speed travel time, comfort, reliability, loss and damage, and costs.

Chapter 7 - Capacity Enhancement Options

Chapter 7 identifies alternative supply-side and demand-side actions for increasing the effective capacity (or improving the performance) of a corridor and its components. Strategies reviewed include providing additional capacity, tapping unused or underutilized capacity, coordinating the movement of traffic, and influencing the demand for transportation services. A brief description of procedures for evaluating supply-side actions is also included.

Chapter 8 - Evaluating Demand Management Options

The objective of Chapter 8 is to provide tools for assessing the costs and effectiveness of demand-side capacity enhancement actions including analytical methods for extrapolating baseline travel demands into future travel demands and incremental analysis. These procedures help qualify and quantify the impacts of demand management strategies on the performance of individual components of a corridor. The occurrence of induced demand is also discussed. A summary of logit coefficients and elasticities for transportation demand modeling is included in the appendix to this chapter (Appendix 8A).

Chapter 9 - Evaluating Economic Capacity

Most capacity analyses are approached from the physical standpoint. The objective of Chapter 9 is to describe an alternative approach that looks at the economic capacity of corridors and specific transportation facilities.

Chapter 10 - Conclusions and Recommendations

This chapter summarizes the results of the research, identifies the problems encountered, highlights valuable insights, enumerates lessons learned, and presents recommendations for refining the *Multimodal Corridor and Capacity Analysis Manual.*

In addition to the main chapters there are two appendix sections. **Appendix A** discusses the feasibility of an overarching approach to capacity determination and analysis that was explored earlier in the project. **Appendix B** summarizes some of the corridor case studies found in the literature.

CHAPTER 3

BASIC CONCEPTS OF MULTIMODAL CAPACITY ANALYSIS

This chapter explains the basic concepts and principles involved in multimodal corridor and capacity analysis. It begins with a historical background on transportation capacity analysis. The current thinking and procedures for capacity determination for various modes are briefly described. Finally, important concepts and terminology relevant to multimodal capacity analysis are identified and defined.

3.1 BACKGROUND

In the period after the Second World War the demand for highway transportation grew rapidly, almost in lock step with the population and the economy. Rising incomes and forces underlying decentralization accelerated suburbanization of metropolitan areas. An automobile made it a viable option for a family to purchase a home in the suburbs, to commute to work in the central city, and to shop at the new shopping malls and convenience stores that seemed to have sprung up everywhere. Also, as economic activity increased and the highway system expanded, trucks carrying goods plied the roads in increasing numbers. Other forms of transportation, such as air travel, also expanded in response to economic and population growth but the facilities or traffic of some modes, such as commuter rail and rail freight transportation, actually contracted in the face of automobile and truck competition. As the magnitude of highway congestion problems became worse, the response of many transportation professionals was to focus more and more intently on highway capacity problems, partly with improved methods of analysis. Ultimately, to a large extent, they responded with highway improvement projects.

Highway capacity became a highly researchable topic. Capacity became the subject of a large number of studies of component parts of the highway system. The topic was reported on annually at the Highway Research Board, which later became the Transportation Research Board. There were studies of city streets, freeways, signalized and unsignalized intersections, weaving sections, on and off ramps, the impact of parking, trucks in traffic streams, climbing lanes, lane width, signs and signals, design speed, gradients, and many other topics. The Bureau of Public Roads published the first HCM in 1950. The Highway Research Board, under the guidance of the Highway Capacity Committee, published the second edition in 1965. Two decades later, in 1985, the Transportation Research Board published the third edition, which was developed under the Committee on Highway Capacity and Quality of Service. A fourth edition was recently published in 1994 *(1)*.

Capacity methods for other modes were refined and improved during the period after the Second World War, but these methods remained largely unknown to the average transportation planner and design engineer in state and local transportation departments and metropolitan planning agencies. Thus, capacity analysis procedures for ports, railroads, airports, bus terminals, and so on remained the province of experts in these areas, usually consulting engineers, or specialists in the modal administrations and other agencies of the federal government such as the Federal Aviation Administration, the Federal Railroad Administration, the Federal Maritime Administration, and the Army Corps of Engineers.

In the late 1960s and 1970s there was much interest in multimodal planning as a result of mounting environmental concerns and legislation and potentially severe energy shortages. States such as New York, California, Wisconsin, and Kentucky made considerable advances in multimodal planning that encompassed the consideration of not only all modes but also low-cost capacity improvements and transportation demand management. Much supporting federal research also occurred during this time. However, during the 1980s multimodal planning languished, and highway transportation and congestion problems once again received the most attention. Transportation capacity analysis procedures continued to revolve around the HCM.

Even as the methods in the HCM became widely accepted and applied in the period after the Second World War, concerns were frequently expressed that transportation analysis was too centered on highway analysis and not enough attention was being given to other forms of transportation. Updates to the HCM remedied this situation in part by adding chapters and sections dealing with transit capacity, pedestrians, and bicycle facilities. Notwithstanding these improvements there remains a need to provide transportation engineers and planners with a synthesis of capacity analysis methods that:

1. Accounts for the role of other modes of transportation, especially intermodal connections, in meeting transportation needs;

2. Considers vehicle occupancy rates and freight load factors;
3. Focuses on the movement not only of vehicles but also of people and freight;
4. Considers factors affecting demand, including demand management strategies and changes in the relative costs to users of different types of transportation; and
5. Addresses the economic dimension of capacity because, in reality, costs and available funding often determine capacity enhancements. A not uncommon definition of capacity applied to nonhighway modes is the level of improvement resulting in a level of throughput at which the extra costs just equal the extra benefits or profit *(2)*.

The first HCM was published in the 1950s at a time when consensus was building for the need to construct the Interstate System. This first capacity manual codified much research, empirical study, and practice that had accumulated to date. It was a crucial document used to guide transportation planners, design engineers, and traffic engineers undertaking the largest public works program in U.S. history as well as many other major and minor capacity improvements to the nation's road network.

3.2 THE NEW PERSPECTIVE OF ISTEA

In 1991, with the Interstate System nearly completed, Congress enacted ISTEA. Although the legislation called for establishment of a national highway system as the centerpiece of the national surface transportation system, it significantly shifted national transportation policy in favor of a more balanced approach that made the best of what each mode had to offer. Moreover, it repeatedly emphasized the need to serve the movement of people and goods within an intermodal transportation system.

Among the purposes set out in Section 3 of ISTEA are

- To provide the resources, processes, and new policy directions to develop a national intermodal transportation system that will move people and goods in an energy-efficient and environmentally sensitive manner;
- To provide the foundation for U.S. industries to improve productivity and the ability to compete in the global economy of the 1990s and the twenty-first century by obtaining the optimum yield from the nation's transportation resources; and
- To include all forms of transportation in a unified, connected manner that uses the most efficient form of transportation at all times.

3.2.1 Statewide and Metropolitan Planning

Although Congress has relaxed some of the requirements of ISTEA, especially with regard to management systems, this watershed legislation has changed the tone of statewide and metropolitan planning, programming, and management. ISTEA established new procedures for statewide and metropolitan planning. It also originally required that states and metropolitan planning organizations (MPO) implement six management systems including those for congestion, intermodal facilities and systems, and transit facilities and equipment.

Each MPO is required to develop a long-range plan and a transportation improvement program (TIP), a listing of projects scheduled for implementation that is financially constrained based upon revenues that might reasonably be expected in the future. Similarly, each state is required to develop a long-range state transportation plan and state TIP in coordination with the metropolitan planning procedures. The statewide TIP must incorporate explicitly or by reference the TIPs that MPOs develop.

Federal regulations for the metropolitan planning procedures require each MPO in urbanized areas with more than 200,000 people to do the following.

1. Identify the projected transportation demand of persons and goods in the area over the planning period.
2. Identify adopted congestion management strategies including traffic operations, ridesharing, pedestrian and bicycle facilities, alternative work schedules, freight movement options, HOV treatments, telecommuting, and public transportation. These options must demonstrate a systematic approach in addressing current and future transportation demand and include regulatory, pricing, and management options.
3. Reflect the results of the voluntary management systems. The original rule stated that in areas not attaining national ambient air quality standards for ozone and carbon dioxide, federal funds cannot be programmed for any project that will cause a significant increase in carrying capacity for single-occupant vehicles such as a new general purpose highway on a new location or adding general purpose lanes, unless the project results from a congestion management system or it involves safety improvements or the elimination of bottlenecks.
4. Assess capital investment and other measures necessary to preserve the existing transportation system and make the most efficient use of existing transportation facilities to relieve vehicular congestion and enhance the mobility of people and goods.
5. Reflect a multimodal evaluation of the transportation, socioeconomic, environmental, and financial impact of the overall plan.

6. Incorporate procedures for alternatives analysis of major metropolitan transportation investments, which can also serve as input to an environmental impact statement or an environmental assessment.
7. Identify study corridors and subareas for major investments where analyses are not complete.
8. Give explicit consideration to many factors including the following:
   - International border crossings and access to ports, airports, intermodal transportation facilities, major freight distribution routes, recreation and scenic areas, and military installations;
   - Methods to reduce traffic congestion and to prevent traffic congestion from developing in areas where it does not yet occur, including methods that reduce motor vehicle travel, particularly single-occupant motor vehicle travel;
   - Preservation of rights-of-way for construction of future transportation projects, including identification of unused rights-of-way that may be needed for future transportation corridors.

3.2.2 Congestion and Intermodal Management Systems

Many states and MPOs may elect to continue developing congestion and intermodal management systems. The criteria for implementing the present voluntary management systems defines a congestion management system as a systematic process that provides information on transportation system performance and alternative strategies to alleviate congestion and to enhance the mobility of persons and goods. A congestion management system includes methods that monitor and evaluate performance, identify alternative actions, assess and implement cost-effective actions, and evaluate the effectiveness of implemented actions. The congestion management strategies typically include but are not limited to the following:

1. Transportation demand management measures such as carpooling, vanpooling, alternative work hours, telecommuting, and parking management;
2. Traffic operational improvements such as intersection and roadway widening, channelization, traffic surveillance and control systems, motorist information systems, ramp metering, traffic control centers, and computerized signal systems;
3. Measures to encourage HOV use, such as HOV lanes, HOV ramp bypass lanes, guaranteed-ride-home-programs, and employer trip reduction ordinances;
4. Public transit capital improvements, such as exclusive rights-of-way (rail, busways, bus lanes), bus bypass ramps, park-and-ride and mode change facilities, and paratransit services;
5. Public transit operational improvements, such as service enhancements or expansion, traffic signal preemption, fare reductions, and transit information systems;
6. Measures to encourage the use of nontraditional modes such as bicycle facilities, pedestrian facilities, and ferry service;
7. Congestion pricing;
8. Growth management and activity center strategies;
9. Access management techniques;
10. Incident management;
11. IVHSs (or intelligent transportation system) and advanced public transportation system technology; and
12. Addition of general purpose lanes.

Congestion management systems are intended to help nonattainment areas achieve compliance with national ambient air quality standards and to emphasize alternatives to single-occupant vehicles.

Intermodal management systems were defined as a systematic process of identifying key linkages between one or more modes of transportation where the performance of one mode will affect another, defining strategies for improving the effectiveness of these modal interactions, and evaluating and implementing these strategies to enhance the overall performance of the transportation system. The intermodal management system addresses transportation needs through a process that considers connections, choices, coordination, and cooperation.

Components of an intermodal management system are

1. Identification of intermodal facilities,
2. Identification of performance measures,
3. Data collection and system monitoring,
4. System and facility evaluation, and
5. Strategy and action identification and evaluation.

The transit facility and equipment management system complements the congestion management system and the intermodal management system as well as the statewide and metropolitan planning processes. The transit facility and equipment management system is conceived largely as an asset management system similar to those for pavements and bridges. However, it does include an element that relates to usage.

ISTEA sought to bring about significant changes in planning and management and a major shift in philosophy and practice from those that had been commonly employed since the Second World War until the close of the Interstate construction era.

3.3 NEED FOR A NEW DEFINITION AND ANALYSIS OF CAPACITY

There is a need for a new, more encompassing definition of capacity and corresponding capacity analysis methods. The definition and analytical methods should fundamentally be multimodal/intermodal and have primacy over the capacity of specific modes. Multimodal capacity should be the key constraint in transportation planning and design with the capacity of particular modal facilities and equipment considered as a secondary constraint.

The new definition and analytical approach need to focus on methods for determining capacity and capacity utilization, especially the most efficient or cost-effective level of throughput of people and goods that can be achieved involving any mode and capacity enhancement action, whether it is supply-side or demand-side.

One objective of this manual is to provide a new definition of capacity pertinent to multimodal transportation corridors. Hand-in-hand with the need for a new definition of capacity is a new analytical framework for capacity analysis.

3.4 TRADITIONAL MODAL CAPACITY CONCEPTS

Because of the dominance of automobile and truck travel, most transportation capacity analyses have revolved around the use of the HCM. In addition, bus, light-rail, and heavy-rail capacity analyses for planning transit service usually focus on the capacity of vehicles, headways, and frequency of service more so than the capacity of the corridors. An exception is corridor analysis involving HOV lanes, dedicated bus lanes, or other joint uses of rights-of-way. Capacity analyses concerning railroad freight, airport take-off and landing, inland ports, seaports, and passenger and freight terminals are also well-defined disciplines. But these methods tend to pertain to specific modes rather than multimodal corridor analysis. The following sections briefly describe some of the existing capacity concepts as applied to various modes of transportation. More details appear in Chapter 5.

3.4.1 Highway Capacity

The HCM recognizes that capacity can be defined as the number of either persons or vehicles that can traverse a point or segment on the highway during a given time period. However, nearly all of the capacity analyses in this standard reference book are expressed in terms of vehicle throughput. Maximum service flow rates per lane are typically expressed in terms of a maximum volume-to-capacity ratio associated with a particular level of service and a capacity under ideal conditions for a particular type of facility (i.e., freeway, multilane highway, arterial with specific design speeds, etc.). The HCM implicitly recognizes that public acceptance of a certain amount of delay and the costs of highway improvements often dictate a level of service that *de facto* implies a "socially and economically acceptable" capacity. To determine the service flow rate for all lanes in one direction, the service flow rate for one lane is multiplied by the number of lanes and a series of correction factors. Correction factors pertain to the effects of restricted lane widths, grade, heavy vehicles in the stream, the driver population, development environment, etc. The HCM also has procedures for calculating the capacity of ramps and junctions and of signalized and unsignalized intersections. Again, the focus is on vehicle throughput as opposed to passenger or freight throughput.

3.4.2 Urban Mass Transit and Intracity Rail Passenger Capacity

Transit capacity analysis, which is also addressed in the HCM, concerns both person capacity and vehicle capacity. Although transit person capacity is dependent upon a great many factors, a gross estimate is the product of the number of transit vehicles per hour past the busiest stop and the maximum number of passengers each vehicle can carry. Many factors influence this number. In fact, terminal capacity rather than capacity of the line-haul system is sometimes the limiting factor. Of considerable importance to multimodal corridors is the interaction between vehicle capacity (for cars and transit) and person capacity. For example, the person capacity of a freeway lane with bus and car traffic can be estimated as a function of the maximum flow rates and occupancy rates for cars and buses or by using the car equivalency of a bus. As the number of buses increases in the traffic stream, the person capacity increases, and the total vehicle capacity drops, with the total person throughput highly dependent on the vehicle occupancy rate.

3.4.3 Intercity Rail Passenger Service

In the United States, intercity rail passenger and freight capacities, although expressed in quite different terms, are highly related because they frequently involve the same track. In fact, except for the Northeast rail corridor between Boston and Washington, D.C., Amtrak operates on tracks owned by freight railroads. Besides factors such as the number of passenger cars per train and the number of seats per car, intercity rail passenger capacity is principally a function of the maximum safe speed of operations. Safe speed is strongly influenced by condition, grade, geometry of the track as well as the number and nature of railroad at-grade crossings, and the degree of interference of freight operations with passenger operations. The speed of passen-

ger trains operating on freight railroads is determined by the alignment and condition of the track, which is a function of the level of maintenance the track receives. The intensity of freight operations diminishes the potential capacity of passenger operations. Where intercity passenger operations do not share tracks with freight, capacity is governed mainly by the same factors that govern rapid rail and terminal capacity.

3.4.4 Freight Capacity

For freight, the proper measure of capacity is more difficult to define because of the large number of commodities carried having different weights, sizes, densities, packaging (e.g. containerized and parcels), and other characteristics such as perishability or hazardousness. Typical rail and waterborne freight capacity measures include gross tons per day over the corridor or gross tons per mile. For truck capacity, vehicles per hour can be translated into tons per hour. However, with the growing importance of high cube freight—including parcels, FedEx, and mail—more useful terms for freight capacity in many contexts are cubic feet per hour or gross cube per day.

The challenge in developing a measure of freight capacity is to be able to express freight shipments in common terms. Densities of different commodity classes can be used to convert freight throughput expressed in either weight or cubic units into common terms. A measure of freight throughput that is not commodity dependent requires an average density for all commodities in the corridor, perhaps based on national statistics. An average density appropriate to a specific corridor can also be derived from an estimate of the current commodity mix and throughput in the corridor.

The many types of freight transport vehicles, containers, and types of carriers further complicate freight capacity analysis. The advent of containerization, including double-stacked containers and RoadRailers, have enhanced capacity not only by increasing the cubic volume that can be transported but also by speeding up handling and throughput. Similarly, innovations in the design of rail cars for carrying commodities such as grain, coal, or gravel can increase effective capacity. Moreover, integrated tug-barges and specially designed tankers provide added capacity. In the trucking industry, the appearance of longer-combination vehicles have increased freight capacity and, recently, proposals such as the Turner Truck, which would increase the number of axles, thus permitting heavier loads without more pavement damage, might ultimately be permitted, perhaps enabling the trucking industry to carry some heavier commodities that historically have been more economical to transport by rail. Potential enhancements to the carrying capacity of transport vehicles and containers need to be directly accounted for in any method of multimodal capacity analysis.

3.4.5 Airport Landside, Takeoff, and Landing Capacity

The major airport hubs in the United States such as Chicago's O'Hare, Atlanta's Hartsfield, and New York's La Guardia have witnessed considerable increase in air traffic (both passenger and freight), which in many instances have exceeded the design capacity of the airports, causing congestion and delays *(3)*. These problems usually arise due to limitations in ground access, terminals, aircraft access, runway capacity, and air traffic control (airspace and ground traffic management). Ground access is important for successful airport operations. Interactions with other modes such as automobile, bus, rail, and trucks that feed movements to and from the airports affect the performance of the aviation system. Virtually all trips by air involve intermodal transfer of passengers and freight at the origin-destination pairs. Transportation of freight by air usually involves goods that have high price-to-volume (and weight) ratios. These goods are normally placed in air containers that are used exclusively for air transport operations.

The number of landings or takeoffs in an airport is controlled by the separation distance between aircraft at the same assigned level and the specified speed for entry into the terminal approach area. This basic runway capacity is adjusted to account for the configuration of the taxiway, the type of aircraft, and airline operations. In order to maintain overall airport capacity while increasing aircraft distance and/or decreasing entry speed, airside and landside (terminal and ground) capacities have to be improved.

3.4.6 Inland and Seaport Capacity

There are three types of water transportation: (1) international/ocean, (2) coastal/intercoastal, and (3) inland waterways. Transportation by water generally involves cargo or freight, which moves in either containers (general cargo) or as liquid or dry bulk (bulk cargo). Although a large part of ocean and coastal movement of goods are containerized and require intermodal transfer, inland waterway transport often involves the movement of bulk commodities on a plant-to-plant basis without intermodal exchange.

Inland and seaport operations include loading, unloading, and handling of cargo at the berthing areas and other facilities of the marine terminals. Transfer to ground transportation modes such as trains and trucks is part of the handling process. For seaports connected to an inland waterway or river system, this includes intermodal transfer of freight from ships to barges. Analogous to airports, the overall capacity of seaports, in terms of volume or tonnage of cargo handled, depends on its waterside and landside facilities. Waterside characteristics include channel depth (or draft), navigation aids, number of berthing or dry-docking facilities, and the size of the channel (in terms of width and radius). Channel design depends on the size of the vessels and the handling

requirements. Landside features include number and area of terminals, number and types of handling equipment, and intermodal transfer facilities such as rail and truck yards, and storage yards.

3.4.7 Terminal Capacity

Terminals or transfer facilities are as important as line-haul facilities in determining capacity and in some cases are even more important. Terminal throughput is the limiting factor in the capacity of many freight systems. FedEx has seen its Memphis hub as the factor limiting the growth of its system generally as well as the limiting element in countless individual corridors. Some flows currently moving through Memphis could move "direct." As these flows are changed to move direct, the capacity in the Memphis terminal is preserved for those moves that need it. Changes elsewhere in the system therefore affect the capacity at Memphis and consequently the capacity of many individual corridors.

Intermodal terminals can be of special importance to public policy planners. Intermodal terminals frequently do not fall under any organization's specific jurisdiction and, consequently, they are the direct responsibility of no one. Sometimes the lack of investment by one of the modes specifically affects the capacity of another mode.

3.5 CONCEPTS AND DEFINITIONS OF MULTIMODAL CAPACITY ANALYSIS

This manual distinguishes between two fundamentally different approaches to capacity determination: (1) physical capacity, and (2) economic capacity. Both have important roles to play. The first accounts for physical constraints within the system and the second accounts for the net economic value that individuals and shippers receive from transportation. The second also accounts for the financial constraints that public and private firms face when deciding on transportation expenditures. While most capacity analysis determination procedures focus on physical capacity, some others also recognize the significance of economic capacity.

3.5.1 Physical Capacity

The definition of physical capacity used in this manual is *the maximum rate of flow of persons, goods, or vehicles that can reasonably be expected during a given time period through a link or node.* Goods movement is expressed in terms of throughput measured in weight, cubic volume, dollar value, or equivalent units of equipment such as truckloads or containers. This definition is rather similar to that in the HCM, which defines capacity as "the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a time period under prevailing roadway, traffic and control conditions."

Because of the variety of passenger vehicles, the different passenger vehicle occupancy rates, and the myriad commodities shipped, any capacity analysis methodology that hopes to reduce various types of passenger and freight movements to respective person and goods movement requires methods for conversion with each measured in common units. The common unit for passenger movement is persons, but the common unit for goods movement can be tons, cubic volume, dollar value, or equivalent equipment movements such as truck loads or containers. In addition, it is desirable to know how capacity that serves passengers might convert into freight capacity and vice versa.

This manual relies on occupancy rates to convert different types of passenger vehicle movements into person movements. It also relies on conversion factors to translate freight vehicle or freight movement into shipments expressed in terms of weight, cubic volume, dollars, or equivalent equipment movements.

There are a number of possible methods for evaluating tradeoffs between passenger and freight capacity. One is to use equivalency factors (e.g., convert freight volumes into equivalent truck loads, then into passenger car units, and finally into person movement). Equivalent capacities for person and goods movement can apply only up to the capacity of a segment to handle freight or passenger movements, one exclusive of the other. Another approach is to use economic analysis to determine mixes of traffic, compatible with physical capacity constraints, that maximize some objective function.

3.5.2 Economic Capacity

Besides the concept of physical capacity determination described above, this manual includes a short chapter (Chapter 9) that deals with procedures for determining capacity based on economic criteria. The chief distinguishing feature is that economic capacity methods use some type of profitability or cost-benefit analysis to determine optimal capacity. Economic analysis methods determine the point at which the extra resources or expenditures for capacity additions are not worth the extra costs *(4)*. Economic methods are sometimes used in the private sector because of the imperative to make profitable investment, maintenance, and operations expenditures. However, economic methods of capacity analysis are not unknown in the public sector and have a number of applications.

To summarize, the economic capacity of an existing transportation corridor or facility is the volume of traffic or the level of throughput for a given time period so that the difference between total benefits and total costs are maximized (i.e., the marginal benefits equal the marginal costs).

3.6 SPEED AND HEADWAY CONCEPTS

Capacity analysis makes important distinctions between speed concepts. Definitions important to understand are

Speed. The rate of motion expressed as distance per unit time, usually as miles per hour or kilometers per hour. Speed is also sometimes referred to as velocity.

Maximum speed. The safe speed achievable under ideal conditions (no delays) and that is technologically and economically feasible. Higher speeds typically require greater spacing between vehicles to assure safety except where an automated guideway can maintain constant headways in tightly packed consists or platoons. Part of technical feasibility is physical feasibility. Normally, heavier vehicles have a lower maximum attainable speed because speed is partly a function of tractive power in relation to weight.[1]

In multimodal capacity analysis it is important to make a distinction between distance and time headway. These are defined as follows:

Distance headway. The distance between two vehicles, persons, etc., following one another.

Time headway. The amount of elapsed time between the arrival of vehicles, persons, etc., at a point.

Distance headway (h_d) and time headway (h_t) are related to one another by speed (S) where $h_d = S * h_t$.

3.7 LEVEL OF SERVICE

A common transportation practice is characterizing the quality of service, whether for person or goods movement, in terms of level of service (LOS), which is defined as follows:

LOS. A measure of the ability of a transportation facility to serve the user, usually described in terms of its operating conditions and how they are perceived by motorists, shippers, carriers, and others. A LOS definition generally describes these conditions in terms of factors such as speed, travel time, reliability, freedom to maneuver, traffic interruptions, convenience, safety, and avoidance of damage.

If LOS can be graded, say from A (highest) to F (lowest), it reduces discussion of traffic problems to very simple measures that often can be visualized (pictures are often used to communicate the meaning of different LOSs) and thus facilitate public policy in terms of setting LOS goals. Indeed, many communities throughout the United States have set LOS goals for highways and mass transit. Moreover, LOS is frequently used as the basis for warrants and justifications for transportation improvement projects. The HCM provides extensive tables and procedures for determining flow rates for different service levels for various types of facilities, which are termed service flow rates. Table 3.1 below shows sample LOSs for basic freeway segments.

The capacity methods can take two approaches to LOS. One is to not condition capacity calculations upon LOS. Capacity is purely a question of physical capacity and LOS becomes a performance measure. The other is to make capacity calculations conditional upon a particular LOS. Frequently, it is desirable to base capacity analysis on a LOS for time or distance headway.

3.8 ADDITIONAL DEFINITIONS FOR MULTIMODAL CAPACITY ANALYSIS

The definitions and concepts of multimodal capacity analysis described here are applicable to most forms of transportation and thus are highly generic in the following respects:

- They apply to different modes,
- They apply to line-haul and transfer facilities,
- They address supply-side and demand-side factors contributing to throughput, and
- They focus on the movement of people and goods in addition to vehicles.

The fundamental concepts can be applied to any level of detail of a transportation facility or area of coverage. However, given that this is a manual intended to support simple analytical methods that can be performed with a calculator or a spreadsheet computer program, practical applications of the concepts are most productive if limited to transportation corridors.

3.8.1 Modes, Vehicle Types, and Corridor Elements

In order to accurately describe the major components of a corridor and to facilitate capacity analysis, this manual adheres to the following definitions:

Mode of transportation. A type of transportation that serves the movement of persons, goods, or both.

[1]The 1994 HCM provides these other definitions of speed:
Average travel speed. The average speed calculated from observations of individual persons, goods, or vehicles, which can be based on space mean speed or time mean speed.
Space mean speed. The average time for persons, goods, or vehicles to traverse a segment. The average is computed as a weighted average of the amount of time each person, good, or vehicle, as the case may be, spends traversing the segment.
Time mean speed. The average speed measured at a point (say by radar) and thus is the average of the observations on the speed of individual persons, goods, or vehicles taken at a physical point.
Average running speed. The distance divided by the average running time to traverse the distance, where average running time includes only the time that the person, good, or vehicle is in motion.

TABLE 3.1 Level of service criteria for basic freeway segments (*1*)

Level of service	Maximum Density* (pc/mi/ln)	Minimum Speed (mph)	Max V/C Ratio	Maximum Service Flow Rate (pc/hr/ln)
Free Flow Speed = 70 mph.				
A	10.0	70.0	0.318/0.304	700
B	16.0	70.0	0.509/0.487	1,120
C	24.0	68.5	0.747/0.715	1,644
D	32.0	63.0	0.916/0.876	2,015
E	36.7/39.7	60.0/58.0	1.00	2,200/2,300
F	Variable			
Free Flow Speed = 65 mph.				
A	10.0	65.0	0.295/0.283	650
B	16.0	65.0	0.473/0.452	1,040
C	24.0	64.5	0.704/0.673	1,548
D	32.0	61.0	0.887/0.849	1,952
E	39.3/43.4	56.0/53.0	1.00	2,200/2,300
F	Variable			
Free Flow Speed = 60 mph.				
A	10.0	60.0	0.272/0.261	600
B	16.0	60.0	0.436/0.417	960
C	24.0	60.0	0.655/0.626	1,440
D	32.0	57.0	0.829/0.793	1,824
E	41.5/46.0	53.0/50.0	1.00	2,200/2,300
F	Variable			
Free Flow Speed = 55 mph.				
A	10.0	55.0	0.250/0.239	550
B	16.0	55.0	0.400/0.383	880
C	24.0	55.0	0.600/0.574	1,320
D	32.0	54.8	0.800/0.765	1,760
E	44.0/47.9	50.0/48.0	1.00	2,200/2,300
F	Variable			

* *Density* is the number of vehicles per unit length (e.g., miles, km) of the highway segment.

Composite mode. A type of transportation that is a composite of the attributes of more than one type of vehicle or mode of transportation. An example of a composite mode for a HOV facility is a mode with dimensions and a person occupancy rate that is a weighted average (e.g., by traffic volume) of the cars, vans, and buses using the HOV lane. A composite mode may be a composite of person vehicles (including pedestrians), freight vehicles, or both.

Consist. A series of vehicles physically connected together into a single unit of movement such as a freight or passenger train.

Platoon. A series of autonomous vehicles that move together in a pack where the headways between the vehicles composing the platoon are maintained at a fixed and usually small distance. Headways between platoons are variable.

Component. A link or node.

Node. One of two defining points of a link. Types of nodes are ramps, intersections, bus stops/berths, bus stations, rail freight yards, intercity passenger stations, commuter/rail train stations, airports, inland ports, and seaports.

Link. A facility, a body of water, or air space within a traveled way on or through which travel occurs between two nodes. Links between nodes can be separate or adjacent, and there can be more than one link in the same traveled way between two nodes. Suppose a traveled way has within it separated rapid rail track, HOV lane, local access general purpose lanes, and general purpose through lanes. Each of these four types of facilities can be defined as a separate link between two nodes. Multimodal capacity analysis can be simplified whenever it is possible to classify links so each type of link corresponds one-to-one with a single mode of transportation.

One-directional link. A link serving traffic in only one direction.

Two-directional link. A link serving traffic in two opposite directions.

Lane. Each part of the traveled way carrying traffic and bounded by markings (such as highway lanes), directed by a guideway (tracks), or restricted by other controls (i.e., air lanes).

Path. A sequence of links and nodes or traveled ways and nodes in one direction connecting an origin and destina-

tion. A corridor usually will have more than one path connecting any pair of origin and destination.

Right-of-way. The land, water, or air space reserved for the current or future use of traffic and for which the right of access is controlled.

Transfer facilities. More widely known as terminals and sometimes called transportation centers, multimodal interfaces, modal interchanges, connectivity centers, or stations. A broad view of transportation terminals encompasses anything from a simple bus stop to rail passenger stations to ports. The basic functions of terminals are to provide passengers and freight with access to the transportation system, points of modal interchange, route connectivity to expand transport network coverage, and facilities for the processing, servicing, and storage of passengers and goods. Transportation terminals may also be used to consolidate and facilitate traffic movement. Interfaces among modes can be complex and time-consuming. Delay and congestion often result *(5)*.

Transportation corridor. This is the right-of-way strip (surface, subsurface, or air) set apart for accommodating major multimodal transportation facilities that either are linear or function as a set of interdependent networks serving various forms of transportation, including terminals. One purpose of the corridor is to provide optimum movement of people, goods, and services by: (1) creating the best possible relationships between transportation facilities and land use activities requiring high accessibility, and (2) minimizing conflict between transportation facilities and all land use activities but especially those not requiring high accessibility. Another purpose of transportation corridors is to coordinate the installation of the various modes of transportation and utility services in a single, ordered channel of movement, with built-in flexibility for accommodating technological changes and even new transportation modes. In addition, corridors stimulate and guide change in land use activities and in the intensity of uses affecting the total land form and provide visual organization of systems and places *(6)*.

Chapter 4 provides a more detailed discussion of different types of corridors and their various components. Four case study corridors are used as examples to illustrate instances of the typology that was developed.

3.8.2 Multimodal Person and Freight Capacity of Links, Nodes, and Corridors

The methods for determining the capacity of segments and nodes using the various methods of capacity analysis must be put into the context of corridor capacity. The following are key concepts for determining multimodal person and freight capacity.

- The person capacity of a link or node is calculated independently of freight capacity unless joint-use facilities exist. Then a portion of joint-use facility capacity may be allocated to person and goods transport with each based on vehicle mix. A possible allocation is to assign all capacity to either person or goods movement.
- The one-directional capacity of a path is determined by the smallest capacity of any component (link or node).
- The two-directional capacity of a link or corridor is equal to the capacity in one direction plus the capacity in the opposite direction.
- Assuming a corridor is composed of parallel paths, the total capacity of the corridor is equal to the sum of the capacities of each path.

Nodal capacity is defined in terms of the average flow rate through the node for passengers and freight. The rate of flow is a function of the physical and operational characteristics of the node (i.e., dimensions, number of transactions involved, number of servers, rate of service, etc.) and the modes or traffic served (e.g., people, containers, rail cars, trucks, aircraft, etc.) The capacity of a node to process persons or goods is defined as follows:

Person nodal capacity. The maximum processing rate through the node in persons per unit time. The maximum rate of flow is limited by that which is safe as well as technologically feasible.

Freight nodal capacity. The maximum processing rate through the node expressed in units of weight, cubic volume, dollar value, or equivalent equipment movement such as truckloads or containers. The maximum rate of flow is limited by that which is safe as well as technologically feasible.

A corridor can be highly directional and linear, containing independent links or nodes. If the corridor can be decomposed into parallel paths the multimodal person and freight capacities can be defined and calculated as follows:

Multimodal person corridor capacity. The sum of the person capacities of each parallel path.

Multimodal freight corridor capacity. The sum of the freight capacities of each parallel path.

Chapter 5 of this manual contains an extensive discussion of modal and multimodal capacity measures and capacity determination procedures.

If the corridor of analysis consists of a network of dependent links and nodes, the capacity cannot be measured easily and without examining the relationships among the elements. The level of difficulty depends upon the number of elements, their characteristics, and their interrelationships. The methods described here are not designed to account for these network-level interactions. Network models must be applied if network

phenomena need to be considered in corridor capacity determination. Such models are beyond the scope of this manual.

3.8.3 Homogeneous Conditions

The methods employed for calculating capacity of facilities apply to specific links or nodes. Links can be any length because the capacity analysis method accounts for variations in facility, traffic, and control conditions along the way. In practical capacity analysis applications, link definitions will vary according to whether the analysis is to occur on a macroscopic or microscopic scale. In more macro analysis, appropriate to broad-brush corridor analysis, links do not have to be as sharply defined. Nonetheless, it is wise to segment the transportation networks according to breaks representing variations in uniform prevailing conditions to the greatest extent practical. It is customary to define links in such a way that they are *homogeneous in terms of their prevailing facility, traffic, and control conditions*:

Facility conditions. These are the geometric, design, and other physical characteristics of transportation facilities including the type, the surrounding environment, the number of lanes or tracks, container processing equipment, and clearances.

Traffic conditions. These are the characteristics of the traffic stream using the facility, including the traffic mix, variations in specific attributes of a particular element of the traffic, and the volume and directionality of traffic.

Control conditions. The types and specific design of control devices and traffic regulations that apply to a specific facility. These include markings for controlling traffic movements, stop and yield signs, railroad signals, automated traffic control devices, and regulatory restrictions on use.

3.9 SUPPLY AND DEMAND

Although pure capacity analysis might be conducted separately from any consideration of demand, an assessment of capacity utilization cannot be. In reality, supply and demand are interrelated in capacity problems:

Demand factors. These include economic, labor and demographic trends, vehicle and commodity characteristics, and human factors including social and economic characteristics. These affect current and future use of transportation facilities.

Supply factors. These are related to the infrastructure and correspond to the capacity of the components of the transportation system (i.e., links or nodes of a certain type, the length of the links), the operational policies governing the use of the transportation system (i.e., speed limits, regulatory policies concerning the placement of signs and markings, limiting use of a road to HOVs), and the quality and reliability of the components of the overall transportation system (i.e., bridge weight restrictions due to unsafe loads, condition of rail track, probability of bus breakdowns).

Demand varies with the time period, by the hour of the day, between peak and off-peak, by the day of week, and by month of the year. It is extremely important to account for variations in demand. For example, a breakdown in traffic flow may occur during a portion of rush hour. During other portions of rush hour the facility has additional capacity that could absorb some of the traffic contributing to the breakdown in flow if users were to shift their times of travel. Congestion waiting time tends to ration the scarce capacity of transportation facilities in much the same way that congestion pricing would. The greater the waiting time due to congestion during a period of time, the more likely users will divert to other routes or time periods in order to avoid severe congestion.

The National Personal Transportation Survey (NPTS) has revealed that over the last three decades the amount of time the average commuter spends in the journey to work has remained roughly constant at about 20 minutes. This implies that people behave as if they have a time budget for commuting. One consequence is that people change the location of their residences in response to traffic congestion in order not to exceed their travel time budget.

Businesses also make location decisions based on congestion and are frequently observed to move from congested areas to less congested ones in order to better meet the transportation needs of the business and of their employees. Change in business location decisions is one type of long-term demand response to congestion.

Supply and demand factors have both short- and long-run impacts, and capacity analysis procedures must address both time horizons. Short- and long-term periods are defined as follows:

Long-term period. This is the period over which changes in land use, population, and economic activity cause the general demand for transportation to change.

Short-term period. This is the period during which the behavior of transportation users and systems may change but the total demand for transportation remains constant.

Chapter 8 of this manual identifies and describes in detail the many factors affecting demand for transportation services and the existing models and relationships that can be used to predict or forecast demand.

3.10 PERFORMANCE MEASURES

Establishing capacity is only one way to characterize multimodal transportation facilities. In practice there are a large number of measures of performance that are of interest in addition to capacity. This manual defines performance (which is to be contrasted with capacity) as follows:

Performance. Attributes of the flow of goods and people within a transportation system or facility (e.g., highway, rail, corridor, etc.) and the degree to which the facility or system attains specific objectives, such as to provide adequate level of service, promote safety, reduce congestion, and abate air pollution. Performance measures include volume/capacity ratios, speed, LOS, emissions, energy consumption, accident rates, and agency and user costs.

Chapter 6 of this manual is mainly devoted to corridor performance measures.

3.11 ACTIONS FOR INCREASING EFFECTIVE CAPACITY

This manual identifies several ways to increase the effective capacity of a transportation facility through supply management, demand management, or other means such as corridor protection and preservation. Terms that have been used in the past to describe classes or categories of actions that enhance capacity or improve capacity utilization, by influencing the supply or demand attributes of a transportation facility, are as follows:

Transportation Systems Management (TSM). This seeks to increase the traffic-carrying capacity by exploiting underutilized capacity inherent in existing systems rather than by building new infrastructure. TSM encompasses a variety of techniques aimed at improving the efficiency of the surface transportation system. TSM includes transportation supply management techniques such as traffic signal coordination and ramp metering, as well as transportation demand management techniques such as promoting carpooling and vanpooling. Over the last 20 years, TSM techniques have repeatedly demonstrated their effectiveness. On the supply management side, evaluations of traffic signal coordination systems continue to show positive cost-benefit outcomes from their implementation. On the demand management side, recent evaluations suggest that techniques such as ridesharing and vanpooling can have significant effects where they are implemented.

Transportation Control Measures (TCM). These are programs or activities that states and localities can implement to encourage the traveling public to rely on the automobile less or to use it more efficiently. These programs include traditional approaches such as improving commuter train service, encouraging employer-provided carpooling incentives, and synchronizing traffic lights to improve the flow of traffic. They also include economic measures, such as imposing regional gasoline taxes and motor vehicle emission fees *(7).*

Transportation Demand Management (TDM). This incluces methods to influence the demand for transportation facilities and services by changing the options or relative attractiveness of options available to users. TDM actions include, but are not limited to, congestion pricing (areawide, facility, or parking); provision of exclusive HOV lanes or specific modes restricting other vehicles; encouragement of flexible working hours; and offering fare discounts and subsidies.

Transportation supply management. This consists of all the actions that may improve transportation performance or LOS by changing the physical or operating characteristics of the traveled route and associated facilities in order to handle transportation demand. These actions include traffic control (e.g., signalization, ramp metering, channelization), providing/improving intermodal transfer facilities (e.g., terminals), automated toll collection, and joint use of right-of-way.

Corridor protection/preservation. This involves the coordination and application of various measures to obtain control of or otherwise protect the right-of-way for a planned transportation facility. Corridor preservation techniques should be applied as early as possible after the problem in a transportation corridor is identified concerning either a new alignment or along an existing facility to prevent inconsistent development; minimize or avoid environmental, social, and economic impacts; reduce displacement; prevent the foreclosure of desirable location options; allow for the orderly assessment of impacts; permit orderly project development; and reduce costs *(8).*

Chapters 7 and 8 provide a more detailed discussion and examples of these capacity enhancement actions including procedures to evaluate their merits and costs.

3.12 REFERENCES

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CHAPTER 4

CORRIDOR IDENTIFICATION AND PROBLEM DEFINITION

This chapter establishes the framework for multimodal corridor and capacity analysis by describing a general process for addressing it. Included are descriptions of corridors and corridor components that typify a variety of multimodal situations. These descriptions are suggestive of different types of capacity problems that can be addressed by the process. The process does not attempt to be comprehensive but instead tries to place capacity problems within a broad and realistic context and is meant to prepare the reader for the capacity-determining procedures of the next chapter. Four case study corridors, (1) New York metropolitan area river crossing in New York City, (2) Altamont corridor in California, (3) Seattle north-south corridor in Washington State, and (4) Madison east-west corridor in Wisconsin, are used as examples to illustrate the concepts and approaches.

4.1 OBJECTIVE

The principal objective of this chapter is to characterize the corridor in terms of its physical features, transportation components, traffic flow composition, travel patterns, and land use. It also sets out the nature of different problems to be addressed in an overall (not detailed) way and helps avoid the pursuit of a solution to the wrong problem through too narrow a focus on physical capacity. The typology and approaches should be applicable to a number of existing corridors.

4.2 STEPS IN THE PROCESS

A 10-step process for addressing corridor identification and problem definition has been developed. These 10 steps are presented below. Subsequent discussion will elaborate the details.

1. Define the study area including the boundaries of the corridor and the jurisdictions covered. Identify the larger system, or transportation network, of which the corridor is one part.
2. Identify the type of corridor that best characterizes the setting and the problem. Distill all relevant information pertaining to the specific corridor type.
3. Identify the primary modes of transportation in the corridor and the links and nodes that serve these modes. Describe both the physical and operational characteristics of each link and node (i.e., capacity). Chapter 5 explains the procedures for determining the link and nodal capacities of various transportation facilities.
4. Determine person trip, vehicle trip, and/or goods movement demand for each link and node. This includes the types of carriers involved, the equipment used, the purpose of trips, peaking patterns (e.g., morning or evening rush hour), and the direction of flow.
5. Identify the principal generators and attractors of traffic that use the links and nodes in the corridor, along with their origins and destinations. These include industrial plants, business offices, wholesale and retail trade establishments, schools, military facilities, recreational facilities, etc.
6. Determine the location, nature, and extent of congestion and capacity problems including the links and nodes involved, the time of day, duration of congestion, types and volumes of traffic affected, and service levels (e.g., air quality, noise pollution, accident rates). Chapter 6 provides a more detailed approach to the performance and LOS determination needed to identify the magnitude of the problem.
7. Examine trends in person trip and goods movement growth. Determine the extent to which land use and other activities affect overall travel demand. Forecast future land use and economic activities. Chapter 8 provides a detailed discussion of factors affecting demand and procedures to forecast future demand.
8. Identify any constraints to capacity expansion of facilities such as physical barriers, sensitive lands (e.g., environmental, historical, or archaeological restraints), and high-priced real estate or infrastructure that is expensive to construct.
9. Develop an initial set of alternatives for dealing with the problem. This list is not meant to be final or limiting, but having a few alternative courses of action allows all parties involved to more clearly focus on the nature of the problem. Guidance on the identifica-

tion and selection of potential alternatives is given in Chapter 7.

10. Summarize with a brief written statement of the problem. Having a written statement of the problem allows it to be circulated to people outside the study team who have reason to evaluate and to add to the understanding of the problem.

4.3 CORRIDOR TYPOLOGY (INCLUDING KEY INTERMODAL COMPONENTS)

The definition of a corridor encompasses a broad and loose meaning of the word. Indeed, there is no hard definition of what constitutes a corridor. Each corridor has a unique set of physical and operating characteristics. Transportation engineers and planners use the term to describe various types of facilities and different areas of coverage.

Most corridors are identified by the primary facility or facilities that are included. For instance, portions of the interstate highway system, freeways, or expressways have been designated corridors for the purpose of transportation analysis and planning. Examples include the Interstate 66 corridor in Northern Virginia, the Northeast rail corridor between Washington and Boston, the Los Angeles-San Francisco corridor on the West Coast, and the Alameda corridor in California. The I-66 corridor is a commuter corridor with automobile, bus, and rapid rail all represented. The Northeast corridor is an intercity rail, air, bus, and automobile corridor. The Los Angeles-San Francisco corridor is primarily an air corridor. The Alameda corridor is an urban freight movement corridor.

In terms of size or scope, corridors can take various forms. There are international corridors, multistate corridors, regional corridors, intercity corridors, and local corridors. The complexity of the transportation system within the corridor and the level of abstraction will vary accordingly. With different corridors the focus of the investigation may change from how to increase capacity to demand management over the alternatives. The objectives of the study can vary, causing a change in the nature of the corridor definition or affecting the details of the approach used to measure capacity. Many types of corridors, however, are repeated over and over across the country. As a consequence, it is useful to characterize the more generic types; these are described below.

4.3.1 Intercity Routes

In many parts of the country identifiable corridors exist between major cities along a commonly used route. In most cases these routes are defined by facilities of different hierarchical levels and/or modes. Frequently these will consist of one or more 2-lane state highways, or county roads, connecting the smaller communities along the general route traveled, an interstate highway, a railroad, and, in most cases, an air corridor. There is also frequently a network of county or secondary roads and sometimes a navigable waterway. If the route passes through difficult terrain, such as mountains, or is constrained by encroaching bodies of water, urbanized areas, or other natural barriers, the capacity of the overall corridor may be limited. In this case the corridor represents precisely the situation where capacity analysis applies. The object is to suggest potential solutions to recurring stoppages or slowdowns on the route.

A prime example of an intercity multimodal corridor is the so-called Northeast corridor where, for example, the same short-term capacity problem will manifest itself from time to time in the section between Washington, D.C., and New York City. The distance between Washington and New York is approximately 200 miles and the driving time is normally 4 hours. However, with congestion this travel time can range from 4 to 6 hours, and in difficult driving conditions it can be much longer. Travel by train requires about 3 hours. By plane, the travel time is less than 50 minutes in good weather, but because of city-to-airport and airport-to-city congestion, elapsed time for the trip can range from 2 to 3 hours altogether.

During inclement weather major components of the system break down, particularly if the bad weather occurs during a prime travel period, such as the Thanksgiving or Christmas holiday periods. Air travel is frequently the first to be affected. Delays in landing and takeoff can push waiting times up by several hours. Switching the trip to rail is difficult because of the distance between train stations and the airports. It is sometimes difficult to reach railroad reservation clerks by telephone since they are also jammed with callers. Typically, the train also becomes overloaded and cannot handle the overflow travelers without large delays. For highway travelers there are many alternative routes that could be used if the travelers knew their way. However, a major accident or traffic jam can leave travelers without information about the nature of the delay. How broad is the problem? When will it be cleared? How does one navigate around the problem area? How does one get out of the current queue to exit the roadway? All of these questions are difficult to answer once the traveler is en route.

4.3.2 Peripheral Routes

The circumferential freeways that have become common around our major cities offer another example of where multimodal capacity problems exist. Many are choked with rush-hour traffic congestion—sometimes in both directions. The Washington Beltway, Boston's Route 128, and Atlanta's Outer Loop (I-295) are typical. A multilane freeway that connects the more important communities at a given radius around the metropolitan area becomes an instant magnet for growth. As the suburbs have grown and as industries have moved from the central cities to the outlying regions, the network of rural roads and former crossroads that historically

connected the small towns of the region often become overloaded and have great difficulty handling the increased traffic demands. The historic infrastructure is unable to cope and the property owners abutting the overcrowded local road are typically opposed to an expansion of the facility on the grounds that it will attract even more traffic. The peripheral route then takes on even more importance as the "only way" to get from place to place in the suburbs.

Large numbers of trucks on an overloaded freeway compound the possibility for serious accidents. Trucks cannot respond to congested traffic conditions as rapidly as automobiles can. Following distances on a crowded freeway are reduced below acceptable levels. Braking response times of heavier vehicles can drop to dangerous levels. A single accident, such as an overturned gasoline truck that ignites, can create an incident that may be fatal to a few individuals and can affect tens of thousands of travelers and cause massive delays in the system.

Peripheral routes are also frequently the intercity bypass routes around the city. Long-haul intercity trucks may not have a reasonable alternative to the beltway. As a consequence, this through traffic is forced onto the same facility as the suburban commuter. Constructing bypass routes for these "through" trips are frequently difficult to do. Environmentalists oppose the bypass route because of its encroachment on nature. Developers support the idea of a bypass, but only if there is an interchange where they are interested in expansion. If the route is built with all of these interchanges, it will no longer function as a bypass in a very few years but instead wind up as just another congested peripheral highway.

There is a need to identify other routes in the corridor and to enhance their capacity as alternatives from former farm roads to market roads and existing 2-lane state routes and major connectors converted into higher capacity routes (which can offer an emergency alternative to some of the travelers who typically use this route). Frequently, all that is required is the clearing of obstructions by adding infrastructure that eliminates the bottlenecks, designating the route, and marking it adequately. Other approaches to accidents on peripheral routes include improved incident management and strategies to reduce overall travel demand on ring roads.

4.3.3 Barrier Crossings

Another common corridor problem in which capacity plays a major role are facilities such as bridges and tunnels that are attempts to overcome a natural barrier. Examples of barriers exist in almost every region of the country. The most typical is a river with urbanized areas on both sides. In many cases these urban areas developed historically because the river offered a natural highway. In many cases the river was more easily navigated than an all-land route, especially if that route was hilly or swampy. The urban areas may have developed where a change of modes was required. For raw materials this may have been at a mill or a factory where the materials were processed. The land on both sides of the barrier eventually developed into urbanized areas. Ferries were introduced very early on and, in many cases, offered better transportation for both passengers and freight than that provided by land-based modes.

With the advent of railroads and later automobiles, the situation was reversed. The river became a "barrier" rather than a "highway." The need for a bridge or tunnel arose and was eventually realized. This led to increased growth and eventually to the need for a second crossing—in some cases, several more crossings. The high cost of creating additional capacity makes these natural barrier crossings chronically short-of-capacity. Examples include New York City and the barrier created by the Hudson River, San Francisco's bay crossings, the Potomac River in Washington, D.C., the harbor in Boston, and the Mississippi River in Memphis. All have major developments on both sides of the natural barrier. Major intracity trips share the existing capacity with through trips, which are frequently characterized by a high percentage of trucks.

Transportation problems associated with natural barriers are particularly hard to address and impossible to eliminate. The cost of constructing a new crossing can be prohibitive and yet serious congestion exists at crossings that often reach their capacities during the peak periods. The need to use an effective strategy to alleviate the problem is strongly felt by the users of the facilities. Solving the problem not only involves highways but other modes as well. Freight is neither immune from the problem nor ignored as part of the solution.

4.3.4 Radial Routes

Radial routes connecting the central city with its outlying suburbs are frequently short-of-capacity. During the early years of the Interstate Highway Program the congested older routes, typically major arterials, were upgraded to freeways. The pent-up demand for housing that existed at the end of the Second World War was satisfied by growing bedroom communities in the suburbs. The growth of the automobile population was encouraged with ever-changing models of cars.

The freeway typically offered such an improvement over the arterial throughway that it immediately attracted more travelers than it could handle, at least during rush hours. But, even with the queuing, the route was better than the alternative. The public, however, felt that the road they had waited for to satisfy their commuting needs did not actually meet their expectations. Now they wanted officials to augment the freeway with subways, so they could have the roadways to themselves. Engineers and planners analyzed what could be done to solve the problem. Some, with public support, pursued the development of subways. Others initiated studies that resulted in many of the empirical relationships embodied in the HCM concerning weaving zones, entrance and exit ramps, and supercritical flow on free-

ways. Transportation professionals experimented with widening the most congested parts, using express lanes and ramp metering, designating bus-only rights-of-way, and developing reversible travel facilities. The HOV concepts were developed and exploited as the first steps in demand management of the multimodal corridor.

Over time, a deeper understanding of the nature of this problem, and its possible solution, has emerged. Failure to solve the capacity problem is giving way to the realization that there is an endemic aspect of the problem that can never be completely eliminated. The high cost of facilities must always be traded off against the temporal demands for travel. With twice the capacity, the peak-hour commute might be half as long, but there will still be a peak hour. New facilities are being requested and new methods for reducing chronic congestion ranging from telecommuting to ITS to growth management are being sought by the public, which has become increasingly more sophisticated about the wide-ranging nature of the problem.

4.3.5 Freeway-on-a-Grid

Many of the larger urban areas in the country have constructed an entire network of freeways over what was already a rectangular grid of streets, complete with local, collector, and distributor streets and major arterials, most of which were developed in an earlier era of the city's history. The circulatory pattern of these underlying networks can, in some cases, be completely independent of the freeway overlay. In those cases, local travel can be completed without using the freeway. In some instances (such as Chicago, Boston, and Philadelphia) this transportation network even includes a subway or an elevated public transportation system. In Los Angeles, Kansas City, New Orleans, and other older metropolitan areas a street railroad once served the resident population but, as travelers abandoned the streetcars and switched to automobiles, tracks and structures were torn out.

For newer communities, especially those constructed after the freeway was completed, travel may be almost totally dependent upon the existence of the freeway. Travel of most kinds, even local trips, depends upon the freeway for access and egress. A failure of the freeway amounts to a complete breakdown of the transportation system. In these situations, there is no redundancy in the system as there is in the case where the freeway has overlaid a complete transportation network.

In many cases of a "freeway-on-a-grid," transportation planners are faced with defining corridors that include non-freeway facilities and modes beyond the single occupancy automobile. The multimodal corridor capacity problem is typified by both a concern with the definition of the problem and a conscious attempt to broaden the scope of the investigation to include all modes, both freight and passengers, long trips as well as local travel, and tradeoffs between travel at one point in time and another. The problem definition phase of this type of situation is more complex than others and the range of solutions that need to be explored can be more wide-ranging.

4.3.6 Transcontinental Intermodal Corridors

The 1993 Mississippi and Missouri River floods revealed the extent to which certain transcontinental routes are major movement corridors for freight. Local commuters and passengers on long-distance bus routes and Amtrak were affected by the floods, but the disruption to freight movements was even more widespread.

The corridor from Chicago to Los Angeles is the densest long-haul freight corridor in the nation. This occurs for a number of reasons: (1) Los Angeles and Chicago are both important cities, the second and third largest in the country, (2) they are "gateway" cities on the railroads, with very large tributary populations. Chicago serves as the gateway to the entire northeast section of the United States. Los Angeles is the gateway to California and to Asia. The major cities of the northeast region—Boston, New York, Philadelphia, Buffalo, Pittsburgh, Cleveland, and Detroit—are all served through the Chicago gateway. San Diego, San Francisco, Sacramento, and all of California's Central Valley are served through Los Angeles.

Because of the configuration of the Rocky Mountains the most favorable rail route to Los Angeles (and to the rest of California) is the southern route through New Mexico and Arizona. Trucks can (and often do) follow the same route, but because they do not interchange the traffic at specific gateway cities like Chicago, St. Louis, Memphis, and New Orleans, they have more flexibility to avoid problem areas like those affected by the floods in the Midwest.

As the flood waters advanced, more and more facilities were placed out of service. Key bridges were closed. Low-lying highways and rail lines had to be abandoned. The routes by which service was normally provided were completely disrupted. Capacity on the few remaining open lines was clearly an issue. Temporary detours were identified and placed into service to allow the various railroads to remain open. New movements were rerouted around the problem areas. Railroad and trucking management worked around the clock to identify solutions and to implement them.

This problem is not unlike the more common capacity problems that come to mind such as a congested road. Certain facilities in the network are on the route of travel for a particular set of origins and destinations. If these facilities are closed, new routes have to be found. The larger and more interconnected the network, the easier it is to find alternative routes. In such a situation, redundancy is warranted. Additional routes provide reserve capacity to the system, even in those cases where it is not used on a regular daily basis. Where capacity is greater than demand, it ensures that the

volume-to-capacity ratio does not approach the limit (e.g., 1.0), which is usually associated with unacceptable LOSs. The key to planning for uncertain events, such as the floods in the Midwest, is to provide reasonable redundancy in the system as a whole. Preserving unused capacity and providing ample interconnections within a modal system and between modes is a way to place capacity in a "bank" for that time in the future when it will be used. The floods in the Midwest are not a unique event.

4.3.7 Recreational Routes

Interstate Route 75 north and west of Denver, Colorado, carries a very high volume of traffic between Denver and Aspen and other recreational communities in the front range of the Rockies. It is also a major truck route. The route consists of I-75, some local roads, a railroad track, and air connections. During major tourist seasons, both summer and winter, traffic volumes are extremely high and subject to breakdown with the least problem. A major snowstorm has very disruptive effects on travel along the corridor. Travelers tend to be "locked in" to a given mode. If they have a rental car it becomes difficult for them to avoid using it in bad weather to travel since it must be returned to the point from which it was originally rented. Likewise, train and plane reservations, though more flexible, are difficult to rearrange because the very large number of people traveling is enough to overload these modes. Once committed to movement by automobile, a traveler may not be aware of conditions en route. Stoppages can be dangerous. Very few alternative routes exist, and tourist facilities are insufficient to deal with the volume of stranded travelers if they occur. The problem is how to deal with these situations when they happen. Additional highway capacity is both difficult and expensive to construct and is not needed on a daily basis. Air and rail capacity are difficult to integrate into the system. Trucks can be a particular problem under slippery road conditions. The multimodal corridor capacity problem is uniquely captured in this situation.

Part of the solution to this type of problem is recognizing those elements that fall outside the scope of work of the typical transportation planner. The planner is not responsible for rental cars, airline reservations, or emergency housing along the route, yet all of these things are important to a solution. The answer may ultimately lie not in building more capacity but in providing information to travelers, both those en route and those preparing to travel. The bottom line may well be that unforeseen incidents can indeed be anticipated.

4.3.8 "Ingrown" Transfer Facilities

Ports, airports, and tank farms are intermodal terminals for the transfer of both freight and passengers from one mode to another. Ports serve as the transfer points from ocean-borne movement to land-based movement. Airports serve a similar function from land to air travel. Tank farms facilitate the transfer from pipeline to rail or truck. With time these facilities, whether they are for freight or passenger, tend to become deeply entrapped in the urban area where they originated. Contiguous land uses may restrict further expansion. The facility becomes increasingly congested, which tends to reduce efficiency and increase costs. Frequently, the reduced effectiveness of the facility serves as a real capacity problem.

Finding solutions to these multimodal capacity problems can be very difficult. In many cases the facility has become highly integrated with many aspects of the local economy. Stevedores are recruited from the areas contiguous to the ports. Distributors have established warehouses in the immediate proximity of the ports. Local merchants provide needed port services and provisions including fuel, pilot services, tugboats, etc. Airports are similarly integrated with the local economy. Nevertheless the facility may be so space-constrained that it can no longer function effectively. Even if it can, it may not be able to take advantage of the current changes in technology or equipment. The runways may need to be lengthened to handle the bigger jets. The channels may need to be dredged to handle deeper draft vessels. Bridges may need to be rebuilt to allow doublestack rail equipment to be used.

Moving the facility to a new location may provide a solution in some cases. Airports have most frequently been handled in this fashion. By finding a new site for a new and larger airport the most important functions can be shifted and the functions that remain at the old site have more room to operate without congestion. For example, international flights requiring larger planes and longer runways can be accommodated. There is an implicit tradeoff, however, in moving to a new, less congested location. The tradeoff typically involves longer travel times for local travelers. Ties to the local economy are also broken and must be reestablished within the new local economy.

For other facilities, moving to a new location may be a far less desirable solution, and in some cases it may not be possible at all. When the number of organizations that use the facility is large, when both public sector and private sector entities are involved or the operations are complex, and when they involve multiple labor unions or overlapping work rules, it may be easier to expand in place than to try to move. Expanding in place, however, may not be a lot easier. This is one situation where a public sector planning authority may have a crucial planning role. By examining the situation from a multimodal perspective, the real bottleneck constraints can be identified and a wide variety of possible solutions explored. Eminent domain powers can be a key element in acquiring additional rights-of-way. Land swaps can be arranged and facilitated by government; tax concessions can ease the cost of moving for those who would otherwise find it burdensome, and changes in land use and zoning can help to facilitate the transition of the local neighborhoods that may

be affected. Expanding in place is one case where effective multimodal capacity planning can be crucial.

4.3.9 System Transfer and Reconsolidation Points

Transfer operations are important to multimodal operations. They can also be extremely important within a single mode. When viewed from the perspective of a single mode, a transfer point takes on a new, systemwide significance as a "reconsolidation" point. A reconsolidation terminal is important whenever there are economies of scale in moving multiple units in a single operation. The modern passenger airline provides an excellent example. Air service, unlike a private automobile, typically serves group movement of passengers between an airport in the region of origin to an airport in the region of destination. Since it is uneconomical to provide service from a single origin to all possible destinations on the air network, airlines tend to be organized around a hub-and-spoke system of regional, national, and international networks. An international passenger trip may consist of a flight from the origin city to a regional hub where the traveler transfers to a national carrier. The national carrier then connects to an international carrier at a gateway terminal. At the destination end the same process may be repeated in reverse.

Freight movements go through the same hierarchy of consolidation and deconsolidation of loads. The freight system that corresponds to an automobile trip is the truckload movement. Here the shipment from a single consignee is moved in a full-truckload quantity directly from the origin to the destination to a single receiver. Other freight loads go through the consolidation/deconsolidation process. Rail typically consolidates individual freight cars from any number of shippers into a train pulled by a locomotive and crew from the origin yard to the destination terminal or to a reconsolidation point. Here the cars from a single train are sorted and may be reassigned to another train to complete their trip. This reconsolidation point plays an extremely important role in the overall movement. It is frequently a gateway point where one railroad connects to another.

From a systemwide perspective, the location, capacity, and efficiency of these reconsolidation points on the network are crucial to the overall performance of the system. Proper spacing to provide the balance between regional and national service is important, as is some separation of the hierarchy. As noted in the previous section on ingrown transfer facilities, a local facility that has inherited a high-level function and become ingrown in the process may no longer function adequately in its reconsolidation role.

The air system provides a good example of an overcongested reconsolidation point. Chicago's Midway Airport in the 1960s was rapidly becoming a barrier to air travel. At that time, it was the principal reconsolidation point in the central part of the nation. Under regulations each airline had a designated system of routes and Chicago was a major interchange point between airlines. Atlanta and New York were reconsolidation points with similar congestion problems.

A new regional Dallas/Fort Worth airport was added to the system in the late 1960s, and it slowly took on the role of a major reconsolidation point as a consequence of the amount of capacity available and the lack of constraints on growth. The turning point occurred when American Airlines moved its base of operations from New York City to Dallas/Fort-Worth airport in the 1970s. It is hard to imagine the U.S. air system without this important systemwide reconsolidation point.

With deregulation of the industry in the 1970s, the rules concerning air routes changed and carriers could operate anywhere they wanted. They could literally have served every individual city-pair market if they wanted to do so. Each airline instead chose one or more major hubs, which they used as reconsolidation points for their own system. USAir, for example, has a major hub in Pittsburgh, and Trans World Airlines (TWA) operates out of a hub in St. Louis. Each of the major airlines does something similar.

The less-than-truckload (LTL) trucking system also has reconsolidation points. Like the airlines, truckers can operate over any route they choose once they apply to the U.S. Department of Transportation and are granted 48-state, general commodity operating authority. They have individually set up a system of "break-bulk" terminals at which the freight is reconsolidated. Consequently, LTL trucking has segregated itself into regional-, interregional-, and national-level carriers and each trucking firm operates on a different scale in the geographic hierarchy.

Unlike the truckers and the airlines, railroads are still confined to operating over fixed routes (typically their own tracks) so rail reconsolidation centers are confined to the gateway points at which railroads interchange traffic. Many of these reconsolidation points are also ingrown transfer points. Chicago's is clearly one of the worst. Most of the intermodal movements between the west coast of the United States and the east coast are interchanged in Chicago. Unfortunately, the ingrown nature of the intermodal terminals and the track connecting them discourages rail interconnections. Also, since the different carriers need to reconsolidate the intermodal units into different trains for delivery to the final destination, the connections between the western carrier and the eastern carrier are typically performed by truck. This degrades the level of service on the expressways in the Chicago area.

Like other multimodal corridor capacity problems, creative solutions to the reconsolidation problem are difficult to achieve. There are multiple parties involved—state and local governments, labor unions, truck and rail management, third-party equipment suppliers, shippers, receivers, and the users of the local highways as well as land owners, residents, and local merchants. Finding ways to improve this key multimodal system is important, however, and techniques that

can be developed to measure capacity and performance are key to success.

4.3.10 Central City Chaos

In the downtown sections of most large cities traffic is intense and there are many sources of delay and congestion. Parking, delivery vehicles, taxis, pedestrians, street turns, one-way streets, and transit vehicles all contribute to impeding the traveler. In most cities if there is a way to avoid traveling through this downtown area, motorists are willing to take a more roundabout path. However, for those with an origin or destination in the central city, there is little way to avoid it.

The multimodal use of the transportation system in central cities presents a particular challenge. Not only is the system complex, it is also politically charged. It is difficult, if not impossible, to remove on-street parking in many cases; merchants do not want to discourage customers from gaining access to their shops, curbside stopping to make deliveries is almost mandatory if the businesses in the downtown area are to be supplied, bus and taxi stops are difficult to eliminate or to minimize without negative effects on accessibility to and from the region, and additional space for parking is expensive to construct. Multimodal travel problems posed in the central city are difficult, yet they are present in virtually every city in the nation. Solving them must be viewed as a high priority. One key to doing this is understanding how multimodal capacity and performance can be measured.

Examining potential approaches toward mitigating the capacity problems that inherently exist in a downtown area can be useful. However, the ultimate economic functions served by a central city must be kept clearly in mind. Maximizing capacity for through travel cannot be considered a high-priority goal in most cases. Facilitating easy access and egress may well be a reasonable performance goal.

Some cities, including a number in Europe (e.g., Florence, Italy), have banned through travel. Streets are configured so that they allow access to the city center but then turn back to force exit in the direction from which entry was initially gained. Pedestrian streets encourage travel by foot within the central city. Public transit may be facilitated by a bus tunnel or a separate right-of-way. In some cities bicycles are allowed on major highways. Still in others, freight deliveries are allowed only during certain hours of the day or they may be restricted to nighttime or to underground tunnels.

In those cases where public parking is allowed within the pedestrian zone, travel can be facilitated by escalators, moving sidewalks, or in a few instances by unmanned automated vehicles. The Westinghouse sky bus system has been employed in a number of airports to good effect where distances are too long for easy access by pedestrians. In fact, it is useful to view airports and amusement parks as examples where public conveyances have been treated as "horizontal elevators." One would never think of charging a fare for the use of an elevator because it is considered as part of the overall building infrastructure. Likewise, if a central city can be viewed as a very specialized pedestrian environment, then certain public conveyances could properly be viewed as part of the infrastructure of the region and more appropriately covered in the rent charged to tenants than as stand-alone transportation units responsible for recovering their construction and operation costs.

4.4 CORRIDOR COMPONENTS

The different types of corridors and intermodal features described above provide a sense of the diversity that can be found in the conditions of corridors throughout the United States and elsewhere. However, to support a more detailed analysis of capacity and performance, a corridor needs to be broken down into its principal components. Each component may be a link or a node, as briefly described in Chapter 3, depending on whether it is a line-haul or a transfer facility. Some links are also either feeder or distribution links.

The performance of an entire corridor is more often the sum total of the performance of its individual components. If the corridor consists of only an arterial road then the evaluation may be straightforward. However, the level of detail required in studying a particular corridor also magnifies the problem. Hence there are network-level procedures that are suitable for large-scale corridors and there are very detailed procedures for project-level analysis of individual components. The approach taken for multimodal corridor analysis allows different levels of aggregation for the corridor and its components. The typical links and nodes are listed and briefly described below:

4.4.1 Links

Interstate highways—Multilane highways with full access control and are included in the federal-aid highway system.

Expressway—A divided arterial highway for through traffic with full or partial control of access and generally with grade separation at major intersections.

Freeway—A multilane divided highway having a minimum of two lanes for exclusive use of traffic in each direction and full control of access and egress. It is an expressway with full access control.

Primary system—Mostly state roads and two-lane or multilane highways with partial control of access.

Arterial road—Signalized streets that serve primarily through traffic and provide access to abutting properties as a secondary function.

Exclusive lanes/HOV lane—A lane restricted to specific types of traffic by special regulations and markings.

Commuter/rapid/light rail—Rail transit passenger service usually serving both residential communities and central business districts within cities and metropolitan areas.

Intercity rail—Freight or passenger rail service between major city pairs.

Intercity air—Air transportation service between major city pairs.

Inland waterway—Rivers or canals that carry barges and other forms of water transportation.

Pipeline—A conduit for carrying gas, liquid, or specific commodities such as coal suspended in a liquid.

Bikeway/bikelane—A path of travel designed for use by bikes, either as part of or separate from another transportation facility.

Pedestrianway—A path of travel dedicated to pedestrians, either as part of or separate from another transportation facility.

4.4.2 Nodes

Ramp—A short segment of roadway (part of an interchange) serving as connection between two traffic facilities and that usually services flow in one direction only.

Intersections—Area where at-grade roads and other facilities meet.

Bus stops—A position for a bus to pick up and discharge passengers, including curb bus stops and other types of boarding/alighting facilities.

Bus stations—Terminal facility for intercity or intracity bus transit service where passengers can either change mode or transfer to other buses.

Park and ride—Parking facility for commuter/rapid transit passengers so they can change modes from automobiles to bus or rail transit systems.

Railroad freight yard—Intermediate or terminal facility for servicing freight trains. The functions of the rail yard/terminal are to receive trains upon arrival, perform any auxiliary service, switch cars into their proper classification, and dispatch these cars in their proper position on outgoing trains.

Intercity passenger train stations—Include all facilities required for the complete accommodation of passengers and their belongings between public entrances and the trains. Included are the main building, connecting concourses, platform access, platforms, parking, and station approaches.

Commuter/rapid rail train stations—Similar to but less extensive than intercity passenger train stations because they usually accommodate relatively short trips.

Airport—All facilities including landside and airside that serve air passengers and freight and the aircrafts themselves.

Inland port—Facility for docking/berthing of barges and inland ferries/boats for the purpose of loading/unloading passengers and freight.

Seaport—Consists of piers, wharves, berths, and all facilities for servicing sea and ocean vessels.

4.5 ANALYSIS STEPS EXPLAINED

The steps recommended for corridor identification and problem definition are relatively straightforward to implement. It is useful, however, to develop them in more detail and to relate them to projects in the real world.

Step 1. Define the Study Area

The transportation networks of most urban areas are very extensive. If the study area was represented by the network detail that has become characteristic of the urban transportation planning process, it would typically have thousands of links and nodes. In many cases such detail is not warranted and can actually detract from the planner's ability to address the most relevant factors. However, it is necessary to define the limits of the study area. What states, counties, and communities should be included? Which can be excluded? How does traffic that originates or terminates outside the area of interest get included? Can such traffic be ignored entirely or should it be aggregated and treated under the category, "all other"?

It is also useful to characterize the problem with a simplified link-node network that includes those facilities that act as the principal capacity-restraining elements in the system. It may be necessary to include their approaches as well. The principal origins and destinations to be served should also be identified. Broad definitions of the origin and destination regions may be satisfactory in many cases. It is also useful to include at least the most obvious alternative route that is outside the area of interest, just so the edge of the problem can be identified.

Step 2. Identify the Type of Corridor

The typology of corridors and components described in Section 4.4 can provide a useful framework for thinking

about the problem. Knowing that a peripheral road exhibits a particular set of multimodal characteristics in one area can lead the transportation planner to question whether the same set of characteristics exists on a peripheral route in another area. Similar problems can suggest similar solutions. Certainly the analysis methods that work in one situation may be extremely helpful in another.

Methods for assessing the impacts of trucks on the capacity of the facility, techniques for measuring air pollution, tradeoffs between passengers and freight, or the maintenance requirements due to trucks are often transferable from one problem to another. Solutions that appear to increase capacity in Kansas City are likely to do the same in Cincinnati.

Step 3. Identify the Primary Modes of Transportation

Before analysis can begin, the modes that are already operating in the area should be identified, along with possible future modes. It may also be appropriate to distinguish between long-haul and short-haul freight modes, since the alternative routes available to the long-haul carrier are quite different from those open to the short-haul carrier. The long-haul carrier also responds to a different set of incentives regarding peak/off-peak travel, the use of bypasses, or the impact of tolls on the choice of route or time of travel. What is also different is the type of vehicle, the size of the load, the location of the driver's residence, and the driver's knowledge of local conditions. Finally, the round-trip nature of local travel differs dramatically from that of the through trip.

In describing the links and nodes of critical links in the network it is important to note the direction and the time of day of travel, the number of lanes and whether they are one-way or reversible, the existence of rail line-haul and terminal facilities and their ownership, the types of trains that are operated over the line and the points where they are made up and broken down, the existence of joint freight and passenger-use facilities, and the right-of-way. Also of interest are the types of land use that exist, the location of wholesale distribution facilities in the area, and the existence of particularly large manufacturing plants.

For some links and nodes in the network the potential for change will also be important. Can a lane be added to the present roadway? Can an existing lane be made reversible during the peak hour? Can a rail right-of-way be placed into dual use? Can potential rerouting of a major route avoid the capacity-deficient area altogether? Can demand be managed to reduce traffic during the peak hour? At this stage it is too early to develop a complete list of alternatives, but it is not too early to begin putting together a list of possible remedies and their characteristics.

Step 4. Determine Current Person Trips, Vehicle Trips, and/or Goods Movement

Traffic demand in the form of existing counts on the network for all modes is important in the planning process. Traffic counts may be obtained from traffic-actuated counters in the roadways, roadside counts between major interchanges, or, in the case of complex operations involving other modes, by the use of counting teams with clipboards and hand-held counters. All major movements should be accounted for. Turning movements can complicate the direction of movement unless actual ground counts exist to verify them. The counts should cover the entire peak period from before the buildup actually begins to the dissipation of standing queues. Understanding the flow on all the major routes is important, since one of the strategies for improving the situation almost certainly involves rerouting some flow over the less crowded links.

Most areas have an existing traffic counting program, covering at least the major choke points. Comprehensive counts over major facilities throughout the entire area of interest are less likely to exist. Complete counts for the specific area are rare. Depending on the nature of the problem being addressed, it may be desirable to plan to develop counts over the entire area. What is needed is a rough idea of the relative flows over the major components of the system and the variability by time of day, day of the week, and season of the year. A well-organized counting effort does not have to be an expensive undertaking. Having the knowledge that comes from the counts may well determine the success or failure of a strategy to improve capacity or reduce excessive utilization.

Step 5. Identify the Principal Generators and Attractors of Traffic

Knowing the existing flows on each link will not necessarily provide information on the flow between regions. The origin-to-destination flow matrix that underlies the traffic flow on the network is important whenever major changes are likely to be made in the network. The addition of a single link to the network at a crucial point could dramatically alter flows over the network. Only by knowing the origin and destination of the movements can this change in the flow over the network be predicted in advance. The key to linking origin-to-destination flows to flows on the network is its routing over the network during the period of interest. The urban transportation planning programs that develop minimum path routings over the link-node network and perform traffic assignment are the most common way of using this information. If the matrix of flows is not too large, it can be used to assign flows by "hand" with a map. Some knowledge of the conditions that prevail on the various links in the network will be necessary. This is one reason for keeping the parameters simple.

Developing the origin-to-destination (O-D) matrix of flows is always a problem. A travel survey of the entire affected population is extremely expensive and may not address the problem with the specificity needed. The planner is therefore left to improvise in most cases. Fortunately, the level of aggregation needed for many problems is not great. It may not be necessary to have hundreds of origins and destinations. It may in some cases be possible to work with less than a dozen. If so, the matrix of O-D flows can be developed

from the flow information on the network with perhaps a bit of outside information, such as the census population counts of a region, or county business patterns data.

Step 6. Determine the Location, Nature, and Extent of Capacity Problems

Once overall flow data are available it is important to understand the nature of the capacity problems that exist over the examined system. If the problem is a bumper-to-bumper traffic condition during the peak periods, which breaks down into standing queues when rain, snow, or a minor traffic accident occurs, then it is important to know which sections are the most prone to breakdown. How often does the breakdown occur? What seems to trigger it? If the problem is queuing over a bridge or at a toll facility, it is useful to know where the queues first appear and at what point in the buildup they begin to occur. What spillover effects are there? Do queues develop on one link first and then "back up" the access ramps and affect other routes?

For freight facilities, is the capacity problem occurring at the terminal or on the line-haul portion of the route? Are there problems with particular types or particular sizes of equipment? How does the problem manifest itself? Is there a visible queue, or does it show as a service or performance problem? How does the problem affect costs? What are the shipper/receiver alternatives—another carrier, another mode, another time of day? It is important to observe the system intently and to understand the full nature of the problem and the tradeoffs that are involved.

Determining the consequential impacts of the lack of capacity on air quality, pollution, noise, and other external costs may take additional data collection. Alternatively, the impacts may be estimated from models developed by prior research in external costs. Emissions, for example, are well known for many types of vehicles operating under a variety of conditions. Models that can develop the total emissions may be available. Hazardous situations that are the consequence of particular environmental conditions are more difficult to predict, such as dense fog caused by local industries under certain atmospheric conditions. Nevertheless, observance of these special consequences of the capacity deficit could be important to a successful overall conclusion to the study.

Step 7. Examine Trends in Person Trip and Goods Movement Growth

Most planners recognize that traffic growth in transportation systems is inevitable. Even highly congested systems continue to grow. Planning for this growth is the principal charge of most planning agencies. However, it is important to recognize from the outset that land use affects traffic volumes, which in turn affects land use. Not only is periodic growth important, but understanding how the provision of capacity seems to generate additional traffic should be kept in mind. The fact remains that other conditions for growth and development have to be right before land development will actually take place. It is important to remember, however, that the lack of transportation capacity may be the only missing link.

Long-term periodic growth has been characteristic of most sectors of the U.S. economy and most regions of the country. It may then be useful to compute traffic growth on the facility at this long-term growth rate (2–4 percent) and to try and understand the implications for increased flow over the facility. Since, by definition, this flow is constrained during peak periods to the maximum capacity of existing facilities, the long-term impact of this growth will likely be a lengthening of the peak periods. It is useful to ask which types of traffic will be most affected. Which sectors of the economy will be most heavily influenced? Which growth is likely to be curtailed? Who gains and who loses?

Since future conditions cannot be known with certainty, growth rates are difficult to predict with any accuracy. Consequently, forecasting is an imprecise art. It is still useful to plan as long as it is done within ranges and its uncertainty is known and appreciated. Using both a high and a low range for growth allows a variety of alternatives to be considered. It also allows the impact of these two extremes to be understood in terms of future income streams, cost-benefit impacts, and/or most favorable and least favorable outcomes.

Step 8. Identify Any Constraints to Capacity Expansion

The reason there is a capacity problem in the first place is because there is usually a constraint to capacity expansion. This may include a natural barrier, such as a river, a mountain, or a coastline, or it may be caused by the need to maintain high capacity over a continuous facility in a high-cost environment. The reason a peripheral route becomes a capacity constraint, for example, is that once the facility has been constructed with a given number of lanes it becomes extremely expensive to add more lanes to any significant portion of the entire ring road. If only selected sections of the peripheral highway are widened, the capacity of the facility as a whole is still constrained by the "weakest link." The expense is magnified by the high cost of land in an urban area and by the disruption to other infrastructure that would be occasioned by a widening of the basic facility.

One must note that environmental or historical concerns are costly only because society has chosen to make them expensive by placing legal or bureaucratic obstacles in the way of their removal.

Step 9. Develop an Initial Set of Alternatives for Dealing with the Problem

It may be hard to come up with any satisfactory final solution to the multimodal corridor capacity problem even after the study is completed. The purpose of this step, however, is to stretch the minds of the study team to include some of the

most obvious solutions regardless of cost. In the case of a natural barrier, for example, it is useful in most cases to understand the approximate magnitude of the cost of a new crossing, a new bridge, or a tunnel. This cost may be in the billions of dollars. It is also useful to understand the cost to the user of using the first alternate route that completely avoids the problem area by going around it or the cost of using demand management strategies. This brackets the solution between the most extreme limits—the higher cost being the long-term capital cost of a new crossing and the lower one being the user cost of going around the capacity-constrained area or suppressing demand if practical. All other alternatives should fall somewhere between these two solutions.

It may be helpful to note that the capital cost solution is a long-term solution. The costs will be amortized over 20 or more years. If the funds are raised with bonds, the payments to retire these bonds will be paid back over many years. The short-term solution is paid for now, that is, each trip is paid for as it is made. Note that the capital cost is likely to be a public cost borne by the public at large through some government agency, the state, the city, or a public authority. In contrast, the short-term solution is paid for privately by the individual user.

Step 10. Summarize with a Brief Written Statement of the Problem

Capturing the essence of the problem in a concise written statement is a very important part of seeking a solution in a pluralistic society. Individuals come to a problem with their own points of view and their own biases. By framing the problem properly, the study team attempts to lay the ground rules underlying the public debate that will accompany discussion of the problem. Those who see the problem entirely differently are free to offer their views. In many instances it may be important to redraft the original problem statement to include the new ways of looking at the problem. Note that at this point in the process, no solutions have yet been advanced. The entire effort, so far, has been directed toward obtaining one concise statement of what the problem is. Once available, it is often easier to find the compromise solution or better yet, although it is not easy, the Pareto-optimal solution (i.e., that solution whereby no one party is worse off than they were before the project was initiated, and some may be better off).

4.6 CASE STUDY CORRIDORS

The procedures and concepts described in the previous sections are applied to the following four case study corridors:

1. New York metropolitan area river crossing corridor;
2. Altamont corridor in Oakland, California;
3. North-south corridor in Seattle, Washington; and
4. East-west corridor in Madison, Wisconsin.

These case studies illustrate for specific corridors how to define the scope of a corridor capacity analysis and how to identify the core problem and preliminary solutions.

4.6.1 The New York Metropolitan Area River Crossing Corridor

In late 1992 the New York State Urban Development Commission, in cooperation with the New York State Department of Transportation, and the Port Authority of New York and New Jersey, began the evaluation of a project that involves freight transportation in a highly congested corridor in the New York metropolitan area (NYMA). The project, the Oak Point rail link, involves constructing a new rail connection that for the first time will allow intermodal traffic to access new rail intermodal facilities located on the east side of the Hudson River. The east side area is currently served from intermodal facilities located in northern New Jersey. Since 65 percent of the population and 73 percent of the employment in the NYMA are located east of the Hudson River and since the corridor currently handles more than 312,000 vehicles per day (each way) this appears to provide an opportunity to reduce congestion and increase capacity over what is a major natural traffic barrier—the Hudson River. This will happen only if the project can successfully attract existing truck traffic off the Hudson River crossing.

Note that the project is directed not toward the slightly different and broader question of what can be done to increase the overall capacity of all the facilities crossing the Hudson River by all modes (i.e., commuter trains, ferries) but toward the more limited objective of examining the implications of removing truck traffic from the crossing by diverting it to an alternate route that avoids the problem area entirely.

Step 1. Identify the Study Area

The geographical area of interest, shown in Figure 4.1, extends out from the rail facilities on the eastern side of the Hudson River—principally, Oak Point on Conrail, Harlem River Yard, Fresh Pond on the Long Island Rail Road, and Bay Ridge on the New York Cross Harbor Railroad (NYCHR)—to all the areas tributary to these facilities. This includes Manhattan, the entire extent of Long Island, the Bronx, and adjacent counties in both New York State and Connecticut. These areas would all benefit from direct intermodal service to the east of the Hudson River from certain regions in the rest of the United States. The area to the west of the Hudson River is also of interest, first and foremost because this is where the facilities are located that currently serve intermodal shippers, but also because there are warehousing and wholesale distribution facilities that serve the east side of the Hudson River from New Jersey and Staten Island.

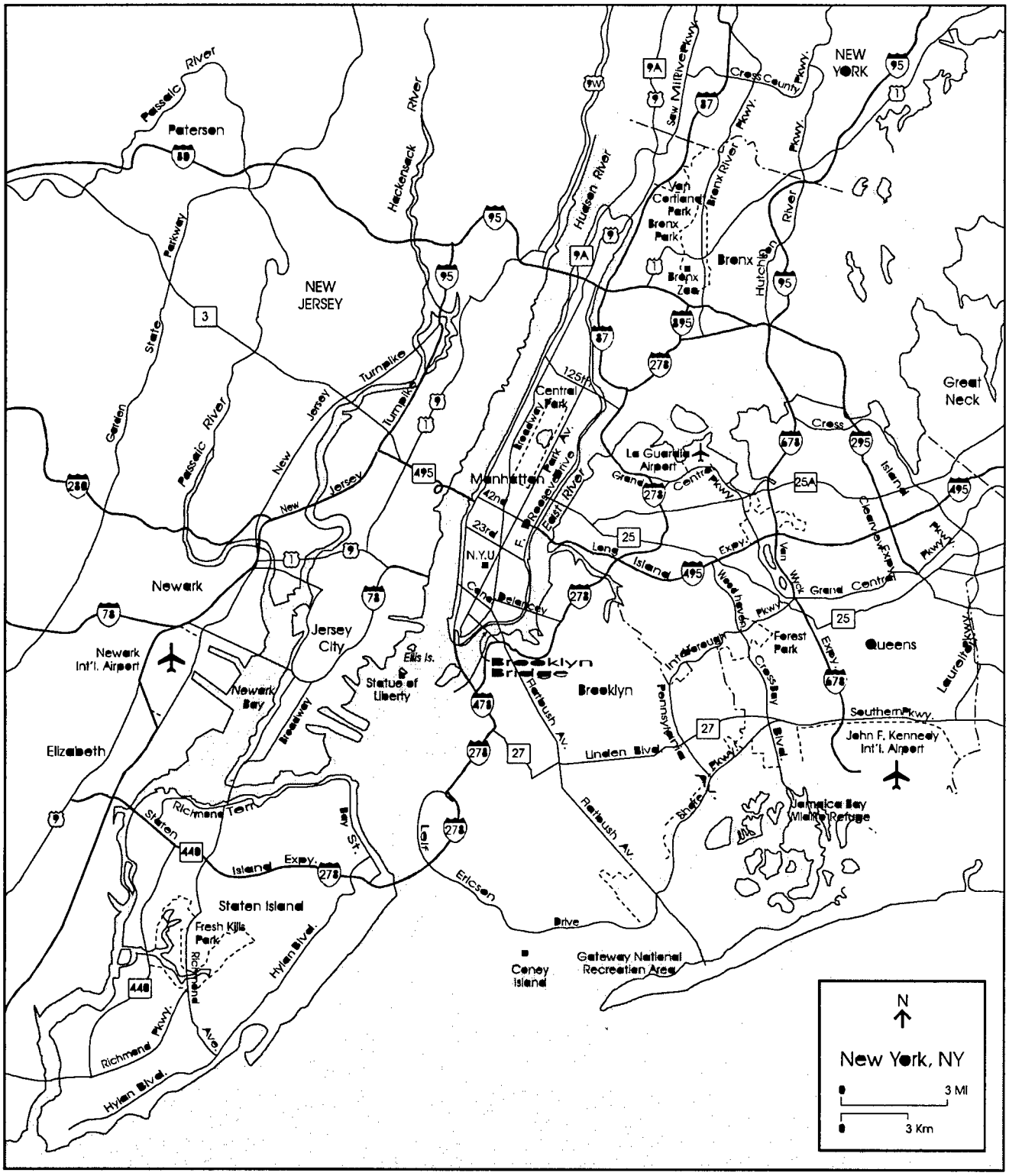

Figure 4.1. Study area: New York metropolitan area.

The existence of the Port Authority O-D truck survey presented the ability to assess eastbound traffic flows to and from 29 counties in the region, as well as business economic areas beyond this one. The counties of interest include all 14 of the counties in northern New Jersey, 12 counties in New York State, and 3 counties in Connecticut.

Step 2. Identify the Type of Corridor

The corridor type is clearly one in which the Hudson River forms a natural barrier between the urban areas on both sides of the river. The waterway provided a valuable means of transportation for both passengers and freight, but as the urban areas developed and the use of rail and automobile proliferated, the Hudson River became more of a barrier than a highway. The size of the region and its importance both economically and historically would constitute a major barrier to through traffic even if the river did not exist as a constraining factor.

Step 3. Identify the Primary Modes of Transportation

The NYMA is geographically complex and the roads, railroads, bridges, and tunnels serving the area play a key role in both mobility within the area and in the region's connection with the rest of the world. The connections across the Hudson River, however, are quite simple; four highway connections are shown in Figure 4.2. Within the area the only direct rail connection from the west is through the Penn tunnel operated by Amtrak exclusively for the use of passengers. The NYCHR provides float service for railroad cars from their Greenville float facility in Jersey City to the 51st Street terminal in Brooklyn, but this has not attracted intermodal service to date. The Poughkeepsie railroad bridge, which was the first railroad crossing of the Hudson River up from its mouth, burned down in 1953 and has not been rebuilt. The next railroad crossing is at Castleton, New York, some 120 miles to the north of New York City. There is also the PATH commuter line operated by the Port Authority. Consequently, intermodal service into and out

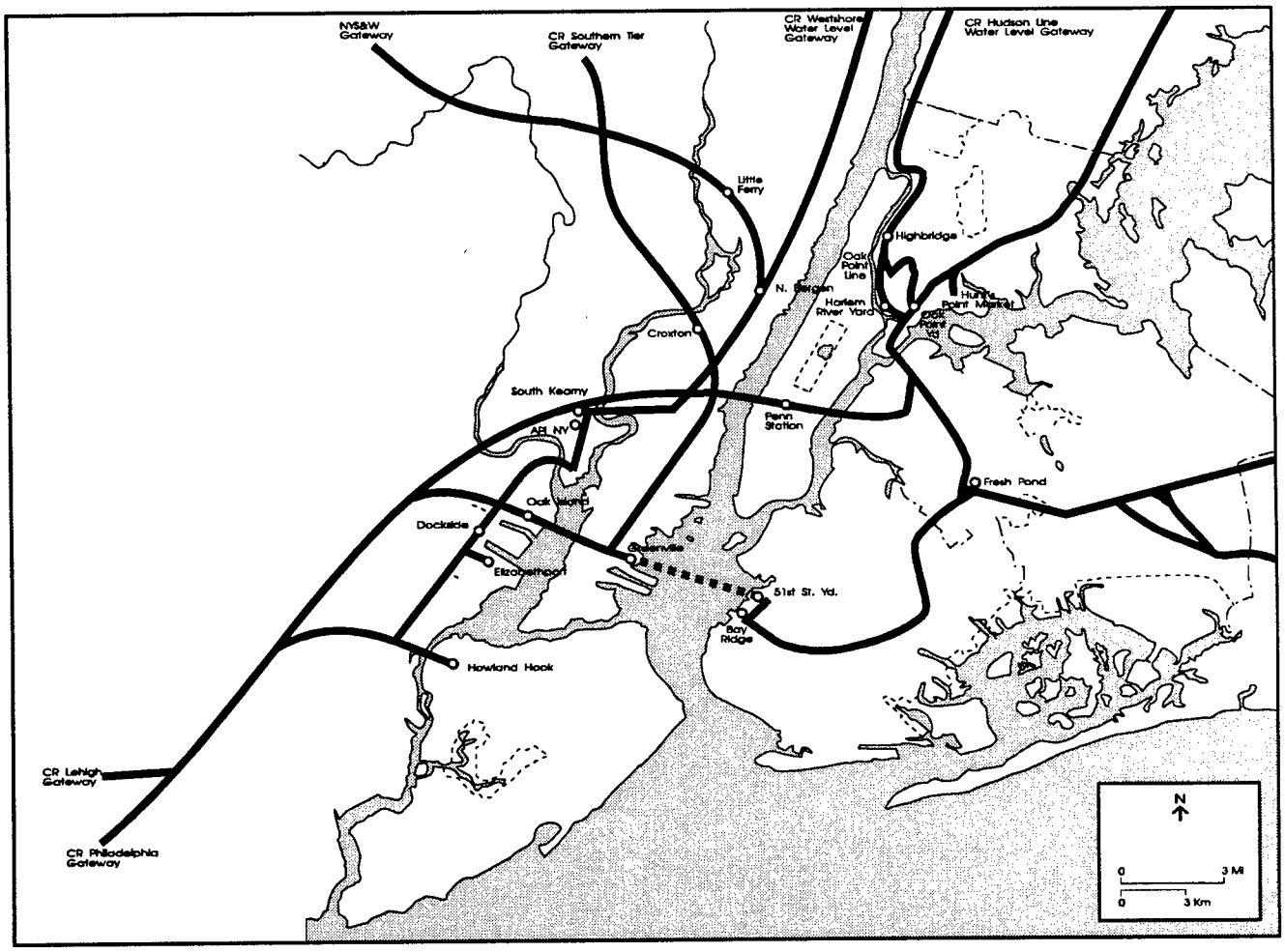

Figure 4.2. Intermodal facilities and their routes of access to/from the region.

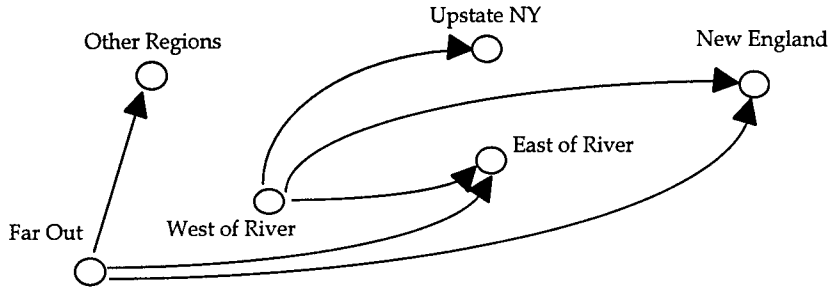

Figure 4.3. Traffic flows in the New York metropolitan area.

of the area is provided by intermodal terminals located in New Jersey.

It is difficult to access the area by truck. The two tunnels leading into Manhattan from New Jersey (the Lincoln and the Holland Tunnels) have restricted overhead clearances. The traffic flows can be represented in a simple link-node diagram as shown in Figure 4.3.

Step 4. Determine Current Person Trips, Vehicle Trips, and/or Goods Movement

The four highway connections across the Hudson River carry a high traffic volume of automobiles, trucks, and buses with commuters and freight that is surprising to travelers from other sections of the country but is an everyday occurrence to New Yorkers. Regarding the transport of freight in this corridor, approximately 50 percent of the trucks are "small" trucks, generally associated with short-haul movements, and the remainder are "large" trucks, which are involved in a majority of the long-haul movements.

Unfortunately for both commuters and truckers alike, the peak hours on the bridges and tunnels leading into New York City from the west coincide closely with the times when intermodal trailers are available for pickup by drayage agents. The hours also correspond with the delivery times of the drivers who pick up their loads in Chicago but are unable to make delivery on a 24-hour schedule. Usually, the drivers stay overnight west of the river and deliver their load early the next morning. Most long-haul trucks that originate more than 800 miles west of New York find themselves in this position. In Table 4.1, daily traffic demand has been quantified for eastbound movements across the Hudson River from New Jersey.

Step 5. Identify the Principal Generators and Attractors

The portion of the metropolitan area east of the Hudson River is larger than that west of the river both demographically and economically. For the 29-county region, slightly more than 64 percent of the population lives east of the river, and almost 75 percent of area employment is there. About 59 percent of manufacturing employment, 61 percent of wholesale employment, and 62 percent of retail employment is east of the river. When viewed in terms of the number of establishments, more than 65 percent of all businesses that are manufacturers, wholesalers, and retailers is found east of the river.

For the area as a whole, manufacturing employment has declined in absolute terms by more than 21 percent since 1975. The same trend, however, can be observed at the national level. For the country as a whole, manufacturing has dropped as a percentage of total nonfarm employment from 24 percent in 1975 to 17 percent in 1990. As a percentage of total employment, manufacturing has declined 27 percent in the same period. The decline in the manufacturing base has been more pronounced east of the Hudson River than to the

TABLE 4.1 The 1991/1992 Hudson River crossings

Crossing	Trucks	Other Vehicles	Totals	Percentage Trucks
GW Bridge beyond Manhattan	13,050	63,500	76,550	20.55
GW Bridge into Manhattan	600	54,950	55,550	1.09
Lincoln Tunnel into Manhattan	700	6,775	7,475	10.33
Lincoln Tunnel beyond Manhattan	2,550	41,250	43,800	6.18
Holland Tunnel into Manhattan	2,100	11,875	13,975	17.68
Holland Tunnel beyond Manhattan	1,350	25,800	27,150	5.23
Verrazano Bridge to Long Island	5,289	82,711	88,000	6.39
TOTALS	25,639	286,861	312,500	8.94

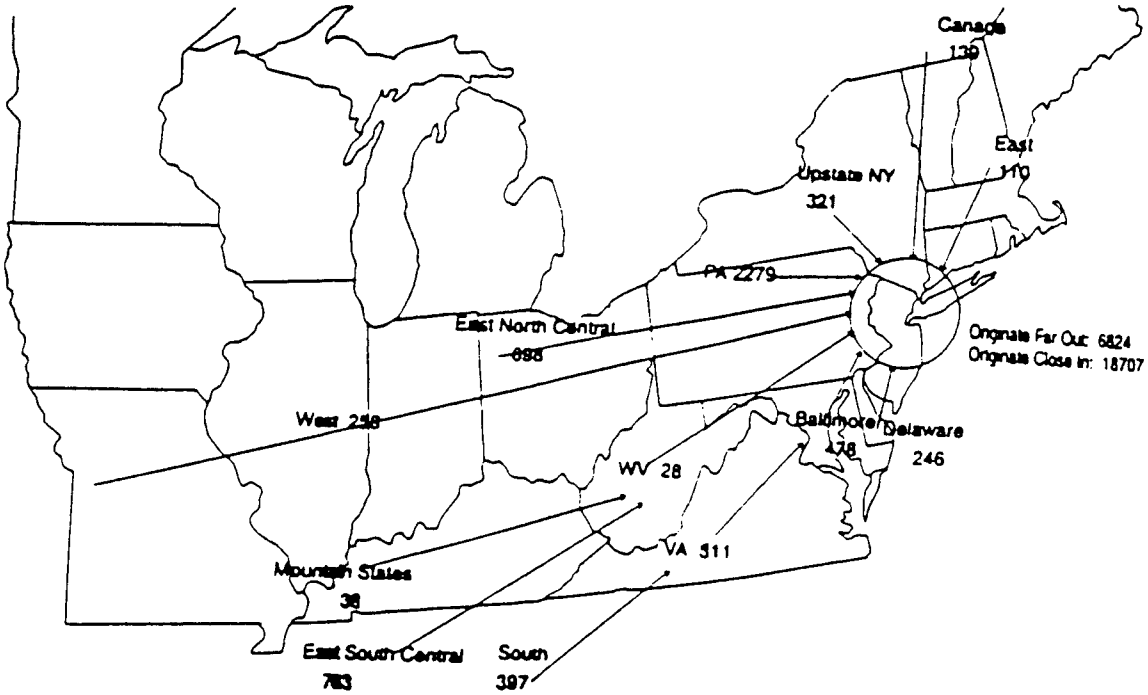

Figure 4.4. Origins of long-haul trips in the study area.

west. The major employment gains have been in the services, government, and construction sectors. The region is increasingly becoming a consumption economy. This trend tends to focus attention on the wholesale sector as a major receiver of inbound freight.

The Port Authority survey shows the origins of truck trips in two categories, long haul and short haul. Short-haul trips originate in New Jersey; long-haul trips are all others. Some 18,707 trips of the 25,531 trips in the survey are classified as short haul. Another 6,824 originate in long-haul markets. The origins of the long-haul trips are shown in Figure 4.4.

Not all of the long-haul traffic terminates in the study area on the east side of the Hudson River. Of the 6,824 vehicles involved in long-haul movements, only 4,303 terminate in the area of interest. Some 2,252 terminate in New England and 269 terminate in upstate New York or in Canada. Regarding the short-haul movements, approximately 14,528 of the 18,707 trips that originate west of the Hudson River terminate on the east side. For the 18,831 truck movements that terminate in the area of interest, 60 percent supply manufacturing demands; the remaining 40 percent satisfy whole-sale/retail demands. The truck flows are detailed in Figure 4.5.

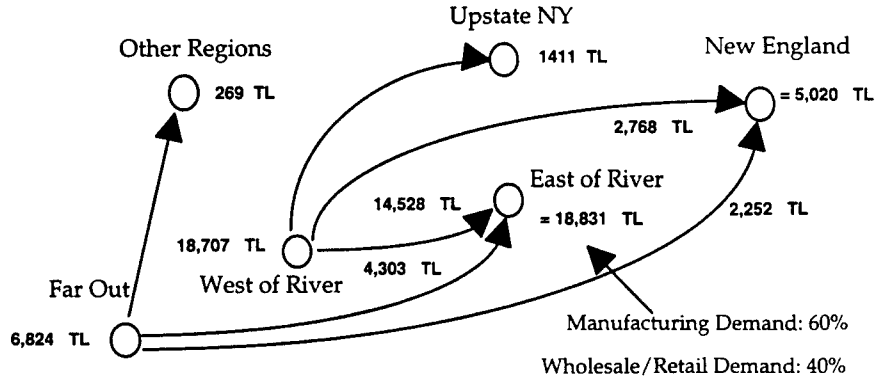

Figure 4.5. Truck flows in the study area.

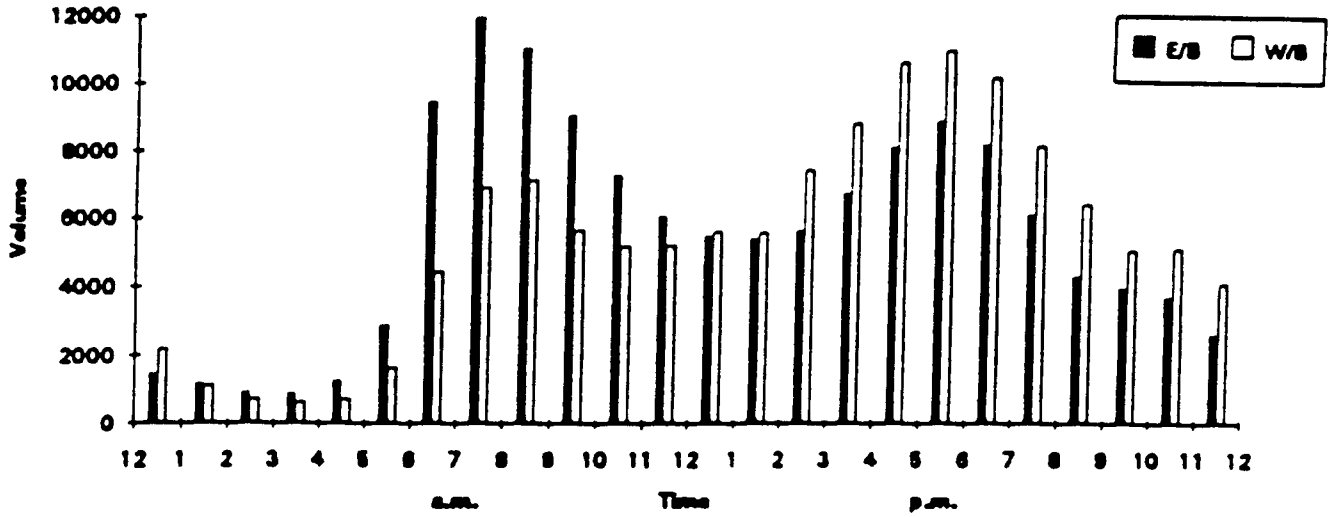

Figure 4.6. Twenty-four-hour vehicular volumes on the George Washington Bridge (NY).

Step 6. Determine the Location, Nature, and Extent of Capacity Problems

Congestion on the bridges and tunnels crossing the Hudson River and on the approaches in New Jersey leading to these facilities have long been a major constraint to continued economic development in the NYMA (see Figure 4.6 for traffic volumes on the George Washington Bridge). The capacity problem exists because numerous radial routes channel into relatively few barrier crossings. Figure 4.7 shows that there is really no time during the day when traffic into and out of Manhattan is not heavy. In fact, for 18 hours of the day the traffic volume is more than 50 percent of that found at the peak hour. The traffic that is unable to cross at the peak hour has, over time, spread further and further into the nonpeak hours.

The situation in the New York area is unprecedented in terms of the total, 24-hour, volume-to-capacity ratio that is observed on the facilities crossing the Hudson River. For the Port Authority facilities, which include the George Washington Bridge, the Holland Tunnel, and the Lincoln Tunnel, the total eastbound average daily traffic volume is 230,745 vehicles. The total eastbound capacity of the three facilities was estimated by taking the peak-hour traffic on each and multiplying by 24 hours. The volume-to-capacity ratio computed by this method is 49 percent. The 24-hour volume-to-capacity (v/c) ratio for most other cities with constricted crossings rarely exceeds 30 percent.

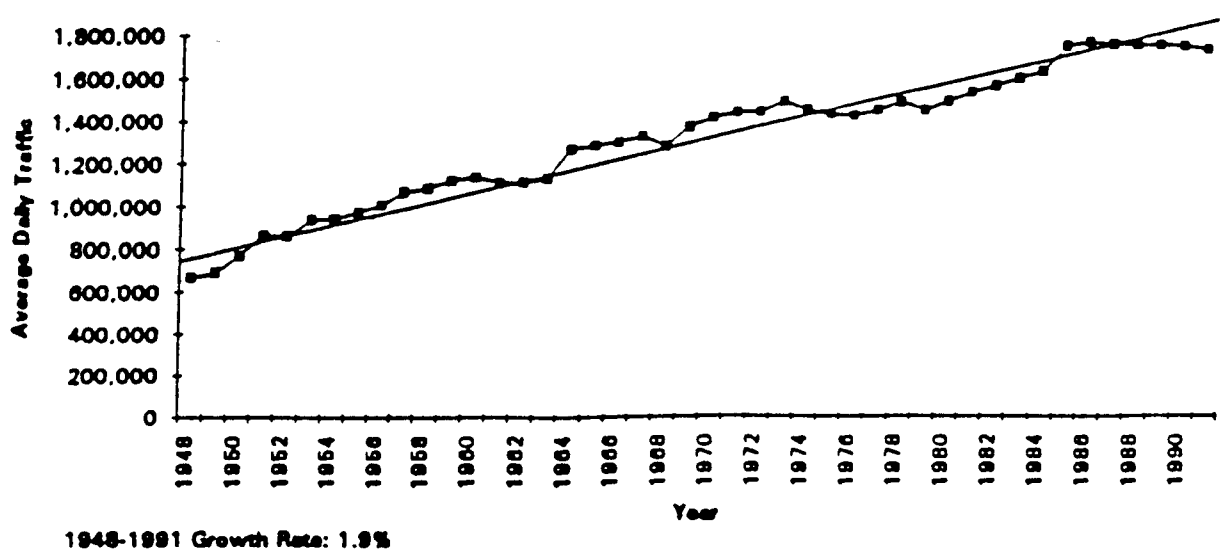

Figure 4.7. Average daily traffic volumes on all Manhattan crossings (NY).

Step 7. Examine Growth Trends in Person Trip and Goods Movement

Traffic into and out of Manhattan has been growing relatively steadily since the end of the Second World War at about 1.9 percent per year. At this rate, one traffic lane would need to be added about every 10 years just to maintain the same service levels. The cost of adding an additional lane across the Hudson River is prohibitively expensive. The last addition was the second level to the George Washington Bridge. It cost almost a billion dollars to add six lanes—which translates into a daily principal and interest payment of $55,000. If this cost had to be borne entirely by the trucks using it during the peak hours, the cost per vehicle would be $55.00. This ignores the cost of other streets and bridges in the system.

Step 8. Identify Any Constraints to Capacity Expansion

The Hudson River, a natural barrier, is the major constraint to capacity expansion in the NYMA. Due to the river's depth and to the fact that it is the location of a major geologic fault zone, the construction of new facilities, either bridges or tunnels, is complicated and prohibitively expensive. In addition, the rights-of-way needed for the location of new facilities, whether they be bridges, tunnels, or roads, is high priced, a factor that further inhibits expansion projects.

Step 9. Develop an Initial Set of Alternatives for Dealing with the Problem

There are many alternatives that could potentially ameliorate congestion. These include extremely expensive construction of a new Hudson River crossing, congestion pricing, and application of advanced traveler information systems targeted at commercial vehicle operations. However, the option highlighted here is the following:

> If 500 trucks could be diverted to a new intermodal service east of the Hudson River, virtually all of the trucks involved in this movement would be removed from the morning peak hour. A similar phenomenon would occur in the outbound direction at the time of the outbound peak. The extent of the impact on total volumes is rather remarkable. Diverting 500 trucks to intermodal would have an effect which is substantially larger on congestion than 500 automobiles because each truck is equivalent to about 6 automobiles in terms of its impact on the traffic congestion. The 500 trucks are equivalent to almost 3000 automobiles. At 20 miles per hour, the capacity of a single traffic lane is approximately 1,600 autos per hour. The 500 trucks spread over 3 hours are equivalent to an entire additional lane of automobile or bus traffic.

Step 10. Summarize with a Brief Written Statement of the Problem

The NYMA is a region of great importance in economic, geographic, and demographic terms. Therefore, the efficient and reliable movement of people and freight is critical. The Hudson River, once valued for its utility as a water highway, now poses several challenges regarding the movement of persons and goods into and within the region, and it is a barrier to continued economic growth. About 64 percent of the population lives east of the Hudson River and an even greater portion of area employment is located there. Hudson River crossing capacity is constrained because numerous radial routes in New Jersey channel into a relatively few number of river crossings. The New York area is unique, not only in terms of the magnitude of the volume-to-capacity ratios on facilities such as the George Washington Bridge but also in terms of the persistence of heavy traffic volumes into non-peak hours. This example, and the approach taken, is limited to a freight modal tradeoff on a single facility, but the framework established in this chapter can be extended to an evaluation of all the facilities and related modes and the uses of each.

4.6.2 The Altamont Corridor in Oakland, California

This case study highlights the need for truck access to and from the East Bay region of Oakland, California, particularly via I-580, known as the Altamont Pass. This case study also includes highways that feed I-580—most important of these are I-880 and the San Francisco Bay crossings.

This example draws upon travel information from three sources:

- The *1992 I-880 Intermodal Corridor Study* (*1*) prepared by Caltrans in cooperation with Alameda County;
- The *September 1994 MTS Management Strategy Corridor Profile: Oakland to Fremont Corridor* (*2*); and
- The *County Business Patterns* (*CBP*) data for Alameda and the surrounding counties to develop an overall picture of freight movements into, out of, and through the region.

The utility of the CBP data was extended by developing an estimate of the freight flows into and out of the businesses in each 4-digit standard industrial classification (SIC) category. Retail flows are developed from the national income and product accounts using the final demand vector of the national input-output table.

The area is of interest for a number of reasons. First, the region serves as a major distribution hub for the West Coast. It is centrally located between Los Angeles to the south and Seattle/Tacoma/Portland to the north. Second, the port of Oakland is a major port, served by three major railroads, and is a point of entry and exit for growing trade with the East Asian Pacific Rim nations. Finally, the region is a major manufacturing center with a very large population base. Sev-

eral industries are located in the East Bay area served by the corridor, and hundreds of secondary service, manufacturing, and distribution industries are attracted by the area's strategic location and large population.

Step 1. Identify the Study Area

The geographical area of interest includes the east-west corridor of I-580 between the San Francisco Bay Area and the San Joaquin Valley (see Figure 4.8). The Altamont Pass through the Diablo range of mountains is important because it is the only direct connection between the Central Valley of California and the Bay Area. The Altamont corridor provides one of the two interstate connections between the Bay Area and the cities of Sacramento, Stockton, and Modesto, all located along I-5, the principal north-south route in California. Access to the Central Valley from the southern end of the San Francisco Bay region using California Route 101 is more circuitous and difficult and there are no major cities at the point where this route finally joins I-5. Furthermore, since I-5 crosses I-80 at Sacramento, the intersection of these two routes becomes a major staging point for freight interchange and a good place to locate distribution centers, manufacturing plants, and agricultural processing facilities. Consequently, the eastern end of the Altamont corridor becomes an important point for originating and terminating freight.

The Union Pacific, the Southern Pacific, and the Santa Fe railroads all have north-south and east-west lines that intersect in the region to the east of the pass. These interchange points have become important junctions on the railroads. The Union Pacific, for example has located a new major intermodal terminal in Lathrop. This terminal is located so that intermodal movements to and from the port of Oakland can be combined with other traffic originating throughout the region to build trains bound directly for the east. This tributary area includes the cities of Sacramento, Modesto, and Stockton as well as other cities in the East Bay. Lathrop, then, becomes a major origination and terminal point on the railroad, and the area around it becomes a prime place to locate distribution centers that serve portions of the West Coast. The same phenomenon takes place for trucking movements.

The study area also includes the I-880 corridor from Oakland to San Jose, Alameda County, and the other eight counties of the San Francisco Bay Area region. The area covers four toll bridge crossings—the Richmond-San Rafael Bridge, the Bay Bridge, the San Mateo Bridge, and the Dumbarton Bridge—and supports a major port, the downtowns of several local communities (including Oakland and Berkeley), a major university, the industrial and distribution base of the region, and a residential population tightly constrained by San Francisco Bay on one side and coastal mountains on the other.

Step 2. Identify the Type of Corridor

The corridor type is clearly one in which natural barriers channel flows into a constrained region. The two major barriers are the mountains between I-880 and I-680, which constrain travel between Oakland and points to the east, and the bay between San Francisco and Oakland. The Altamont Pass, which serves as a gateway from the Central Valley to the Bay Area, is the area's most heavily traveled truck route. This corridor is constrained by the mountains between I-880 and I-680. Moreover, north-south travel through the region is constrained by a heavy population along the corridor. Only the southern portion of the corridor is expected to have any significant growth in population or employment over the next 20 years. Overall growth in demand for interregional movement, however, is likely to continue to cause growth in traffic volumes that would like to use the facilities.

Step 3. Identify the Primary Modes of Transportation

Trucks, vans, and passenger cars on I-580, I-880, and the bay crossings are among the primary modes of transportation. Since truck traffic is the focus of this case study, the other highway modes are mainly of concern for the congestion and delay they cause to truck traffic. As mentioned earlier, the Union Pacific, the Southern Pacific, and the Santa Fe railroads all have north-south and east-west lines that intersect in the region east of the Altamont Pass. The Union Pacific has a major, new intermodal terminal in Lathrop.

Much of the truck traffic feeding I-580 flows along the I-880 corridor (Figure 4.9). I-880 extends from Oakland to San Jose and provides access to the four San Francisco Bay crossings. The connections across the San Francisco Bay are quite simple; there are only four highway connections shown in Figure 4.9. Route I-80 provides access from Solano County. In addition to I-880, other north-south freeways include I-580 in the northern portion of the study area and I-680 in the south. The east-west freeways include I-980 and I-238 between I-580 and I-880, and State Routes 84 and 92 west of I-880. The arterial systems of East 14th Avenue/Mission Boulevard, Hesperian Boulevard, and Alvarado Boulevard serve important roles for north-south access.

The Fremont-to-Daly City and Fremont-to-Richmond Bay Area Rapid Transit (BART) lines are in the eastern portion of the corridor. There is also ferry service across the bay. Three Amtrak trains run daily on the western portion of the corridor between Sacramento, Oakland, and San Jose. The Southern Pacific Transportation Company has a right-of-way through the area, and the intermodal facilities of the port of Oakland and the Oakland International Airport are in the northern portion of the study area. Both Southern Pacific and the Santa Fe Railroad serve the ports in the region with access through the region along different rights-of-way.

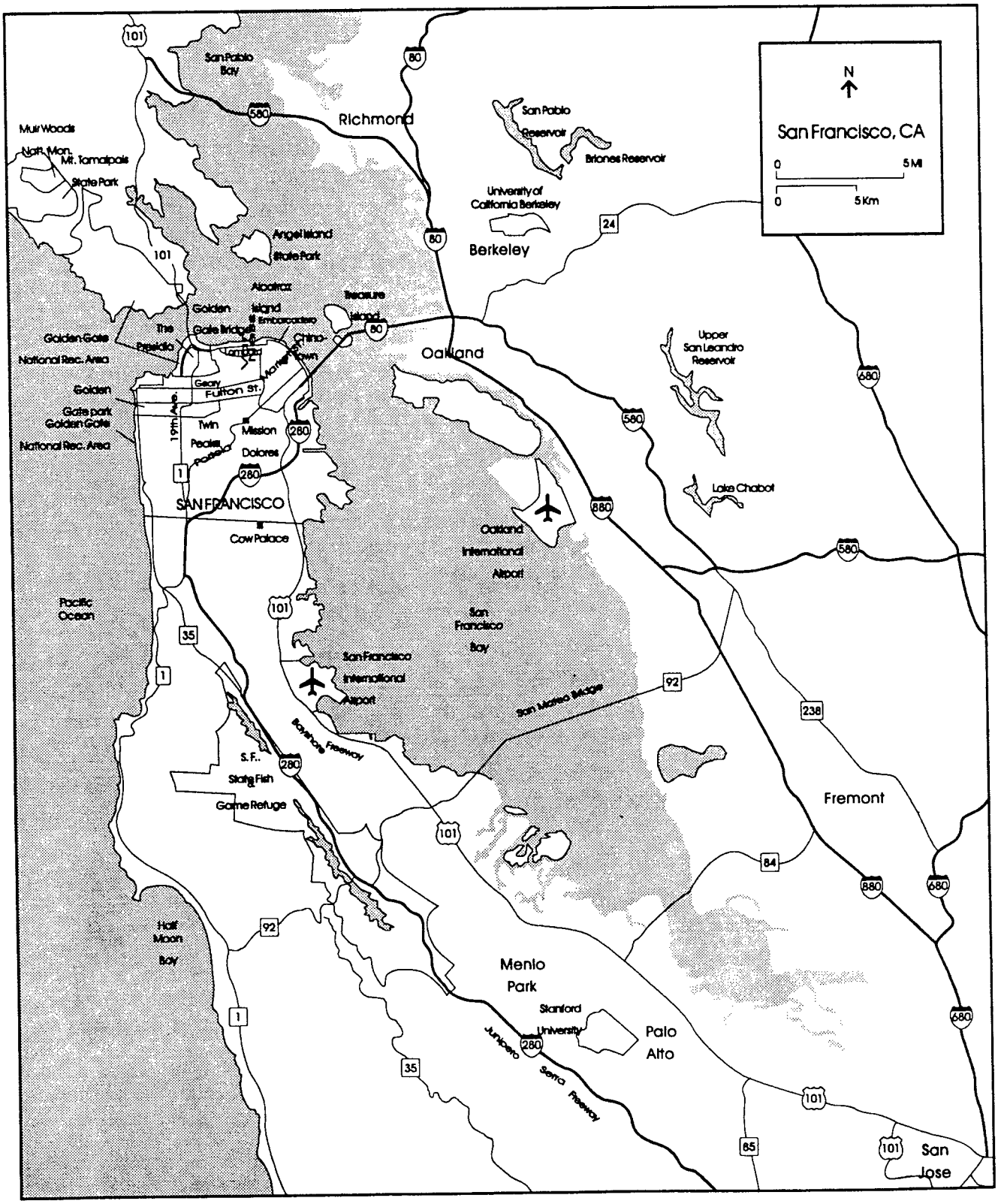

Figure 4.8. The Altamont Corridor study area (Oakland, California).

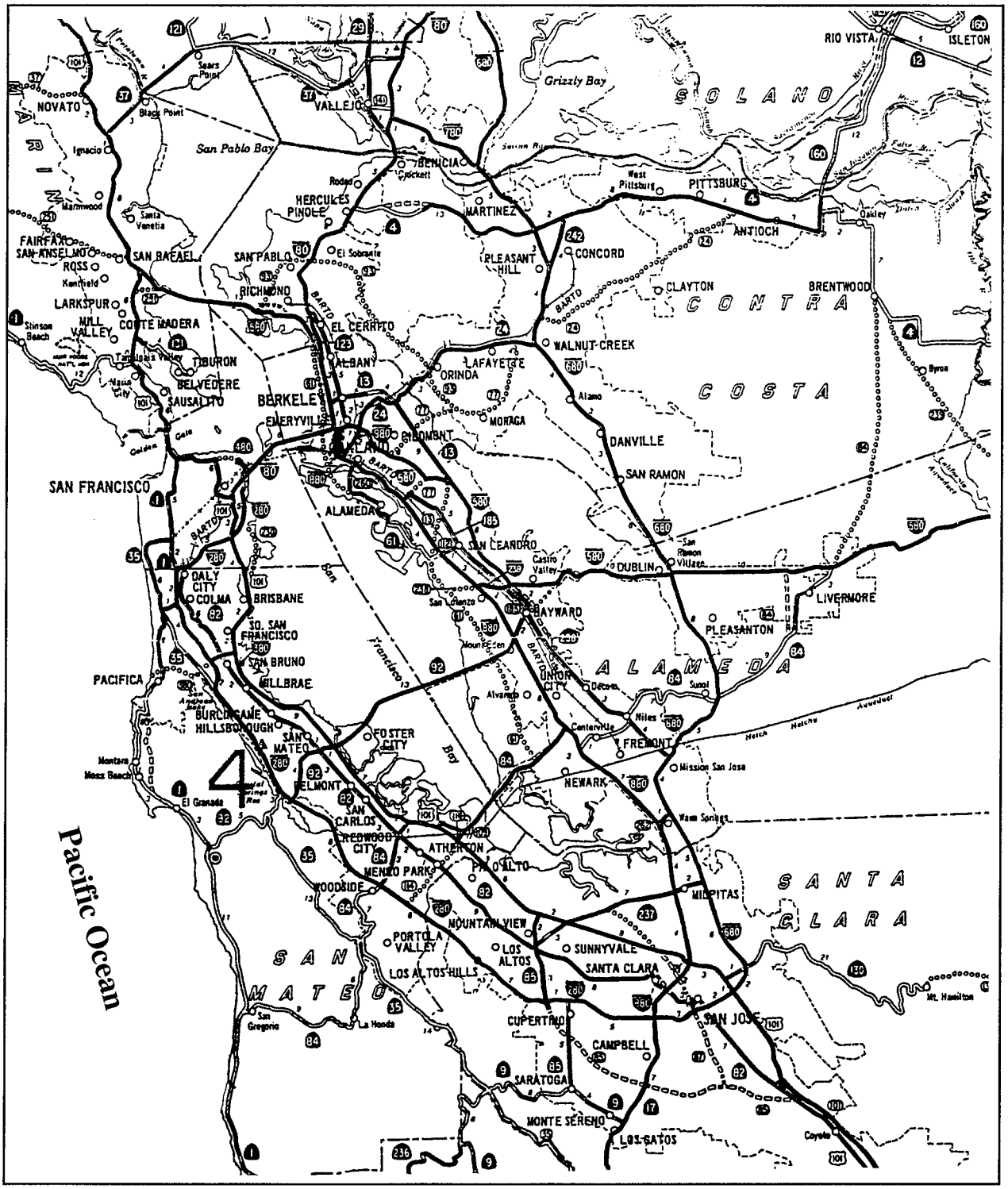

Figure 4.9. Intermodal facilities and their routes of access to and from the region (Altamont Corridor).

Step 4. Determine Current Person Trips, Vehicle Trips, and/or Goods Movement.

Traffic headed over the mountains on I-580 is heavy in both directions. Much of the traffic feeding over I-580 flows along the I-880 corridor where there is no dominant north-to-south or south-to-north flow during the peak periods. The peak direction does vary by segment with the dominant flows being northward in the morning peak in the northern segments and southbound in the southern segments. The central segment is heavy in both directions with considerable traffic from I-580 westbound to the San Mateo Bridge via SR-92 or I-238 and I-880.

Nearly 7 percent of the vehicle miles traveled in the 10 counties of the study area are truck miles. The greatest por-

tion of truck miles occur in Alameda and Solano counties. Caltrans reported the following statistics for traffic volumes along the Altamont Pass for 1993:

- Average daily traffic (ADT) through the pass—103,000 vehicles/day;
- After Livermore—145,000 vehicles/day;
- Before the I-680 interchange—164,000 vehicles/day;
- After the I-680 interchange—134,000 vehicles/day; and
- Maximum volume at I-238 interchange—145,000 vehicles/day.

The 1991 Barton-Aschman study counted trucks at a point just west of Greenville Road in the westbound direction. It found that truck traffic averaged between 20 and 22 percent daily. Over half of that truck volume was from trucks with four or more axles.

On I-880, the greatest concentration of truck travel is in Oakland at High Street. The largest traffic volumes occur in San Leandro and the junction of Route 238. *Table 4.2*, which is adapted from the December 1992, *I-880 Intermodal Corridor Study* (*1*), shows 1989 annual average daily traffic (AADT) on the I-880 Corridor as reported by Caltrans in 1990.

Large trucks are a small portion of the vehicles traveling during the peak commute periods. Only 4.2 percent of all vehicles in the morning peak and 2.4 percent in the evening peak are large trucks. Figure 4.10 shows the hourly distribution of trucks as a percentage of the 24-hour total traffic as reported in the December 1992 *I-880 Intermodal Corridor Study*. As the figure illustrates, large trucks are already peaking at different times than automobiles and other vehicles. One can conclude that trucks are doing this in an attempt to avoid delays due to congestion.

Some of the traffic moving east-west across I-580 moves across the San Francisco bridges. Data on vehicles using the San Francisco Bay bridges show that trucks account for less than 5 percent of the total vehicle trips. In Table 4.3, traffic demand has been quantified for truck travel on the San Francisco Bay bridges, as reported in the December 1992 *I-880 Intermodal Corridor Study*.

Data concerning the flows through the port of Oakland were reported in the December 1992 study as well. The report states a total of 662,355 containers per year, or 2,650 containers per day, move in and out of the port.

The Association of American Railroads maintains a stratified, random sample of movements for all of the Class 1 railroads. These data are available to individual states for use in transportation planning for all of the rail movements origi-

TABLE 4.2 Annual average daily traffic (AADT) truck volumes and total volumes on I-880 (Nimitz Freeway)

City and Location	2 Axles 6 Tires	3 Axles	4 Axles	5 or More Axles	Total Truck AADT	Trucks as a Percentage of AADT	Total Vehicle AADT
Oakland, Oak Street	6,566	4,178	880	19,792	31,416	13.6	231,000
Oakland High Street	8,264	5,450	2,309	20,066	36,089	15.1	239,000
Oakland, Hegenberger Rd.	10,301	5,073	1,712	14,036	31,122	13.3	234,000
San Leandro, Davis St.	7,236	3,029	1,403	13,370	25,038	10.7	234,000
San Leandro, Jct. Rte. 238	8,380	4,675	1,176	15,172	29,403	12.1	243,000
Hayward, Jct. Rte. 92	7,563	2,913	1,354	10,747	22,577	10.7	211,000
Union City, Industrial/Dyer	4,420	1,550	602	7,778	14,350	8.2	175,000
Fremont, Jct. Rte. 84	6,189	2,276	765	8,554	17,784	11.4	156,000
Fremont, Mission Blvd.	3,940	1,147	823	7,583	13,493	10.3	131,000
Milpitas, Jct. Rte. 237	5,158	2,496	793	6,503	14,950	11.5	130,000

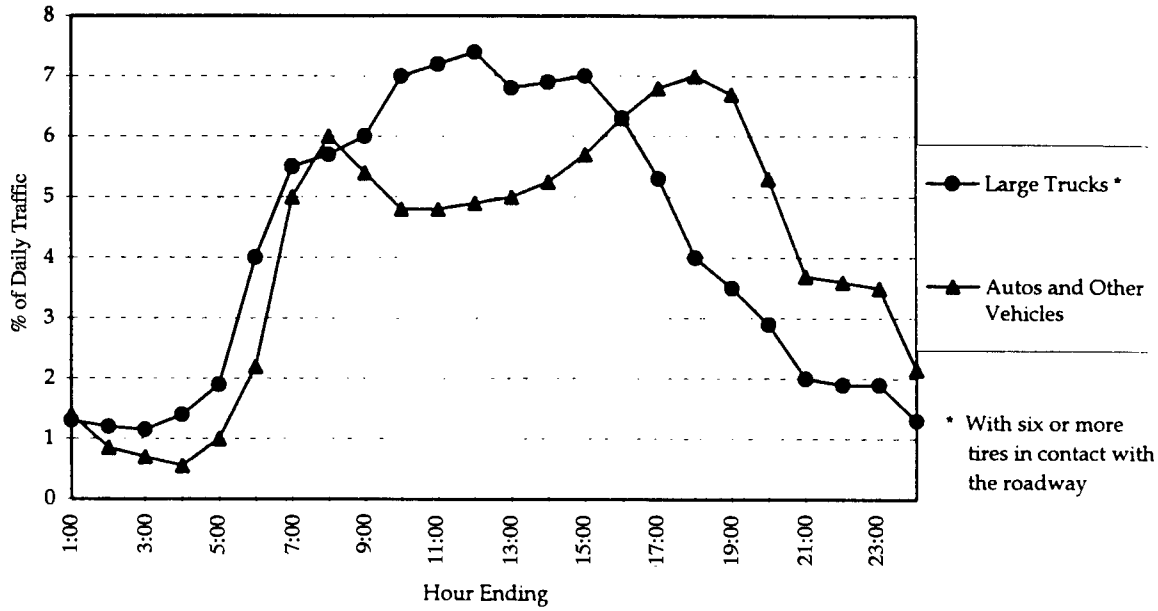

Figure 4.10. Hourly traffic distribution as a percentage of the 24-hour total (San Francisco Bay Area).

nating, terminating, or passing through the state. Permission was requested to access these data for 1992. They were used to examine rail flows into and out of the San Francisco Bay Area. Each observation in the data contains information on the number of trips that observation represents. This allows the total flows to be estimated by carrier, type of movement, origin, destination, commodity, and a variety of other variables of interest. Estimates of the flows into and out of the region for each category were developed. The results are shown in Table 4.4. The volumes of flow are then expressed in truckload equivalents (TLEs). Using TLEs allows a common unit of measurement across all modes.

These data show that the demand from counties in the Central Valley, both inbound and outbound, makes up a significant portion of the overall demand in the region and thus explains why so much traffic is moving across the Altamont Pass and connecting to I-880.

Step 5. Identify the Principal Generators and Attractors

Several types of truck trips occur in the region. Some of the freight moving by rail originates and terminates east of the Altamont Pass and moves by truck along I-580 between the Bay Area and Lathrop. Other freight trip generators in the corridor include the port of Oakland, Oakland International Airport, the U.S. mail distribution center, the United Parcel Service distribution center, a major industrial plant, and various other pockets of development. Truck trips can be classified as

TABLE 4.3 Truck travel on San Francisco Bay bridges (*3*)

Location	Autos and Others	2 Axles	3 Axles	4 or More Axles	Total Trucks	Total Vehicles
Bay Bridge	3,619,701	49,276	11,604	43,254	104,134	3,723,835
	97.2%	1.3%	0.3%	1.2%	2.8%	
Richmond-San Rafael Bridge	800,251	13,658	4,485	20,676	38,819	839,070
	95.4%	1.6%	0.5%	2.5%	4.6%	
San Mateo Bridge	1,082,321	28,202	6,169	20,223	54,594	136,915
	95.2%	2.5%	0.5%	1.8%	4.8%	
Dumbarton Bridge	785,106	13,987	2,912	7,261	24,160	809,266
	97.0%	1.7%	0.4%	0.9%	3.0%	

TABLE 4.4 Waybill estimates of the carloads, containers, and trailers into and out of the region

Inbound County	State	FIPS State	FIPS County	Container	Trailer	Total Intermodal	Carloads	Total Units	TLEs
Alameda County	CA	06	001	129,726	25,280	155,006	37,596	192,602	305,390
Contra Costa County	CA	06	013	36,584	48,920	85,504	25,620	111,124	187,984
Marin County	CA	06	041	-	-	-	200	200	800
Napa County	CA	06	055	-	-	-	4,024	4,024	16,096
San Francisco County	CA	06	075	3,352	40	3,392	4,904	8,296	23,008
San Mateo County	CA	06	081	-	-	-	3,496	3,496	13,984
Santa Clara County	CA	06	085	-	7,280	7,280	27,731	35,011	118,204
Solano County	CA	06	095	-	-	-	17,032	17,032	68,128
Sonoma County	CA	06	097	-	-	-	2,208	2,208	8,832
Totals				**169,662**	**81,520**	**251,182**	**122,811**	**373,993**	**742,426**

Outbound County	State	FIPS State	FIPS County	Container	Trailer	Total Intermodal	Carloads	Total Units	TLEs
Alameda County	CA	06	001	65,024	18,280	83,304	16,300	99,604	148,504
Contra Costa County	CA	06	013	36,584	41,724	78,308	22,804	101,112	169,524
Marin County	CA	06	041	-	-	-	-	-	-
Napa County	CA	06	055	-	-	-	2,860	2,860	11,440
San Francisco County	CA	06	075	1,956	-	1,956	748	2,704	4,948
San Mateo County	CA	06	081	-	-	-	40	40	160
Santa Clara County	CA	06	085	-	-	-	7,364	7,364	29,456
Solano County	CA	06	095	-	-	-	3,916	3,916	15,664
Sonoma County	CA	06	097	-	-	-	80	80	320
Totals				**103,564**	**60,004**	**163,568**	**54,112**	**217,680**	**380,016**

follows: local trips, internal to external trips, external to internal trips, and external to external trips. Local, or internal, trips can be categorized as linked, garage-based, and port-related. A table from the Barton-Aschman report, reproduced as Table 4.5, shows daily vehicle hours traveled by trip type.

Trips are generated by manufacturing employers, by the port of Oakland, and by other land use activities such as construction. Employment data for the *I-880 Intermodal Corridor Study* was broken down into four categories—manufacturing, retail, services, and other. The study surveyed employers. Based on those results, the overall daily truck trip generation rate for all types of employers was determined to be 12.6 trips per 100 employees. Table 4.6 shows estimated truck trip generation results as reported in the December 1992 Barton-Aschman report.

In addition, the *I-880 Intermodal Corridor Study* looked at trips generated by the port of Oakland. The port is located on San Francisco Bay just south of the Bay Bridge in West Oakland. Two-thirds of maritime cargo moving into and out of the port travels by truck on the land portion of its shipment. Ten percent of the truck traffic entering the port of Oakland originated in Contra Costa County. Another 13 percent originated in the Central Valley. This makes for a total of 23 percent of the truck travel that originates east of the mountain

TABLE 4.5 Daily truck vehicle hours traveled (VHT)

Trip Type	2 Axle Trucks	3 Axle Trucks	4 or More Axle Trucks	Total	Percent
Internal-Internal					
Linked	32,427	4,306	11,149	47,882	37.0%
Garage Based	22,971	1,667	9,803	34,441	26.6%
Port	0	395	1,028	1,423	1.1%
Internal-External	14,782	2,292	24,598	41,672	32.2%
Internal-External Port	0	196	1,066	1,262	1.0%
External-External	454	50	2,346	2,849	2.2%
Total	70,634	8,905	49,990	129,529	100.0%
Percent	54.5%	6.9%	38.6%	100%	

TABLE 4.6 Truck trip generation rates

Employment Category	No. of Employees in Survey Sample	No. of Truck Trips	Daily Truck Trips per 100 Employees
Manufacturing	5,669	483	10.3
Business Services	11,898	103	0.9
Retail	4,325	1,001	23.1
Other	5.645	1,874	33.2
Total	27,537	3,461	12.6

barrier between I-880 and I-680. This seems to indicate the importance of the Altamont Pass, particularly for international movements through the port of Oakland. A table from the Barton-Aschman report, reproduced in Table 4.7, shows the origin of truck trips entering the port of Oakland.

Analysis of the CBP data reveals a great deal about truckloads into, out of, and within each of the nine counties by industry type. The CBP is an annual reporting by the U.S. Bureau of the Census of the number of establishments operating in each county by Standard Industrial Classification (SIC) and by size of establishment (number of employees). The 1992 CBP data were used for the nine counties in the I-880 intermodal corridor region to assemble economic information on the region.

The utility of the CBP data was extended by developing an estimate of the freight flows into and out of the establishments within the region in each 4-digit SIC category. This was done by using the value-added coefficients from the

TABLE 4.7 Origin of truck travel entering the port of Oakland (*4*)

Geographic Location	Number of Total Trips	Percent of Total Trips	Number of Non-Local Trips*	Percent of Non-Local Trips*
Alameda County	284**	45%	83	19%
Santa Clara County	33	5%	33	8%
Contra Costa County	43	7%	43	10%
San Francisco	51	8%	51	12%
San Mateo County	26	4%	26	6%
Solano County	6	1%	6	1%
Napa County	7	1%	7	2%
Sacramento Area	16	3%	16	4%
Central Valley, CA	55	9%	55	13%
San Joaquin County	24	4%	24	6%
Northern Coast - CA	16	3%	16	4%
North Central - CA	19	3%	19	4%
Southern California	12	2%	12	3%
Central Coast - CA	21	3%	21	5%
Oregon & Washington	2	0%	2	0%
Nevada & Utah	16	3%	16	4%
Southern US	0	0%	0	0%
Northern US	0	0%	0	0%
Canada	0	0%	0	0%
Total	631	101%	430	101%

Note: Totals may not add to 100% because of rounding error

* Non-local trips are defined as those originating outside the City of Oakland

** Of the 284 trips originating from Alameda County, 201 or 32 percent came from the City of Oakland

national income and product accounts to develop an estimate of the output of each industry category in dollars. This dollar figure is converted into pounds by using the commodity attribute file, which contains the value per pound of products at the 5-digit SIC level. The output is expressed in TLEs of annual production. A similar process is used to estimate the amount of input required to produce this amount of output, again in TLEs per year.

This process using the CBP works well for developing flows for the goods-producing sectors. It does not, however, hold for the wholesale and retail sectors, where the value-added coefficient reflects the wages earned by workers in the distribution of retail business and not the amount of goods handled. These figures are estimated by using the final demand vector of the national input-output table. Final demand includes personal consumption, direct investment, purchases by government, and changes in the balances caused by inventory adjustments or foreign trade. The population of each of the counties in the region is used to estimate the amounts of TLEs required to serve the population of the region. These numbers have been assembled for each of the counties in the region.

A summary of the results of these two sets of computations for each of the counties is shown in Table 4.8. This table shows that the inbound freight to manufacturing or wholesale distribution operations within the area is 8,115 TLEs per day and the outbound freight from producers is 9,880 TLEs per day. It also shows that on the outbound side, Contra Costa County makes up a significant portion of the TLEs per day.

The result provides an overall framework for developing freight flows into and out of the region. It is important to note that the total number of TLEs in and out includes freight movements by all modes and from all points. It also includes some undercounting because shipments into the wholesale sector will subsequently be delivered to final destinations in the retail sector, to one of the goods-producing industries, or to a service establishment. Furthermore, TLEs will frequently involve the use of smaller vehicles for delivery (in some cases, local delivery straight trucks and minivans) and larger vehicles in others (i.e., rail cars, air freighters, barges, or bulk ocean carriers).

Step 6. Determine the Location, Nature, and Extent of Capacity Problems

The I-580 corridor serves as a gateway to the Bay Area. It is constrained by the mountains between I-680 and I-880. This eight-lane highway and I-880, which it feeds into, have high volumes of truck traffic both in absolute terms and as a percentage of total traffic. Because I-880 connects several key activity centers and there are no alternative routes to the east in the corridor for trucks, I-880 to I-580 is a primary Bay Area goods movement route.

TABLE 4.8 Truckload equivalents (TLEs) per day by county, inbound and outbound for the I-880 intermodal corridor region

Inbound

County	State	FIPS State	FIPS County	Ag. Serv.	Mining	Constr.	Manuf.	Transp.	Whol.	Retail	Personal Consumption	Gross Investment	Government Expenditures	Total Inbound per day
Alameda County	CA	06	001	0	0	425	1,448	1	1,617	5,413	306	196	86	2,035
Contra Costa County	CA	06	013	0	0	302	637	1	361	3,863	227	145	64	1,072
Marin County	CA	06	041	0	0	62	129	0	149	1,296	86	55	24	294
Napa County	CA	06	055	0	0	31	197	0	39	543	28	18	8	251
San Francisco County	CA	06	075	0	0	370	308	1	662	3,259	230	147	64	749
San Mateo County	CA	06	081	0	0	222	320	1	580	3,099	202	129	57	708
Santa Clara County	CA	06	085	0	0	487	1,212	1	1,31	6,362	403	258	113	1,986
Solano County	CA	06	095	0	0	93	251	0	1124	1,450	69	44	19	384
Sonoma County	CA	06	097	0	0	124	456	0	214	2,030	94	60	26	636
Totals				0	0	2,115	4,959	5	5,057	27,314	1,644	1,051	461	8,115

Outbound

County	State	FIPS State	FIPS County	Ag. Serv.	Mining	Constr.	Manuf.	Transp.	Whol.	Retail	Personal Consumption	Gross Investment	Government Expenditures	Total Outbound per day
Alameda County	CA	06	001	0	598	949	992	0	1,659	0	0	0	0	1,591
Contra Costa County	CA	06	013	0	501	543	4,408	0	595	0	0	0	0	4,909
Marin County	CA	06	041	0	184	74	77	0	189	0	0	0	0	262
Napa County	CA	06	055	0	34	74	130	0	77	0	0	0	0	164
San Francisco County	CA	06	075	0	156	17	177	0	780	0	0	0	0	333
San Mateo County	CA	06	081	0	215	955	212	0	613	0	0	0	0	427
Santa Clara County	CA	06	085	0	52	600	737	0	1,444	0	0	0	0	788
Solano County	CA	06	095	0	206	11	491	0	236	0	0	0	0	697
Sonoma County	CA	06	097	0	399	755	309	0	296	0	0	0	0	709
Totals				0	2,346	3,939	7,534	0	5,890	0	0	0	0	9,880

Note Inbound and outbound totals do not sum in every column because this would double count some movements.

Travel along the corridor is critical for economic activity within the region as well as for industry connections between the region and others. Some of the movement can and will be diverted to rail, primarily intermodal rail, and this will ease travel along the corridor. To the extent that congestion in the area makes the port less attractive, other ports on the west coast can be used, but this would account for only a few vehicles a day either way. The primary problem is that trucks need to make pickups and deliveries to businesses during working hours. Congestion from passenger travel on the primary roadways slows their travel and causes incidents that lead to frequent breakdowns of capacity on the facilities. Schedules are then unreliable, which increases the cost of operation dramatically and causes companies to carry additional safety stock in order to avoid stockouts.

The entire freeway system in the area is subject to potential capacity breakdowns. Bridge approaches have major queuing for both the morning and evening peaks and sometimes at times in between. The system is operating at or near capacity for so many hours of the day that an incident anywhere in the system causes major problems that may extend for many miles upstream from the incident and require hours to work off even after the problem is cleared. Since there is insufficient capacity on alternative routes within the corridor many vehicles are delayed. For trucks, the delay is particularly costly and the economy of the region suffers from the increased cost of truck travel.

Step 7. Examine Growth Trends in Person Trips and Goods Movement

Traffic demand has been growing along the Altamont corridor, which is an important point for originating and terminating freight. Increasingly, the freight traffic is competing with the growing passenger traffic along the corridor. The increased demand is illustrated in Table 4.9, which is reproduced from the Metropolitan Transportation Commission's *Bay Area Travel and Mobility Characteristics Working Paper #4.*

Most of the corridor is heavily populated and is fairly stable in economic terms. Significant population or employment growth over the next 20 years is expected only in the southern portion of the corridor. The Metropolitan Transit System management strategy corridor profile of the Oakland to Fremont corridor reports a 1990 census population estimate of 950,000 in the Oakland-Fremont corridor. Another source, the Association of Bay Area Governments (ABAG) projects an 8 percent increase in residents to 1.027 million by the year 2000. The region as a whole is expected to grow by 15 percent over this same period. From 1990 to 2010 the Oakland-Fremont corridor area population is expected to grow by 14 percent and the region is expected to grow by 25 percent. ABAG projects employment in the corridor to grow by 3.5 percent from approximately 450,000 to 467,000 by the year 2000. Employment for the region is forecasted to grow by 13 percent over the same period.

Step 8. Identify Any Constraints to Capacity Expansion

The Altamont Pass, which extends through the mountains situated between I-680 and I-880, serves as a gateway to the Bay Area. It was not designed to serve the volume or density of traffic that it sees daily. A network of boulevards and expressways is needed to supplement the Altamont Pass. The high grades of the coastal mountains make it both difficult and expensive to add more capacity.

The San Francisco Bay, a natural barrier, is a major constraint to capacity expansion in the area. The water's depth and the fact that the bay marks the location of a major geologic fault zone complicate the construction of new facilities, such as bridges or tunnels, and make it prohibitively expensive. Moreover, real estate in the area is costly, a factor that further prohibits expansion projects.

Step 9. Develop an Initial Set of Alternatives for Dealing with the Problem

There are many ways to increase capacity in the corridor but most ideas involving new construction are infeasible. Either the cost of building additional facilities is too high or the displacement of existing economic activity will be strongly opposed by the affected parties. The region is also constrained by environmental concerns. The Bay Area recently became an attainment region, but there are continuing air quality concerns, especially regarding particulates.

Some improvement in capacity might be achieved by selective reengineering of particular ramps, queuing areas, weaving sections, etc., but this will do little to reduce the problem overall. Two major approaches should be explored in detail. These are electronic toll collection, combined with congestion pricing, and review and improvement of the secondary road system.

TABLE 4.9 Increase in passenger demand along the Altamont Corridor

Commuter Trips	1980	1990
From San Joaquin and Stanislaus Counties to Alameda County	3,000	16,950
From San Joaquin and Stanislaus Counties to Santa Clara County	600	7,000
From San Joaquin and Stanislaus Counties to all Bay Area Counties	5,250	30,650

The secondary road system of the region is of particular significance as a backup facility in those instances when an incident on the major roadway causes large delays. The secondary road system provides redundancy in travel alternatives. For short trips it supplies a route without entering the freeway system and during an incident it provides a way around the problem. The key to making it work is finding through routes that could be established by the selective addition of new links to the secondary network. A route might be completed by the simple addition of a small bridge across a water barrier, the completion of a street between two existing stubs, the elimination of on-street parking, and signal timing over an existing arterial route. The problem in many cases will be local opposition to changes in the street system. Convincing local officials that the change is in their own self-interest may be difficult. Another issue is the high cost involved in enhancing these systems, particularly in the coastal mountain region.

Another approach for dealing with a shortage in capacity on a facility such as that along the Altamont Pass is to try to influence the demand for the facility. Measures for influencing demand include employer-based programs that promote telecommuting, compressed work weeks, ride sharing, and greater use of transit. For freight, incentives could be added that would shift more of the loads to rail, moving it directly into Oakland. This alternative, however, is based on the market for the specific types of commodities hauled.

Where suitable rights-of-way can be found (an abandoned railroad or an industrial street that could be upgraded) it may be feasible to establish a truck-only facility. Such a facility could be provided in the areas serving the port or the airport. It might also be explored for major industrial areas. If a truck-only facility is infeasible it still might be desirable to reengineer the route to make it truck-friendly, with adequate turn radii, signal timing that favors trucks, truck turn-lanes, and off-street loading for trucks.

Electronic toll collection is both technologically and economically feasible. Automatic vehicle identification, at highway speeds, can be accomplished for any vehicle that uses the facility on a regular basis. It could therefore be applied to both commercial vehicles and daily commuters. A radio-frequency transponder installed on the vehicle is electronically read by a ground-based reader. The transaction is then debited against the customer's account and the vehicle is allowed to pass without stopping. The installation of this equipment could be paid for by the toll collected. Improvement in capacity for the facility could be dramatic in some cases. In addition to electronic toll collection, peak-hour pricing could help further shift some of the peak-period truck demand to less congested times of day. Time-of-day incentives could be built into the peak-hour pricing with incentives and disincentives provided by mode.

Other alternatives include a variety of incentives for shippers and carriers to operate during off-peak periods.

Step 10. Summarize with a Brief Written Statement of the Problem

Travel into and out of the Bay Area is constrained along the Altamont Pass, I-880, and the bay crossings. Truck travel, which is constrained by the high grades of the coastal mountains on the I-580 corridor, is a particular problem. This traffic must be diverted to I-880. There are few alternatives for freight moving east-west through the region. Additional capacity is constrained by difficult terrain, environmental concerns, overdevelopment, and cost. Several alternatives to improving east-west travel have been proposed. Proposed alternatives include electronic toll collection coupled with congestion pricing and adding additional capacity to the secondary roadway system. There is no single solution to the capacity constraints in the Bay Area. Different alternatives will typically be endorsed by different parties.

4.6.3 The North-South Corridor in Seattle, Washington

In late 1994 the Puget Sound Regional Council did a study of freight movements in the Puget Sound region (*5*). This study focused on the four types of freight trips through the region—long-haul traffic, short-haul extraregional traffic, local distribution traffic, and through traffic—and their underlying relationship to the region's economy. With data from this study, and following the outlined steps, an example of the multimodal capacity analysis process for the Puget Sound region was developed.

Step 1. Identify the Study Area

The geographic area of the Puget Sound study region includes King, Kitsap, Pierce, and Snohomish counties. Interstate 5 extends through the study area from the port of Tacoma at the southern end, through Seattle, and past the intersection with Highway 405. Highway 405, which runs parallel to, and east of, I-5 and the mountains that separate them, is an alternative to the I-5 corridor. The port of Seattle is accessible from the east by I-90, which cuts across the mountains intersecting both I-405 and I-5. Additional roadways into the region include SR-99 (which runs in a north-south direction to the west of I-5), SR-520, SR-900, SR-169, SR-18, and SR-516, all serving as alternates to I-90 for access from the east. SR-167 also serves as a parallel route to I-5 from the port of Tacoma north to Seattle. All of these are shown in Figure 4.11.

Step 2. Identify the Type of Corridor

The corridor type is clearly one in which the mountains between I-5 and I-405 form a natural barrier between the port of Seattle and points to the east. In addition, travel north-

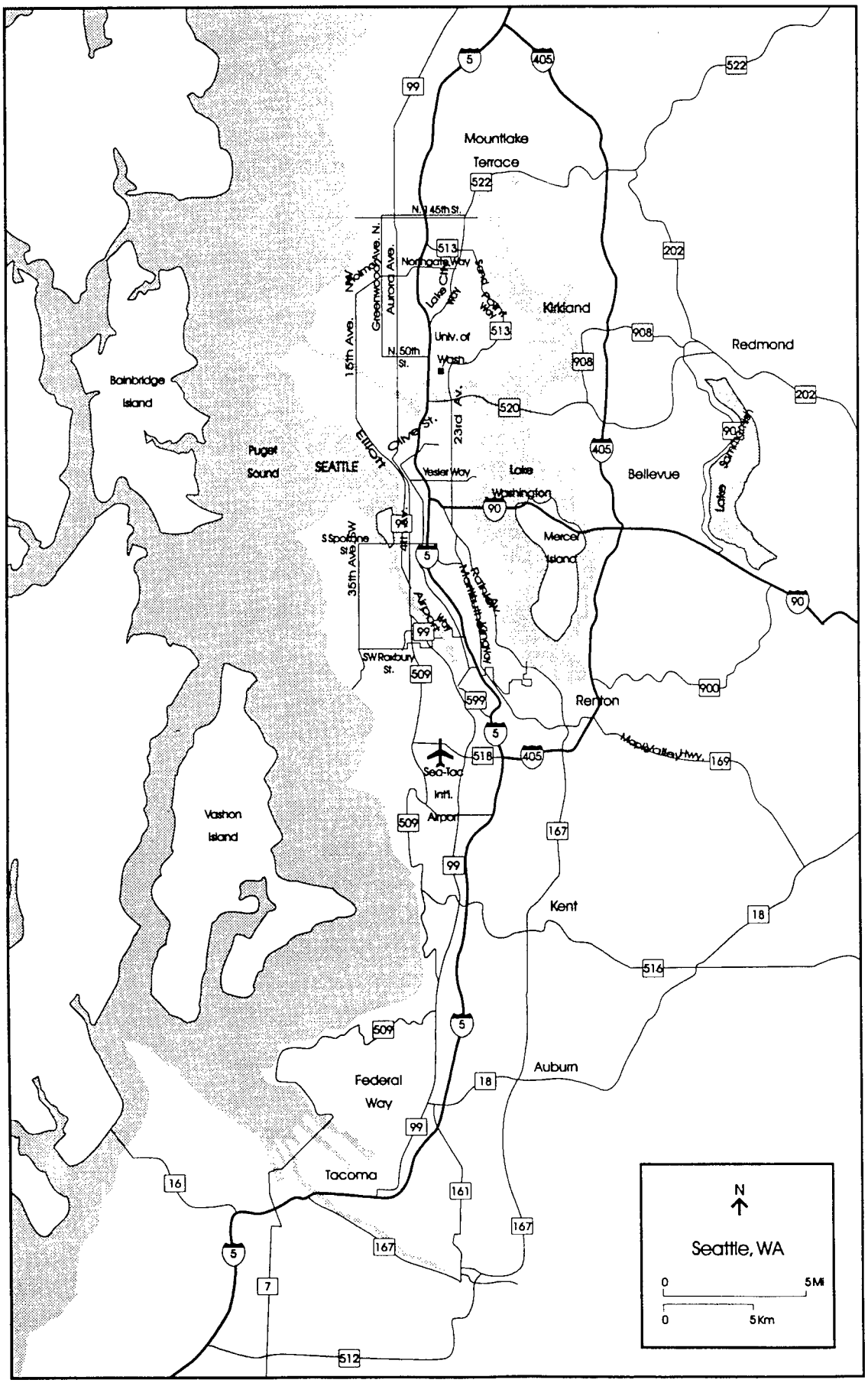

Figure 4.11. The North-South Corridor study area (Seattle, Washington).

south through the region is constrained by heavy development along both the I-5 and I-405 corridors and by Lake Washington, which separates the two routes. The size of the region, the amount of goods moving through the ports of Seattle and Tacoma, and its importance economically constitute major barriers to through-traffic even if the mountains, Lake Washington, and Puget Sound did not exist as constraining factors.

Step 3. Identify the Primary Modes of Transportation

The I-5, I-405, and I-90 corridors along with several state routes that run parallel to these corridors are the primary truck routes. The ports of Tacoma and Seattle both have maritime flows into and out of the region. Each of these ports is served by rail as well. The two major railroads serving the region, the Burlington Northern Railroad and the Union Pacific Railroad, are confined to routes in the same corridor. The I-5 highway extends through the study area from the port of Tacoma past its intersection with I-405. There are two airports in the Puget Sound region, the Seattle Tacoma International Airport and the Snohomish County Airport.

Step 4. Determine Person Trips, Vehicle Trips, and/or Goods Movement

As indicated in the previous corridor example, the Association of American Railroads maintains a stratified random sample of movements by rail for all of the Class 1 railroads. These data are available to individual states for use in transportation planning for all of the rail movements originating, terminating, or passing through the state. Under the auspices of the Washington State DOT, the Interstate Commerce Commission has granted permission to access these data for 1992 and they were used to examine rail flows into and out of the Puget Sound region. Each observation in the data contains information on the number of trips that observation represents. This allows the total flows to be estimated by carrier, type of movement, origin, destination, commodity, and a variety of other variables of interest. Estimates of the flows into and out of the region by each were developed. The results are shown in Table 4.10. Note that even though the numbers for containers are broken out separately, it is not possible to distinguish between domestic and international containers. That distinction can be developed only after additional information is available from the ports.

TABLE 4.10 Waybill estimates of carloads, containers, and trailers into and out of the Puget Sound region in TLEs per day

	Total					
	Trailers	Containers	Intermodal	Carloads	Total Units	TLEs
Inbound	526	1,596	2,122	553	2,675	4,334
Outbound	228	1,396	1,624	445	2,069	3,404

The Washington State Department of Transportation maintains continuous traffic counters on all the major highways coming in and going out of the region. These have been compiled into a map showing traffic levels on each of the major facilities. For the purposes of this example, traffic levels were converted into number of trucks per day in each direction crossing a screen line around the perimeter of the region. A map with these numbers is shown in Figure 4.12. The counts crossing the screen line have been summed to obtain an estimate of the number of trucks entering and leaving the area every day. The numbers are shown in Table 4.11. The low resolution recorded in the count information allows rather poor definition of the total, so it is shown as a range.

Data concerning the flows through the ports of Seattle and Tacoma show more than 2 million 20-foot equivalent units (TEUs) flowing through the two ports in both directions during 1992. Of this total almost 400,000 TEUs moved through the separate port facilities serving carriers moving to and from Alaska and Hawaii. This translates into about 2,100 containers in each direction, most of which were full. Of this total more than half of the inbound containers had destinations that were reached by rail, mostly by doublestack railcar over the rail systems and connections of the Burlington Northern Railroad or the Union Pacific Railroad. In the outbound direction these figures were approximately reversed, with 73 percent of the loaded outbound movements originating on the west coast, mostly within the Puget Sound region. The balance of loaded movements came from the interior of the United States by rail doublestack. The results for each of the two ports are summarized in Table 4.12 for three types of traffic—containers, bulk flows, and automobiles.

These numbers can be coordinated with the figures by rail to produce a combined picture of all container movements into and out of the region by noting that the rail carload waybill statistics for 1992 showed 1,596 loaded container movements inbound to the Seattle/Tacoma area and 1,396 outbound from the region. Since over time inbound containers must balance with outbound movements, the difference can be accounted for by adding 200 outbound empty containers per day to the outbound movement. A similar set of coordinated figures can be obtained by observing the bulk flows into and out of the Puget Sound region by ship and by rail. These can be obtained from the 1992 port flows. The overall results are shown in Figure 4.13.

By using simplified assumptions of flows within the urban area described above, along with the available statistics, an overview of the transport flows that occur in the Puget Sound region was constructed. It is useful to summarize the long-haul transportation figures developed from each of the modes. The short-haul inbound and outbound movements are

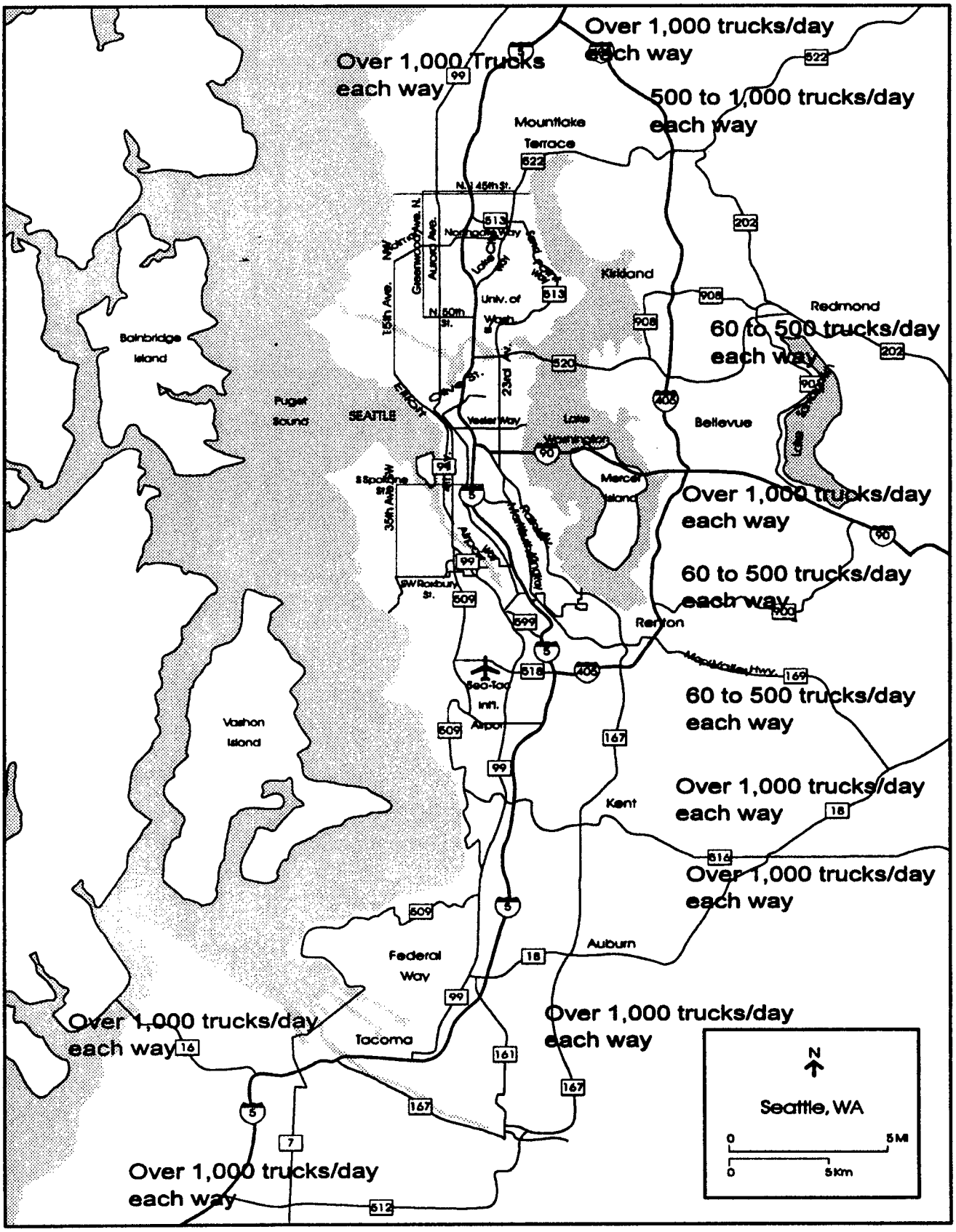

Figure 4.12. Number of truck movements into and out of the Puget Sound area.

TABLE 4.11 Volume levels per day on major highways entering and leaving the area

Highway	Vol (low)	Vol (high)
SR 99	2,000	2,400
I-5n	2,000	4,000
I-405	1,500	1,500
SR 520	560	560
I-90	2,000	4,000
SR 900	560	560
SR 169	560	560
SR 18	2,000	2,400
SR 516	2,000	2,400
SR 167	2,000	2,400
I-5s	2,000	4,000
SR 16	2,000	2,400
Totals	19,180	27,180

TABLE 4.12 1992 flows through the ports of Seattle and Tacoma

Seattle	Totals	Inbound	Outbound
Containers			
Intn'l TEUs	911,260	469,127	442,133
AL & HI TEUs	142,539	71,335	71,204
Total TEUs	1,053,799	540,462	513,337
Tons	7,793,618	3,997,114	3,796,504
Bulk Flows			
Grain	1,707,902		1,707,902
Petroleum	1 705,14	836,080	869,065
Breakbulk	[5] 492,707	242,120	250,587
Subtotal Tons	3,905,754	1 078,200	2,827,554
Autos			
Count	38,766	38,321	445
Tons	45,223	43,610	1,613
Total TEUs	1,053,799	540,462	513,337
Total Tons	11,744,595	5,118,924	6,625,671
Tacoma	**Totals**	**Inbound**	**Outbound**
Containers			
TEUs	1 054,000	474 328	579,672
Int'l Tons	5 602,000	2,729 686	2,872,314
Alaska Tons	1,788 000	596 010	1,191,990
Subtotal	7 390,000	3,325,696	4 064,304
Bulk Flows			
Grain	2,730,000		2,730,000
Logs	1,019,000	-	1,019,000
Alumina	579,000	579,000	-
Wood Chips	778,000	-	778,000
Gypsum	308,000	308 000	-
Breakbulk	289,000	50,740	238,260
Subtotal Tons	5,703 000	937,740	4,765,260
Autos			
Count	127,000	121,920	5,080
Tons	459,740	441,350	18,390
Total TEUs	1,054,000	474,328	579,672
Total Tons	13,552,740	4,704,786	8,847,954
Grand Total TEUs	2,107,799	1,014,790	1,093,009
Grand Total Tons	25,297,335	9,823,710	15,473,625

Notes: [a] Assumes 51 27 % outbound = '93 ratio
[b] Assumes 66 66 % outbound
[c] Assumes 82% outbound = '93 ratio
[d] Assumes 96% outbound = 93 ratio

the residuals between the long-haul movements and the total inbound and outbound requirements produced with the CBPs. Working in TLEs per day, the numbers are shown in Figure 4.13.

The first conclusion to be drawn from the inbound and outbound requirements produced with the CBP and the long-haul modes of transportation is the development of the number of direct (long-haul) movements versus indirect (short-haul and local) deliveries to the principal sectors. These are also shown in Figure 4.13.

The number of full TLE movements for the four counties in the Puget Sound region is 6,644 TLEs inbound and 5,334 TLEs outbound per day. The inbound movements include some direct and indirect movements. The 6,644 inbound TLEs per day include 5,299 TLEs into the manufacturing sector, but not all of these are long-haul direct. Some come from the wholesale distribution sector. An estimate of the number served by the wholesale distribution sector is 2,373 TLEs per day, developed during expansion of the CBPs. If one assumes that all the retail sector (1,345 TLEs) is served by short-haul and local transportation through the wholesale distribution industry, this leaves 1,028 TLEs for indirect (short-haul and local) delivery to manufacturers from the wholesale distribution sector. If it is assumed that all the indirect short-haul and local deliveries are made by truck (which seems plausible enough) and that each delivery truck makes 12.75 deliveries (which is the average number of deliveries made by a truck in the shipper survey of the Puget Sound region) the 2,373 wholesale TLEs per day expand into 30,256 actual point-to-point movements on the street on an average day. When added to the 4,271 direct manufacturing movements and the 2,373 direct wholesale movements the total comes to 36,900 daily trips on the network. Note that this still does not include through trips.

Turning next to the movement by mode of transport, it is possible to use the truck flow figures from the traffic density map of the region presented in Fig. 4.12 in conjunction with the total figures developed above to estimate the number of truck trips moving through the area. From Table 4.13, the number of long-haul TLE movements crossing the imaginary cordon line circling the region is 1,380 per day. To this must be added the 697 short-haul inbound movements, some of which will be performed in smaller trucks. Longer delivery movements could account for between one-third to one-half of the 30,256 deliveries developed above. Long-haul drayage of maritime and rail intermodal outside of the cordon could be as much as two-thirds of these trips. The total of trips is added to the 2,312 long-haul and short-haul movements just computed to yield truck trips per day crossing the cordon. This leaves between 2,019 and 4,976 through trips to make up the difference. Note that this figure does not include local deliveries that take place within the cordon.

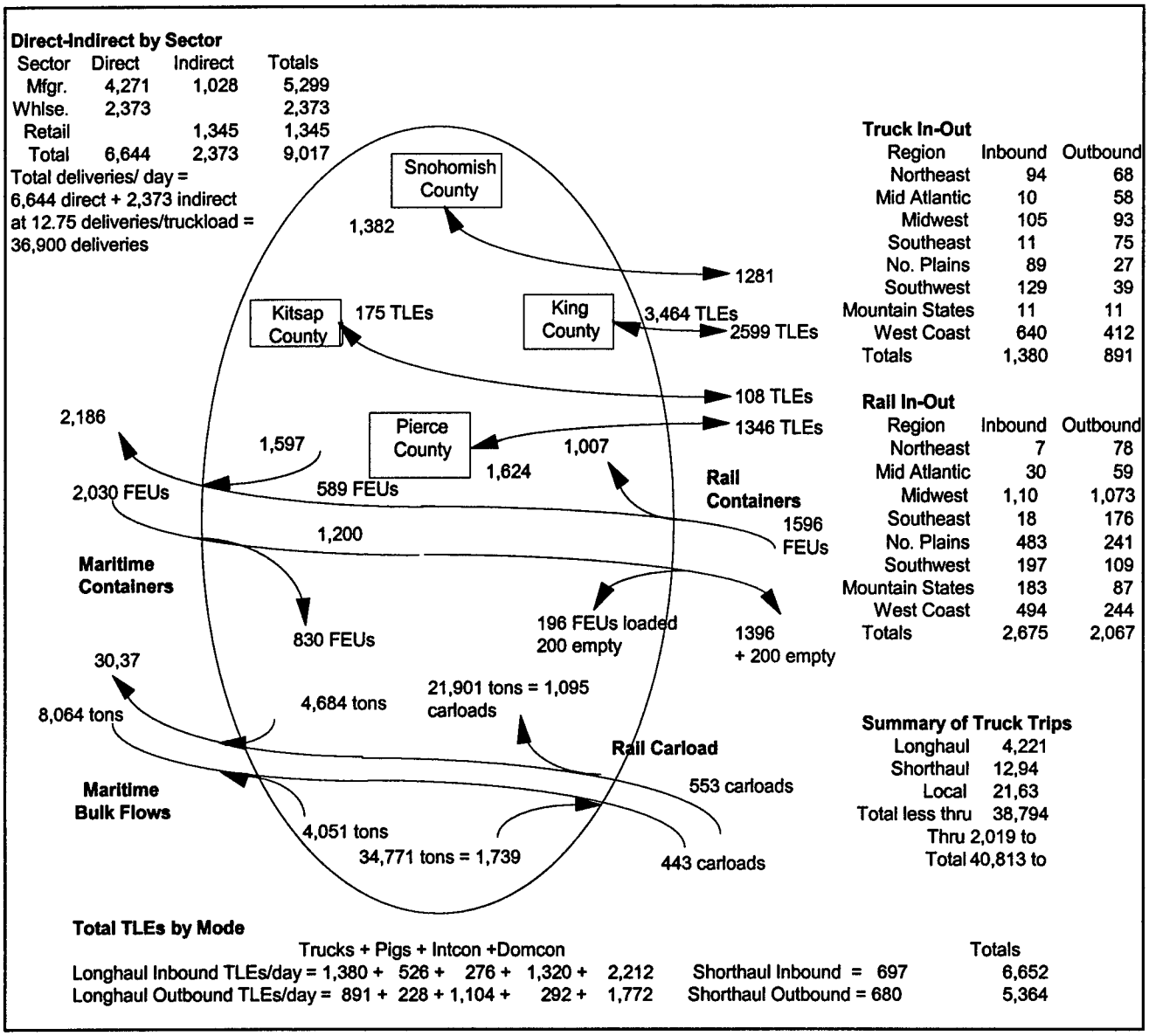

Figure 4.13. Summary of movements into and out of the Puget Sound area.

The overall summary of movements is presented in Figure 4.13. The one most striking aspect of the analysis is the very high proportion of the movements involved in delivery-type movements. With only 1,380 long-haul truckload movements inbound and 891 loaded long-haul truckload movements outbound, long-haul truckload movements account for less than 10 percent of the deliveries made in the region. This does not mean that they are unimportant, only that even if long-haul trucks were completely eliminated, there would still be very significant local truck traffic making deliveries and performing service functions.

The other striking aspect of the analysis is the importance of intermodal transportation to the region. Intermodal trailers and containers account for a larger volume of movements into and out of the region than does long-haul truckload. In addition is the importance of intermodal containers involved in the region's foreign trade to the economy of the Puget Sound region. The size of this trade has important implications for those transportation policies that facilitate the handling of intermodal traffic and the economics of port operations within the region.

Finally, truck travel in the area has been compared with overall travel in the area to get a percentage of truck vehicle miles traveled in the region. As the calculations below show, nearly 6 percent of all VMT in the Puget Sound region are from truck trips.

TABLE 4.13 Trucks crossing the cordon (by type)

	Low Estimate	High Estimate
Longhaul trips inbound (1,380/day) + Shorthaul trips inbound (697/day) x 2 =	4,154 trips/day	4,154 trips/day
Longer delivery trips = 1/3 to 1/2 of 30,256 trips/day =	10,085 trips/day	15,128 trips/day
Longer drayage of maritime and rail intermodal units = 2/3 x 4,384 =	2,922 trips/day	2,922 trips/day
Total longhaul trips/day into and out of the region less through trips =	17,161 trips/day	22,204 trips/day
Through trucks trips/day =	2,019 trips/day	4,976 trips/day
Total through trips crossing cordon =	19,180 trips/day	27,180 trips/day

Long-haul

6,644	direct inbound FTEs
5,354	repositioned within the area for outbound movement
6,644	outbound movements
18,642	long-haul movements in and out

Short-haul

2,373	retail FTEs through wholesalers
1,345	mfgrs FTEs through wholesalers
3,718	FTEs (40,000 lbs/truck)
× 4	street delivery vehicles @ 10,000 lbs/truck
14,872	street delivery vehicles, each delivers 12.75 stops
×12.75	stops/delivery vehicle (reflecting "trips"/truck in shipper Survey)
189,618	movements between stops
14,872	return movements to distribution center
204,490	short-haul movements (in and out)

Refuse Removal/Mail Delivery

Assume 2 deliveries/household/week $= \frac{2{,}000{,}000}{4 \times 7} = 71{,}429$ stops/day

Through Truck Trips

10,019 = max number of through trips from cordon

Summary

Long-haul		Short-haul		Refuse/Mail		Through Truck Trips		
18,642	+	204,490	+	71,429	+	10,019	=	304,580

Truck Trips As a Percent of Total Trips

$\frac{304{,}580}{8{,}700{,}000} = 0.03501$ (or 3.5%)

Truck Vehicle Miles As a Percent of Total Vehicle Miles

Regional VMT (autos and trucks)	= 61,000,000 auto miles
18,642 long-haul trips × 50 miles/trip	= 932,100 truck miles
204,490 short-haul trips × 8.0 miles/trip	= 635,920 truck miles
71,429 refuse/mail × 8.04 miles/trip	= 571,432 truck miles
10,019 through trips × 50 miles/trip	= 500,950 truck miles
total	= 3,640,402 truck miles

$\frac{3{,}640{,}402}{61{,}000{,}000} = .05968$ (or 6%) of total vehicle miles

Step 5. Identify the Principal Generators and Attractors

Some trips are generated by the manufacturing sector shipping its output to its customers. For the larger manufacturers the destination of most of these trips is outside the region. Those trips that do stay within the region are typically specialized in nature, such as the movement of ready mix concrete to construction sites or the distribution of bakery products to retail establishments. Trip generation, then, is closely related to employment in certain industries.

Trip attraction is also closely related to employment in certain industries. For manufacturing, this includes those industries with extensive inputs. The largest attractors of trips, however, are the retail industries. Virtually all of the products sold in retail stores have to be delivered to the stores by truck. Many of these delivery trips are by small, single unit trucks. These trucks account for more than 70 percent of the trucks on the street. Consequently, they deserve a special place in the attraction of truck trips. Most of the long-haul trips are either inputs to the manufacturing process or shipments to wholesale distributors who will redistribute them to retail outlets for sale to the public.

Employment by sector is used to develop principal generators and attractors and to distinguish between long-haul trips, short-haul trips, and local trips since many aspects of the movement are different between the three. Long-haul trips have one end of the trip outside the region. Most short-haul trips begin and end in the region but may go beyond the region in the process. Local trips have both ends in the region and typically use smaller equipment, such as minivans, panel trucks, or single unit straight trucks.

This study is too limited in scope to attempt to develop explicit point-to-point movements of these local trips. It is possible, however, to sketch out a simplified procedure by which these figures can be obtained. The process involves the following three steps:

1. Use existing information on the number of persons employed in each transportation analysis zone (TAZ) to develop the number of truck trips generated per employee by sector. Since employment data for a TAZ are available only at the 1-digit SIC level, the annual number of trucks generated per employee for each of the 1-digit sectors was derived from the trucks generated in each 4-digit SIC. The results over the 4-digit categories were averaged within each 1-digit category.
2. The total number of outbound trucks are divided by the total number of employees in each 1-digit sector to produce the number of trucks generated per employee.
3. This process is repeated for the inbound truck trips. Note that the number of truck trips generated by the retail sector is typically very small (virtually nothing). On the other hand, the number of truck trips attracted per employee are quite significant. Since the employment in the retail sector is typically much larger than other sectors much of the attraction of truck trips will be to the retail sector.

The generation and attraction, measured in annual number of trucks per employee, for King County was:

	Generation	*Attraction*
Long-haul	4.58	8.73
Short-haul	9.79	14.54
Local	9.54	14.54

The numbers are developed as follows:

Long-haul generation = manufacturing outbound
Short-haul generation = wholesale outbound
Local generation = 0.9 (wholesale outbound) + 0.1 (construction outbound)
Long-haul attraction = 0.33 (manufacturing inbound) + 0.67 (wholesale inbound)
Short-haul attraction = retail inbound
Local attraction = retail inbound

Manufacturing Flows Developed from the CBPs. Analysis of CBPs reveals a great deal about truckloads into, out of, and within each of the four counties by industry type. As stated earlier, CBP is an annual reporting by the U.S. Bureau of the Census of the number of establishments operating in each county by SIC and by size of establishment (number of employees). The 1992 CBP for the four counties of the corridor was used to assemble economic information on the region.

The utility of the CBP data was extended by developing an estimate of the freight flows into and out of the establishments in each 4-digit SIC category. This was done by using the value-added coefficients from the national income and product accounts to develop an estimate of the output, in dollars, of each industry category. This dollar figure is converted into pounds by using a commodity attribute file, which contains the value per pound of products at the 5-digit SIC level. Ultimately the output can be expressed in TLEs of annual production. A similar process is used to estimate the amount of input required to produce this amount of output, again in TLEs per year.

Retail Flows Developed from the National Income Accounts. Like the previous case study corridor, the process using the CBP works well for developing flows for the goods-producing sectors in this region. It does not, however, hold for the wholesale and retail sectors, where the value-added coefficient reflects the wages earned by workers in the distribution or retail business instead of the amount of goods handled. These figures are estimated by using the final demand vector of the national input-output table. Final demand includes personal consumption, direct investment, purchases by government, and changes in the balances caused by inventory adjustments or foreign trade. The population of each of the counties in the region was used to estimate the amount of TLEs required to serve the region. These numbers have been assembled for each of the counties in the region.

A summary of the results of these two sets of computations, manufacturing and retail, for each of the counties is shown Table 4.14. This table shows that the freight inbound to manufacturing or wholesale distribution operations within the area is 6,644 TLEs per day and the freight moving outbound from producers is 5,334 TLEs per day.

The result provides an overall framework for developing freight flows into and out of the region. It is important to note that the total number of TLEs in and out includes freight movements by all modes and from all points. It also includes some undercounting because shipments into the wholesale sector will subsequently be delivered to final destinations in the retail sector, to one of the goods producing industries, or to a service establishment. Further, TLEs will frequently involve the use of smaller vehicles for delivery, in some cases local delivery straight trucks and minivans, and larger vehicles in others (i.e. rail cars, air freighters, barges, or bulk ocean carriers).

The truckload movement sample was described briefly earlier. It is a sample of long-haul truckload movements developed by interviewing truckload drivers at more than 20 truck stops located strategically across the country. These interviews were weighted by using passing counts at each of the interview locations and an expansion factor developed to expand the observation to the universe of all long-haul movements. The database created from this sample was queried to determine the total number of loaded long-haul truckload movements coming into and out of the Seattle/Tacoma

TABLE 4.14 TLEs per day by county, inbound and outbound for the Puget Sound region

Inbound County	Agriculture Services	Mining	Construction	Manufacturing	Transportation	Wholesale	Retail	Personal Consumption	Gross Investment	Government Expenditures	Inbound per day
King	-	-	618	2,620	1	1,839	8,394	440	281	123	3,464
Kitsap	-	-	21	98	-	29	780	40	26	11	175
Pierce	-	-	11	1,402	-	303	2,561	11	74	32	1,624
Snohomish	-	-	295	1,179	-	202	2,168	605	67	30	1,381
Subtotals	-	-	846	5,299	1	2,373	13,903	701	448	196	6,644
Outbound											
County	Agriculture Services	Mining	Construction	Manufacturing	Transportation	Wholesale	Retail	Personal Consumption	Gross Investment	Government Expenditures	Outbound per day
King	-	854	1,354	1,745	-	2,425	-	-	-	-	2,599
Kitsap	-	44	72	64	-	67	-	-	-	-	108
Pierce	-	267	21	1,079	-	413	-	-	-	-	1,346
Snohomish	-	458	283	823	-	315	-	-	-	-	1,281
Subtotals	-	1,623	1,920	3,711	-	3,220	-	-	-	-	5,334

Note: Inbound and outbound totals do not sum in every column because this would double count some movements

region. The result of the analysis for the region is shown in Table 4.15.

Step 6. Determine the Location, Nature, and Extent of Capacity Problems

There is a constantly recurring congestion problem on the I-5 and I-405 corridors due to inadequate capacity. The capacity problem exists because of the large demand for north-south movement within the Puget Sound region. Due to land use patterns and the mountain region between the two roadways, there is no room for adding capacity. The mountain region is a natural barrier to access of the port of Seattle from the east and to adding additional capacity along the I-90 corridor.

Step 7. Examine Trends in Person Trip and Goods Movement Growth

Traffic in the Puget Sound region has been growing relatively steadily over the past few years at about 3 percent.

TABLE 4.15 Regional long-haul truckload movements per day into and out of the Puget Sound area

Region	Inbound	Outbound
Northeast	94	68
Mid Atlantic	101	58
Midwest	105	93
Southeast	111	75
No. Plains	89	27
Southwest	129	39
Mountain States	111	119
West Coast	640	412
Totals	1,380	891

The region has undertaken some dramatic efforts to slow down and to channel this development. It has inaugurated "growth poles" where it is encouraging growth in areas of relatively dense urban concentrations, well-served by public transportation. In between these relatively dense areas it has adopted land use zoning that discourages development. Transportation between these dense areas could be facilitated.

Step 8. Identify Any Constraints to Capacity Expansion

The I-5 corridor of the Puget Sound region is bound by natural barriers of water to the west and mountains to the east. In addition to these natural barriers, the real estate needed for the location of new facilities, whether they be bridges, tunnels, or roads, is expensive, a factor that further inhibits expansion projects.

Step 9. Develop an Initial Set of Alternatives for Dealing with the Problem

Alternative remedies for preserving multimodal capacity in the Puget Sound region are limited. There appears to be no space for additional north-south freeways in the region. The physical barriers are too formidable. It is not clear that additional lanes on the existing freeways would help much either, although there are undoubtedly points on the existing network where additional lanes, more carefully designed weaving areas, or new interchanges would increase capacity and smooth traffic flow. Further, there is no sentiment in the region for building more highway facilities since there is fear

that additional capacity means additional single-occupancy vehicles, which contribute to degraded air quality.

Adding rail capacity is also problematic, since the same physical constraints exist for rail that exist for truck. There is talk of adding commuter rail services on top of the existing freight lines to provide a rail commuter alternative to single-occupancy vehicles. This might help reduce congestion during peak hours by eliminating passenger cars from the freeways. One wonders whether other commuters would rush to fill the void. Those who depend upon good rail freight service fear that inaugurating rail passenger commuter service could potentially degrade freight service and actually hurt the economy rather than help it.

Concern for preserving the health of the economy leads one back to the need for ensuring that freight vehicles, particularly trucks, can travel freely throughout the region with minimum travel delay and high reliability. As this example dramatically shows, more than two-thirds of truck travel is related to the distribution function, with pickup and delivery of goods flowing between different sectors of the economy. The city, in many ways, is merely a "distributed factory," and the roads and streets of the region are the "factory floor" with goods flowing between work stations to produce the final product.

What appears to be needed is some way to give preferential treatment to truck movements. This could include allowing commercial vehicles to use the HOV lanes on the freeway, creating truck-only roadways, or giving them the ability to go to the head of the queue in some instances. Completely separating freight flows from passenger flows is desirable where this can be done. Consequently, the concept of freight-only roadways is particularly appealing. Where toll facilities are contemplated, whether for financial purposes such as raising the money to build the facility or as part of a congestion management system, the price charged to commercial vehicles should be carefully considered. It may make sense to actually charge commercial vehicles proportionally lower tolls than those charged to single-occupancy vehicles.

Step 10. Summarize with a Brief Written Statement of the Problem

Physical barriers, existing land use patterns, environmental concerns, and political resistance stand in the way of adding new highway capacity to serve north-south traffic in the Puget Sound region. If public policy sharply distinguished between ways to meet demand for freight and person transport, potentially more effective strategies for satisfying needs for north-south traffic movements might become apparent. For example, there may be merit in having separate facilities for freight transport or in pricing strategies that favor truck transport by discouraging commuter use of highways. Complementary strategies to increase alternatives to single-occupant automobile travel may be necessary. Public policy that favors truck transport over person transport on highways also needs to consider the impact on rail transport. Commuter rail service on freight lines, and policies that give trucking a significant time and cost advantage over rail, could meet stiff resistance from railroad companies.

4.6.4 The East-West Corridor in Madison, Wisconsin

The heart of the City of Madison, Wisconsin, faces a challenging transportation capacity problem. Significant person travel flows east and west past a major university and state government offices in an area constrained by three lakes. The most constrained portion of travel occurs on an isthmus between two of these lakes. This corridor runs east and west to two separate shopping malls. Many other cities have highly constrained areas that limit expansion of roads and transportation facilities, but what makes Madison unique is the high percentage of people who bus, bike, and walk, particularly near the university. One reason is the existence of exclusive bike and bus paths in the university area. In addition, railroad rights-of-way exist through much of this corridor and can potentially serve light-rail transit and other modes. Madison is therefore a good case study to illustrate the potential of nonautomobile modes of transportation in addressing severe practical limitations on the increase of roadway capacity and to highlight some of the modal tradeoffs involved.

Step 1. Define the study area

The corridor discussed in this case study lies in the center of the Madison urbanized area, which includes the City of Madison, the incorporated and unincorporated areas of Monona and Middleton, and the Village of Shorewood Hills. The principal geographic features are two large lakes, Mendota and Monona, and a smaller lake, Wingra. The Wisconsin state capitol is located on the isthmus between Lake Mendota and Lake Menona, and the University of Wisconsin campus runs along the south shore of Lake Mendota. The corridor extends from the East Towne mall shopping area near the intersection of East Washington Avenue and I-90, passes through the narrow isthmus between Lakes Mendota and Monona, and continues out to the West Towne shopping mall, located near where Gammon Road intersects the Beltline (U.S. Highways 12 and 14).

During peak periods there is significant congestion involving automobile, pedestrian, bicycle, and bus traffic in the isthmus and near the east end of campus. Traffic traveling between the east and west side of the town often seeks to avoid this congested part of the city by using the Beltline (Highways 12, 18, 14, and 151) for part of the trip. The Beltline is located south and west of Madison. Key roads that can carry traffic from the east side of the city to the west, via north-south routes and then the Beltline, include I-90 and

South Stoughton Road. Key routes on the west side of town that connect with the Beltline and can serve east-west traffic include Whitney Way Road, Gammon Road, Mineral Point Road, and University Avenue. The study area is thus bounded by I-90 on the east, the Beltline on the south and west, and, finally, by the south shore of Lake Mendota on the north, which closely runs parallels to University Avenue.

Step 2. Identify the type of corridor

This is an example of a corridor that is highly constrained by physical features (in this case by two lakes). It also has the characteristics of central city chaos caused by competition between automobile, bus, bike, and pedestrian traffic; one-way streets (Gorham and Johnson streets); and an automobile-free zone along State Street connecting the entrance to the University of Wisconsin with the Capitol Square, the site of the state capitol. Urban goods movement is not a major factor in the downtown area as it is in most large cities.

Step 3. Identify the primary modes of transportation

The principal modes of person travel serving the corridor are drive-alone, shared-ride, walking, biking, and busing transportation. These last three modes are particularly important in the vicinity of the university and the state capitol. State Street, which connects the east end of the campus and the Capital Square, is an automobile-free zone that carries only buses, pedestrians, and bicycles. There are also exclusive bus and bicycle lanes running along University Avenue near the east end of campus.

Rail rights-of-way are located in strategic places along much of the corridor and can potentially be used to serve other modes of transportation. Rail rights-of-way run from near Old Middleton Road and then along University Avenue and Campus Drive on the west side. Rail rights-of-way also run parallel to East Washington Avenue toward East Towne.

Step 4. Determine person trips, vehicle trips and/or goods movement

The Traffic Volume Report, prepared by the Department of Transportation of the City of Madison, provides traffic count data pertinent to the corridor. Seasonal factors are applied to sample counts, taken biannually at 900 to 1400 city-wide locations, to create the city's annual traffic flow maps.

Based on these traffic flow maps, the 1993 average weekday traffic volumes for the portion of the corridor lying in the isthmus to the east of Blair Street totals over 100,000 vehicles.

East Washington Avenue (east of Blair; both directions)	40,700
Williamson Street (east of Blair; both directions)	21,100
East Johnson St. (east of Blair; one-way)	18,800
East Gorham St. (east of Blair; one-way)	21,650

A significant portion of the traffic found east of Blair (37,900 per weekday) leaves the isthmus corridor and uses John Nolan Drive, which heads southwest.

Most of the traffic passing through the isthmus and found immediately west of the state capitol travels primarily on West Johnson Street and West Gorham Street, which becomes University Avenue. Average weekday traffic volumes on these roads are as follows:

West Gorham St. (one-way)	24,200
West Johnson St. (one-way)	23,100

In other words, there are between 40,000 and 50,000 vehicles per weekday, roughly half in each direction, traveling on Gorham and Johnson Streets through the narrow isthmus. Virtually all of this traffic consists of automobiles, vans, and light trucks. Virtually none of it consists of heavy trucks. Heavy trucks use alternate routes such as John Nolan Drive and the Beltline.

Hourly traffic count data at strategic locations, generally in the Madison east-west corridor, have been averaged to show peaking characteristics of demand. Average weekday traffic volume by hour in the corridor follows the peaking pattern in Figure 4.14.

The Wisconsin Department of Transportation estimates that the modal split (percent) for person travel in Madison for all trips is as follows:

Single-occupant	65
Shared-ride	11
Walking	14
Biking	5
Busing	5

The mode split figures are probably even higher for walking, busing, and biking for the portion of the isthmus corridor in the vicinity of the university, given the 40,000 students enrolled at the University of Wisconsin. Evidence for this comes from The City of Madison, which collects bike traffic count data on the bike lanes of University Avenue. This information reveals that bike traffic volumes are in the range of 6,000 to 7,000 per day during the summer and drop to between 1,000 and 2,000 per day during the winter.

Transit ridership, at 9.2 million boardings per year, is high compared with similar-sized cities where annual boardings are typically in the 1.5 to 5.0 million range. The Madison Metro runs about 170 buses on 21 routes, most of which travel through the isthmus. Boardings total more than 40,000

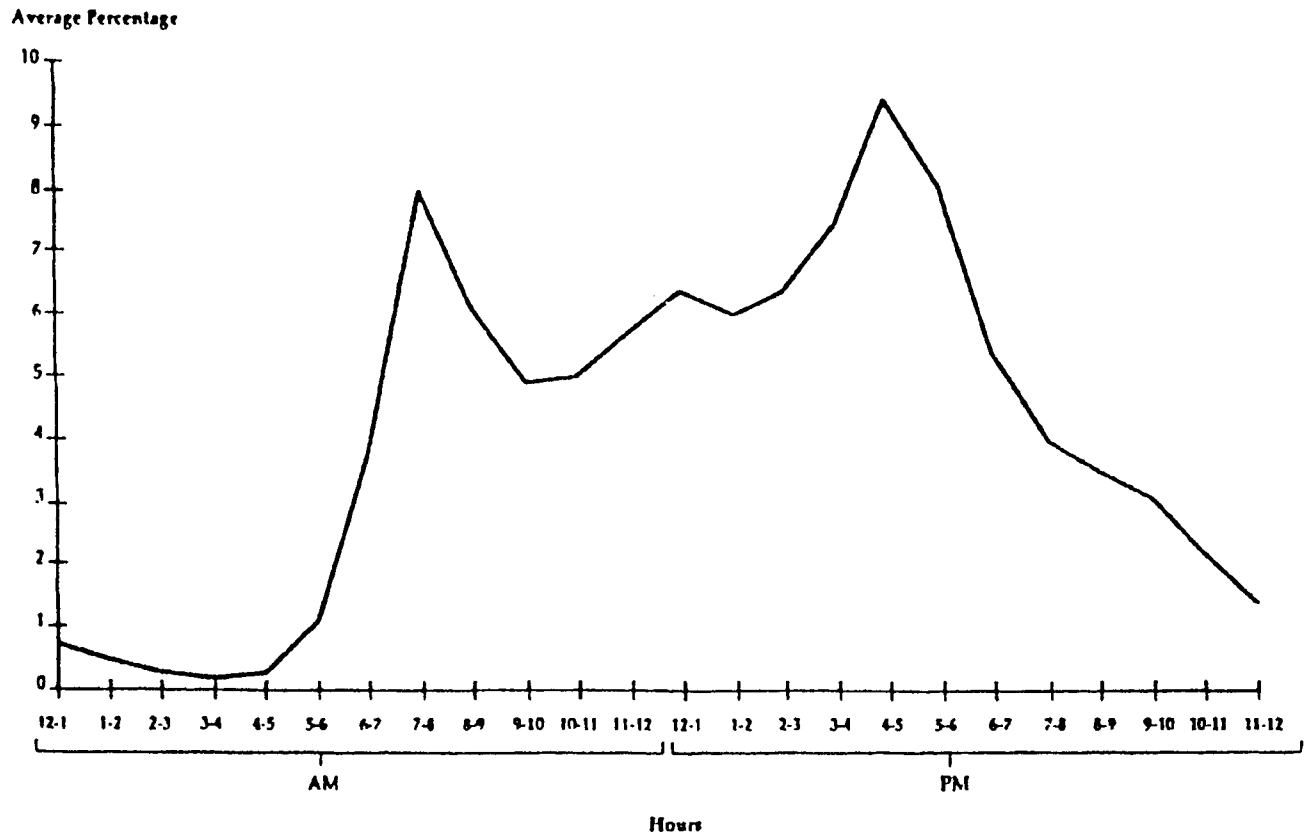

Figure 4.14. Average weekday traffic volume by hour.

per weekday and are most heavily concentrated in the corridor under study.

Step 5. Identify the principal generators and attractors of traffic

The two largest traffic generators and attractors are the University of Wisconsin and state government buildings near the Capitol Square. The major shopping centers of East Towne and West Towne (with ever-expanding strip retail businesses around both malls) Hilldale, and the retail stores along State Street are all major traffic generators and attractors. Others include the hospitals and most medical centers in the corridor; some industry on the east side (e.g., Rayovac); major office expansion far to the east of I-90 (with a big office park complex and the American Center built by American Family Insurance) and far to the west of U.S. Highway 12 (Greenway and Sauk Trails office parks); plus the University Research Park at Mineral Point Road and Whitney Way on the west side.

Step 6. Determine the location, nature, and extent of capacity problems

Lakes Mendota and Monona squeeze the land available for travel between the east and west sides of the city through the city center into a strip only ¾ mi wide. Many roads and streets that might otherwise carry traffic terminate at the Capitol Square, the site of the State Capitol building, and some of these roads and streets are no longer suited to carrying significant amounts of vehicular traffic. Gorham and Johnson Streets cross State Street near the capitol building. But State Street is closed to general automobile traffic and, as noted above, carries only pedestrians, bicyclists, and buses. The outer lane around the capitol building is reserved mainly for buses and is the main bus transfer area in the City of Madison. Access to and egress from the road around the Capitol Square is limited. Also, the State Capitol stands between East and West Washington Avenues. Although East Washington Avenue has considerable capacity on the east side, traffic headed west on it must, for the most part, swing north onto East Gorham Street or southwest onto John Nolan Drive.

Pedestrians, buses, and bikes have priority of movement in the vicinity of the campus and up and down State Street. Automobile drivers must be particularly careful of pedestrians and bicyclists. University Avenue, the extension of West Gorham Street, also has exclusive bicycle and bus lanes, which leave only two lanes for other motorized traffic. The bus and bicycle lanes impede turning movements, especially to the parking ramps at the foot of the campus.

In sum, Johnson and Gorham Streets carry only two lanes of automobile traffic in each direction. Near the capitol and

campus they become the principal choke points within the Madison east-west corridor through the city center. These streets are ill-equipped to handle the 40,000 to 50,000 vehicles per weekday, particularly during peak periods when considerable congestion results. Much congestion occurs at other times of day when pedestrian, bike, and bus traffic interferes with automobile travel. Problems are often most acute when classes let out and thousands of students walk back and forth across University Avenue and Park Street.

Summer road maintenance or improvements in the isthmus plus the university area can all bring traffic to a standstill. It becomes a major incentive for east-west traffic to avoid the central city at all costs. For many consecutive years from the mid 1970s through the early 1980s the east and west sides of Madison were almost inaccessible to one another via the isthmus during the summer when improvements were being made to University Avenue.

Step 7. Examine trends in person trip and goods movement growth

The Madison urbanized area contains about 244,000 people, based upon 1990 Census data. Of this total, 191,000 people live in the City of Madison. The greater Madison area including surrounding communities such as Sun Prairie and Verona, which are outside the urbanized area defined by the census, contains about 300,000 people. Population growth has been steady and moderate over the last 20 to 30 years. Most growth and development have occurred near I-90/94 on the east side and along the Beltline highway.

Traffic count trends at three screen lines near the center of the city indicate steady growth in average weekday motor vehicle traffic volumes through the corridor:

Screen Line	*1980*	*1992*
Midtown	102,000	135,000
Near east side	90,000	107,000
Near west side	117,000	150,000

A 1992 study titled "Transit Corridor Study—Feasibility Analysis of Light Rail and Improved Bus Services," contains population and employment projections for the Madison east-west corridor, as shown in Table 4.16. The Dane County Regional Planning Commission projected that population would decline slightly in the corridor from 42,492 in 1990 to 42,094 in the year 2010, and employment would rise slightly from 64,655 to 67,817 over the same period. Population in the corridor would be 37 percent greater under Scenario A, one of the transit alternatives, than projected by the Dane County Regional Planning Commission. This merely represents a redistribution of overall growth for the Madison urbanized area to areas near and within the corridor due to growth management strategies intended to substantially increase population and employment densities from 1990 levels.

Step 8. Identify any constraints to capacity expansion

Lakes Mendota and Monona and the State Capitol building impose severe constraints on the expansion of road capacity within the isthmus area. Residential areas, two parks, the university campus, and office buildings further constrain the possibilities for expanding the main arteries through the isthmus, particularly Johnson and Gorham streets and University Avenue. Much land near the lakes is environmentally sensitive. State and federal regulations protect some of this land and for all practical purposes keep it from being used for transportation purposes.

Compared with other cities of similar size throughout the United States, the community in Madison is more supportive of nonautomobile modes of transportation. There is strong political support to limit the role of automobile travel near the campus.

Step 9. Develop an initial set of alternatives for dealing with the problem

More so than capacity problems in other corridors, the Madison east-west corridor through the isthmus is particularly conducive to multimodal solutions, mainly due to the community support for nonautomobile forms of travel and the large role that walking, biking, and buses already play. Any of a wide variety of strategies that offer alternatives to single-occupancy automobile travel is worth considering:

- Further restrictions to on-street parking,
- More separated bicycle lanes,
- Pedestrian overpasses,
- Increased ridesharing, and
- Ways to direct more east-west traffic onto routes not through the isthmus.

TABLE 4.16 Population, employment, and density projections for the Madison East-West Corridor

	1990	RPC 2010 Projection	Scenario A 2010
Core Corridor			
• Population	42,492	40,094	57,802
• Employment	64,655	67,817	79,329
• Population Density (Persons/Acre)	14.4	14.3	19.6
• Employment Density (Jobs/Acre)	22.0	23.0	27.0
Total Regional Population	236,087	263,124	263,124
Total Regional Employment	165,746	200,891	200,891

One of the most promising options that has received considerable study in recent years is the establishment of a light-rail line in the corridor, which would make use of considerable existing rail rights-of-way. The transit corridor study cited above explores whether growth management strategies combined with light rail could be deployed for acceptable capital and operating costs, taking into account the ridership that might be attracted.

Five different alignments were considered for light rail, as shown in Figure 4.15. The most promising alignment is as follows:

1. Begins at a park-ride station near West Towne Mall and continues in the median along Mineral Point Road to Whitney Way;
2. Turns north and runs in the Whitney Way median to Old Middleton Road;
3. Continues along the railroad right-of-way to near Hill Farms State Transportation building and then along the rail right-of-way parallel to University Avenue and Campus Drive up to where the tracks cross University Avenue near Randall Avenue;
4. Runs along the north side of University Avenue by the university campus, where it would turn north on Lake Street and onto State Street;
5. Goes up the State Street transit mall and then around the Capital Square in mixed traffic by going south on Caroll Street, east on Main, and north on Pinckney;
6. Extends out East Washington Avenue to East Towne mall and possibly beyond.

Redistribution of population to areas near and within the corridor would be necessary to make light rail feasible at all during the next several decades. In addition, redevelopment of some built land parcels would be necessary to provide enough area to support target levels of employment and housing while achieving densities conducive to light-rail transit. Some of the assumptions for redistributing growth in this manner are as follows:

- Thirty-eight percent of new housing units would be located within ⅓ mi of the light- rail line in the section spanning the central part of the city (i.e., between Hilldale and Union Corners).
- Thirty percent of new jobs would be located within the central business district.
- Housing densities within this core portion of the corridor would lie in the range of 15 to 20 units per acre.
- The Floor Area Ratio (FAR) for employment space would not exceed 3.75, and building heights would not exceed 10 stories (assumes two parking spaces per 1000 ft^2 of development).

Land use changes such as these could have a major impact on transit ridership in the corridor and could increase regional transit ridership by 22 to 25 percent compared with base-level forecasts. The net effect on traffic congestion on the primary east-west routes of Gorham and Johnson Streets is uncertain. Everything else being equal, some diversion of traffic from automobiles, bicycles, and buses to light rail can be expected, and automobile traffic on Gorham and Johnson Streets would be expected to improve in comparison to what it might otherwise be. The question is whether growth management strategies that would increase employment and residential densities in and near the corridor, particularly near the central city, would exacerbate rather than improve congestion if they are combined with the deployment of light-rail transit.

Step 10. Summarize with a brief written statement of the problem

The City of Madison has a serious congestion problem in the east-west corridor passing through the center of the city. With two lakes creating a narrow isthmus, the State Capitol building, and other developments place serious constraints upon expansion of road capacity. Automobile, bus, bicycle, and pedestrian traffic exacerbate congestion and create serious delays common to other central cities of much larger size.

The heavy reliance on nonautomobile modes of transportation is both part of the problem and potentially part of the solution. Rail rights-of-way exist within the corridor that are underutilized from the standpoint of meeting transportation needs.

Like most other cities, growth in Madison has been strongest on the edges. In Madison this has occurred near the East and West Towne malls at the two ends of the corridor.

Perhaps the central challenge is to concentrate growth as much as possible near the central city and existing growth centers within the corridor; exploit the willingness of people in Madison to use other forms of transportation besides automobiles; take advantage of the rail rights-of-way for added transportation capacity; and mitigate the congestion caused by modes interfering with one another particularly near the university campus, State Street, and the State Capitol.

4.7 SUMMARY AND CONCLUSIONS

The steps illustrated in each of the case studies are simple yet helpful in analyzing and finding a solution to capacity problems in the real world. Nothing, however, will replace the analyst's creativity and resourcefulness in seeking potential solutions. Remember also that there is no such thing as a perfect solution. Typically, alternatives will be endorsed by different parties. Each solution may be favored by one or more parties and may be completely unacceptable to the remaining groups. The creative analyst is the person who can see "one more solution" that overcomes the objections of all parties. Ultimately, there are political as well as technical trade-offs that must be made if a project is to progress from

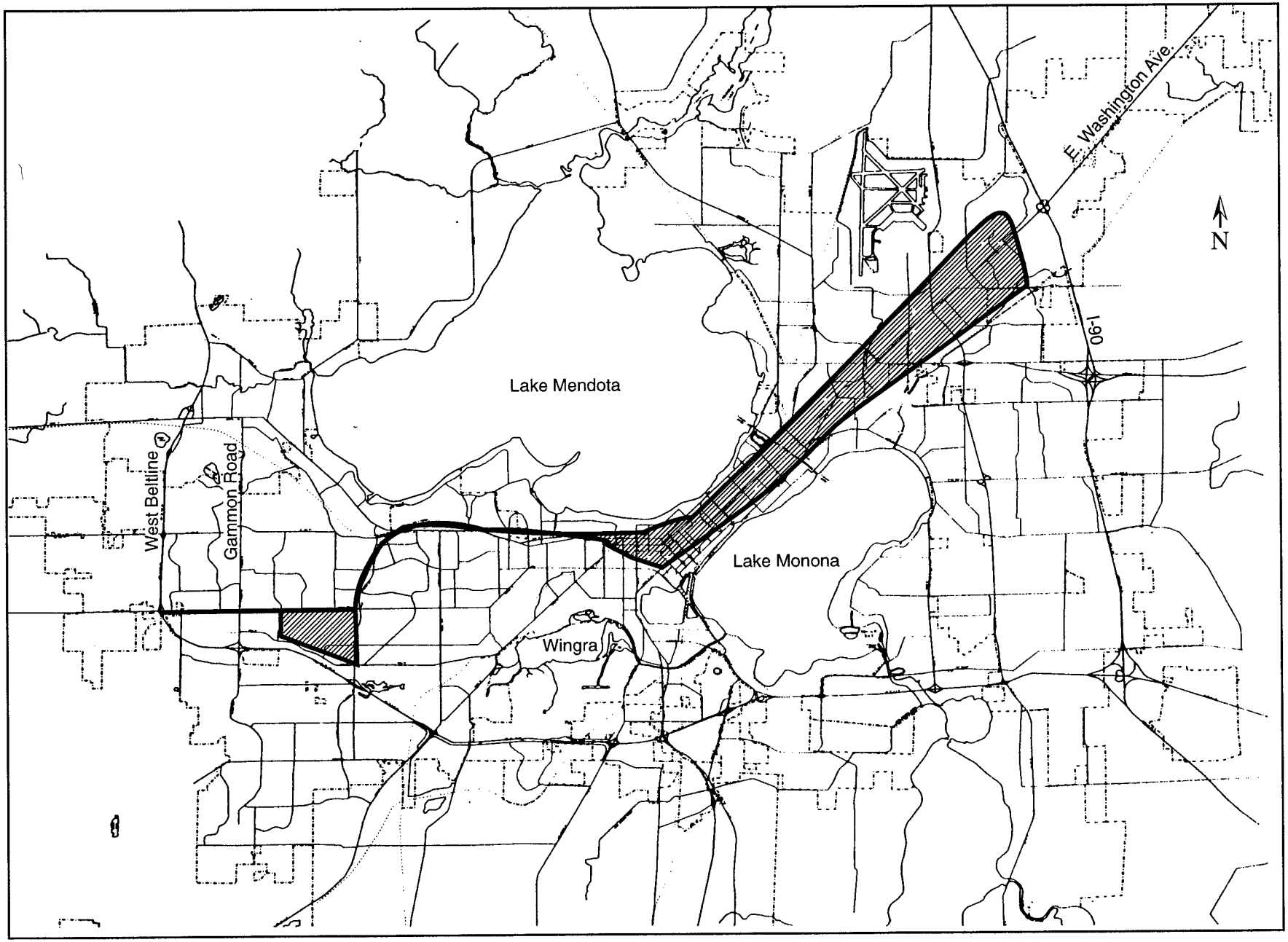

Figure 4.15. Alternative light-rail transit alignments in the Madison East-West Corridor.

a study to a real-world solution. The process described above will not find that compromise solution. It should, however, assist in the search and evaluation process.

4.8 REFERENCES

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CHAPTER 5

CAPACITY DETERMINATION AND ANALYSIS

This chapter builds on the general understanding of the multimodal corridor capacity determination problem and the typologies of corridors identified in Chapter 4. Chapter 5 explains the procedures to use in calculating capacities for vehicle, carrier, person, and freight for various components of transportation corridors. These are the building blocks for estimating the multimodal capacity of a corridor. Procedures for determining the capacity of highways, railroads, waterways, air transport, and pipelines are explained. The capacities of nodes and other transfer facilities including ports are also discussed in this chapter.

5.1 OBJECTIVE

The aim of this chapter is to describe existing procedures for determining the capacity of various components of multimodal corridors in terms of the volume of vehicles, carriers, passengers, or freight traffic per unit time. Modal and multimodal capacity measures can be computed for each of the individual components (links and nodes). The capacity of the corridor can then be described in terms of the capacity of each individual component that makes up the corridor (in case of independent links and nodes); in the case of interconnected links and nodes, the components are combined and analyzed according to their relationships and the allowable/possible movements of traffic on the combined links and nodes. The steps are described below.

5.2 STEPS IN THE PROCESS

1. **Identify and characterize the links and nodes.** The corridor should be broken down into its various components. The types and descriptions of links and nodes that are found in multimodal corridors are described in Chapter 4. Describe the types of movement that exist on these components and the relationships/connections among these components.
2. **Calculate the modal capacity of each component.** Based on physical and operational characteristics, the capacity in vehicles or carriers per unit time of each component is calculated using existing capacity determination formulas provided in this chapter.

   Since some of the links or nodes could accommodate different types of vehicles or carriers, capacities are calculated for each type of vehicle or carrier. If the vehicles or carriers can be converted into a common unit for analysis, the capacities are expressed in those units as well.

   Some of the existing capacity measures are already expressed in passenger or goods movement (e.g., containers per hour serviced by an intermodal transfer facility).
3. **Calculate the multimodal capacity of the corridor.** Convert the vehicular or carrier capacity of each component into equivalent passenger or freight capacities for each component using the maximum occupancy or handling rates of the modes and the applicable measures of goods movement. Qualify and/or quantify how the capacity of each component is affected by the capacity or operating characteristics of other physically or functionally connected components. Determine the overall capacity of the corridor.

5.3 LINK AND NODE IDENTIFICATION (STEP 1)

The capacity determination procedures included in this chapter apply to various links and nodes described in Chapter 4. To begin with, it is desirable to prepare a map of the corridor's key links and nodes. The procedure set out in Chapter 4 is a starting point for identifying the most important links and nodes.

Links should be defined wherever possible so that they pertain to just a single mode of transportation. Thus a traveled way that contains separate facilities for more than one mode needs to be divided first into links unique to each mode. For example, if two inland ports are connected by a railroad and river for barge transportation, the river and the railroad line should each be treated as separate links. In many instances it will not be possible to treat each mode separately (e.g., an HOV lane that carries cars, vans, pickups, and buses). However, a mixed-mode facility such as this can be treated as a single composite mode represented by a vehicle whose length is a weighted average of the different types of vehicles using the HOV facility.

The links should ideally be homogeneous in their prevailing conditions from the standpoint of the type of modal facility, physical characteristics, and operating conditions. However, as we shall explain in the next section, existing capacity determination procedures can be used to account for the changes in physical and operating conditions on some links by applying adjustment factors to the ideal, uninterrupted speeds and flow rates.

5.4 COMPONENT CAPACITY ANALYSIS (STEP 2)

Existing capacity measurement procedures are facility and mode dependent. Traditionally, highways, railroads, waterways, airways, and ports have been treated differently and separately. The capacity of some types of facilities, such as highways, has been treated largely in terms of vehicle movements. Generally, no common approach exists for assessing capacity of intermodal facilities or points of interchange among modes.

An overall approach to capacity analysis involving all modes does not appear to be practical (see Appendix A). However, there are some principles generic to many types of capacity analysis that can be used as a check on the reasonableness of some mode and facility specific capacity calculations. The following formulas should be used with exceeding caution and not in lieu of procedures tailored to specific circumstances.

1. Capacity as the product of speed and density

A standard formula for calculating throughput or rate of flow in many calculations follows:

$$\text{throughput} = \text{speed} * \text{density}$$

This expression means that if N number of objects in a group (e.g., vehicles in a platoon or pedestrians in an escalator) are all moving at the same speed, V, their rate of movement (throughput) is equal to $N * V$. Note that there is at least one combination of speed and density consistent with maximum throughput (or capacity) as follows:

$$\begin{aligned}\text{throughput}_{\text{max}} &= \text{capacity} \\ &= \text{speed}_{\text{at max. throughput}} * \text{density}_{\text{at max. throughput}}\end{aligned}$$

Moreover, this expression for capacity can be used in both two- and three-dimensional analyses.

2. Capacity of a linear traffic facility or guideway as a function of speed, object length, and distance headway

If a linear facility is involved in the analysis, and the objects are arranged in a series (such as a queue of cars in a single lane or a series of rail cars on a single track), the throughput can be expressed in terms of speed, average length of the object, and the average distance between the objects (headway) as follows:

$$\text{throughput}_{\text{linear facility}} = \text{speed}/(\text{average length of object} + \text{average distance between objects})$$

The capacity of the linear facility is determined by at least one combination of speed, length of object, and distance headway that results in maximum throughput.

This formula is a special case of the general formula involving speed and density since, for linear facilities, the linear density is equal to one standard unit of length measurement (e.g., 1 mi or 1 km) divided by the sum of the average length and average headway of each object expressed in the same type of unit as the standard unit of length as follows:

$$\text{linear density} = 1/(\text{average length of object} + \text{average distance headway})$$

3. Capacity of a linear facility or guideway as a function of speed, object length, and time headway

Distance headway and "time" headway (e.g., the time needed to cover the distance between two objects) are related with speed as follows:

$$\text{distance headway} = \text{speed} * \text{time headway}$$

Therefore, the throughput of a linear facility or guideway can be expressed as a function of time headway as follows:

$$\text{throughput}_{\text{linear facility}} = \text{speed}/(\text{average length of object} + \text{speed} * \text{average time headway})$$

4. Capacity of a point or node as a function of processing time or delay

If an object (e.g., a vehicle) comes to a stop at a point (e.g., a traffic light or a toll gate) and remains at that point for a certain length of time (in seconds), the throughput per hour of the point, assuming that all objects encounter the same situation, can be calculated as follows:

$$\text{throughput}_{\text{point}} = 3{,}600 \text{ sec per hour}/(\text{average time at the point in seconds per object})$$

The capacity of the point is equal to the maximum throughput, which occurs when each object spends the minimum average time at the point.

5. Capacity of a linear facility equals the smallest capacity of any segment or point

The segment or point that represents the greatest bottleneck along a linear facility (e.g., link) determines the capac-

ity of that link. For example, let $X_1, X_2, X_3, X_4, \ldots, X_n$ represent the capacities of n segments and points along a link. Then,

$$\text{link capacity} = \min\{\text{cap}(X_1), \text{cap}(X_2), \text{cap}(X_3), \text{cap}(X_4), \ldots, \text{cap}(X_n)\}$$

6. Capacity of parallel and independent links is equal to the sum of their capacities

When two or more linear facilities (links) are parallel and there is no interaction among the objects on each, then capacity (or throughput) can be expressed as follows:

$$\text{capacity of parallel and independent links} = \sum \text{capacities}_{\text{individual links}}$$

The remainder of this section describes techniques of capacity analysis pertinent to specific modes, facilities, and types of traffic. Some of these techniques use the basic relationships or concepts described above. The following sections cover, to some extent, transfer facilities (e.g., ports) measured in terms of passenger or freight movements as opposed to vehicle movements. The following are modal capacity analysis procedures for various links and nodes in a corridor.

5.4.1 Highways

The individual components of the highway system have different capacities. The nodes in most street systems have less capacity than the links that connect them. In fact, the number of lanes is typically increased at intersections to increase the capacity at that point. For example, a left-turn lane and sometimes also a right-turn lane are provided at many intersections. At toll plazas, the roadway may be increased from 2 or 3 lanes to 8 or 10 lanes just to maintain the overall capacity of the node. Traffic signals are coordinated to allow vehicles to pass multiple signals with minimum delay. This increases capacity by eliminating the startup delay and low-capacity portion of movement at traffic lights when the signal changes.

The 1994 HCM (*1*), a TRB publication and the fourth in a series dating back to 1950, provides extensive information to transportation planners on the capacities of various highway components (see Table 5.1), including the impact of various kinds of traffic signals, ramps, weaving sections, curvature, gradient, lane width, and surface type. The HCM contains instructions and guidelines on how to calculate the capacities of highway segments and other facilities under prevailing traffic and roadway conditions. Worksheets and examples are also provided. A variety of computer software is also available commercially and is used extensively by traffic engineers and planners. The software automatically calculates capacity and LOS for highway links and nodes when given a set of input variables.

5.4.1.1 Link Capacity

Capacity Under Ideal, Uninterrupted Conditions. The HCM defines the basic modal capacity of a freeway segment under ideal, uninterrupted conditions as 2,200 passenger cars per hour per lane (pcphpl) for a 4-lane segment and 2,300 pcphpl for a 6-lane segment (see Table 5.1). The basic capacity of a multilane highway is the same as a 4-lane freeway (2,200 pcphpl). Other types of highway links such as 2-lane roads, weaving areas, and 1-lane ramps have lower maximum capacities because their physical design characteristics do not allow vehicle speeds similar to those on freeways and multilane highways.

Past studies of highway traffic volume, speed, and density have resulted in a number of models that presumably describe the relationships between these three traffic parameters. For example, Greenshield calibrated a model from observed data that puts the maximum free-flow volume (or capacity) at 2,240 vehicles per hour (vph) (a vehicle is equivalent to a passenger car). However, according to the model, this can be realized only at an average speed of 23 mph and a density of 98 vehicles per mile (*2*). Greenshield's empirical model for the speed-volume relationship under free-flow conditions is as follows:

$$\text{volume} = 175 * \text{speed} - 4.86 * \text{speed}^2$$

Other speed-volume-density models exist with different functional forms and parameters that have been fitted from empirical data. For example, Greenberg's speed-volume model is as follows:

$$\text{volume} = \text{speed} * (227e^{-(\text{speed}/17.2)})$$

These relationships (shown in Figures 5.1 and 5.2) indicate that traffic volumes under free-flow conditions (high speed, low density) may also be attained under congested conditions (low speed, high density). However, traffic flow is very unstable under congested conditions when vehicle movements are restricted by traffic volume, and often a queue forms. If the queue moves at a constant speed, it is possible to attain the volume specified by the above equations, but low speeds and queues often result in stoppage. Variability in speed among vehicles also affects the movement of traffic, unlike the situation under low-density conditions when different speeds do not restrain vehicle movements because there is enough room to maneuver. The theoretical capacity of a particular highway segment is actually a function of both the density and the speed of the vehicles. If a platoon of vehicles spaced close together (e.g., 200 cars per mile) can move at 120 mph (the maximum speed of automobiles observed on the Autobahn in Europe), then the ultimate capacity of the highway can be calculated ($200 * 120 = 24{,}000$ cars per hour per lane in this example). The density is constrained only by the length of the vehicle and the safe headway at a given speed. Speed, however, is constrained by many factors.

TABLE 5.1 Highway capacity by facility type (*1*)

FACILITY	UNITS	TIME PERIOD[a]	AREA	UNITS OF FLOW	CAPACITY (IDEAL CONDITIONS)
UNINTERRUPTED FLOW FACILITIES					
Freeway					
Basic section, four lanes	Passenger cars	Hour	Lane	pcphpl[b]	2,200
Basic section, six or more lanes	Passenger cars	Hour	Lane	pcphpl	2,300
Weaving area	Passenger cars	Hour	Lane	pcphpl	1,900
Ramp junction	Passenger cars	Hour	Merge or diverge area	pcph	2,000
One-lane ramp	Passenger cars	Hour	Ramp Roadway	pcph	1,700
Multilane highway	Passenger cars	Hour	Lane	pcphpl	2,200
Two-Lane highway	Passenger cars	Hour	Both Lanes	pcph	2,800[c]
INTERRUPTED FLOW FACILITIES					
Signalized intersection	Passenger cars	Hour of Green	Lane	pcphgpl	1,900[d]
Unsignalized intersection					
Two-way stop controlled	Passenger cars	Hour	Lane or movement	pcph	1,060[e]
All-way stop controlled	Vehicles	Hour	Entering Lane	vph	500-1,100[f]
Urban arterials[g]					
Exclusive transit bus lane on urban arterial with stops	Buses	Hour	Lane	bphpl	90-120
Pedestrian Walkway	Pedestrians	Minute	Ft. of effective width	p/min/ft	25
Bikeway	Bicycles	Hour	Lane	bike/hr	2,150[h]

[a] Time periods of 1 hr. are usually based on a peak 15-min volume expanded to an "hourly rate of flow"
[b] Passenger cars per hour per lane.
[c] For 50-50 volume, split by direction.
[d] Saturation flow rate, in passenger cars per hour of green time per lane.
[e] Potential capacity with no conflicting volume.
[f] Depending on volume distribution from conflicting approaches.
[g] Capacity usually measured and controlled by most restrictive signalized intersection.
[h] Middle of reported range.

Because of the instability of forced-flow conditions, and the current observation that free-flow conditions exist even under high traffic volumes approaching capacity and high speeds (which do not follow the relationships described above), the speed-volume relationships used for analysis in the new edition of the HCM have been modified for freeway segments as shown in Figures 5.3 and 5.4. Note that based on these graphs, maximum capacities for freeways can be achieved even at speeds of 60 mph.

Adjusted Link Capacity. An ideal, uninterrupted highway link condition means that there is full access control and there are no restrictions to vehicle movement. Sources of nonideal conditions and uniform linear interruptions to highway traffic that reduce speed and cause delay follow:

a. Grade (vertical alignment),
b. Curvature (horizontal alignment),
c. Traveled-way/pavement distress,
d. Lateral clearance (parking, shoulder),
e. Trucks, tractor-trailers, and vehicles with low speeds,
f. Speed limit, and
g. Weather conditions (visibility).

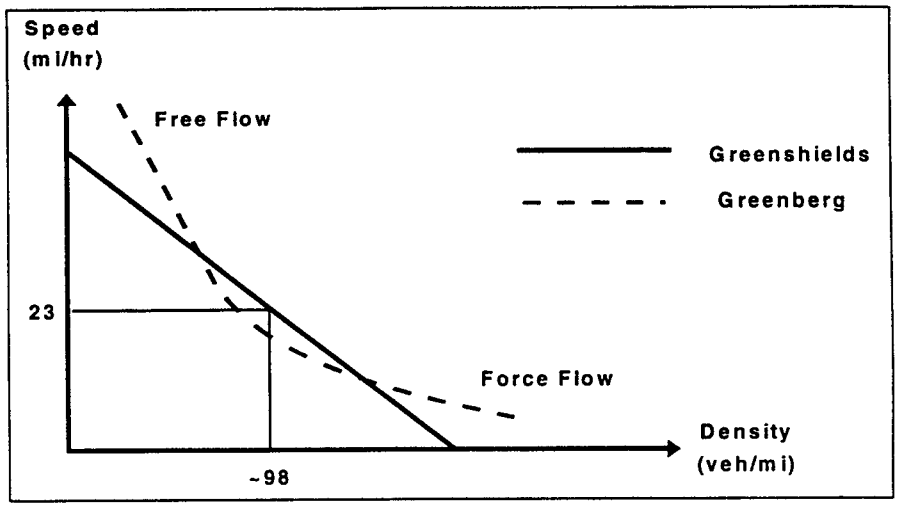


Figure 5.1. Speed-density relationships.

For each type of highway link or corridor these sources of interruptions to ideal traffic flow may or may not apply. For example, most HOV lanes and expressways have full access control and little lateral clearance restrictions, resulting in smooth flow of traffic.

The maximum capacity of a uniform highway segment under ideal conditions is adjusted for the impacts of some or all of the factors identified above, as follows:

$\text{capacity}_{\text{adj}} = \text{capacity}_{\text{max}} * \text{adjustment factor}$

adjustment factor = f(prevailing conditions)

The adjustment factor depends on the type of highway link and the sources of impedance to ideal traffic flow. For example, the expression for the adjusted capacity of a freeway segment from p. 3-11 of the HCM is as follows:

$\text{capacity}_{\text{adj}} = \text{capacity}_{\text{max}} * N * f_w * f_{HV} * f_p$

where

$\text{capacity}_{\text{adj}}$ = flow rate under prevailing conditions,
$\text{capacity}_{\text{max}}$ = maximum flow rate under ideal conditions (depending on design speed),
N = number of lanes,
f_w = adjustment factor for restricted lane widths and lateral clearance,
f_{HV} = adjustment factor for presence of heavy vehicles, and
f_p = adjustment factor for effect of driver population.

The HCM contains a whole gamut of procedures (with step-by-step worksheets) for calculating the capacities of different

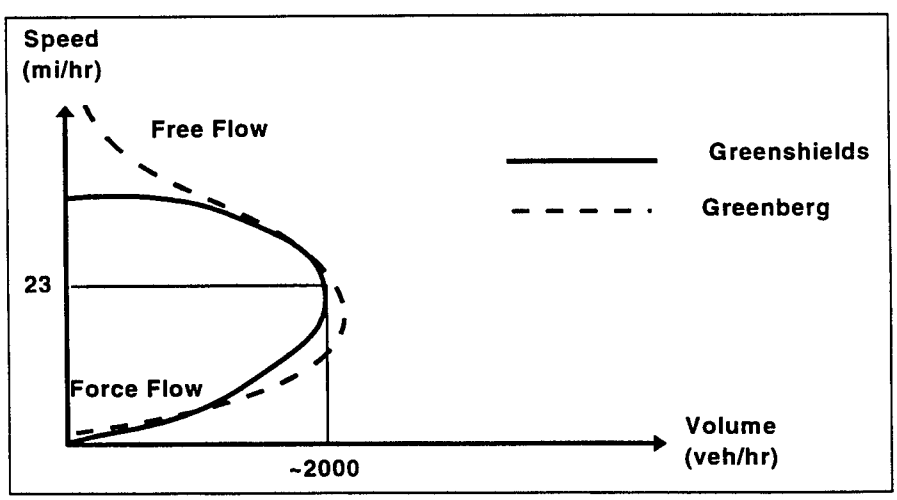


Figure 5.2. Speed-volume relationships.

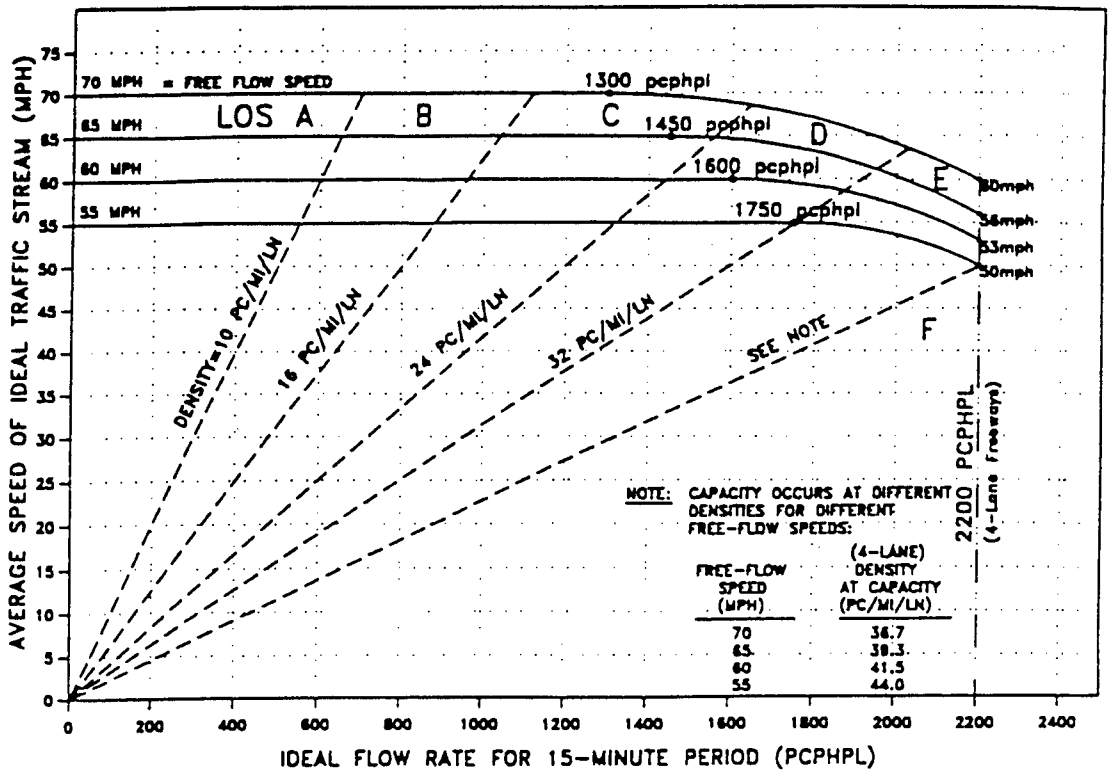


Figure 5.3. Speed-volume relationships for 4-lane freeways (1).

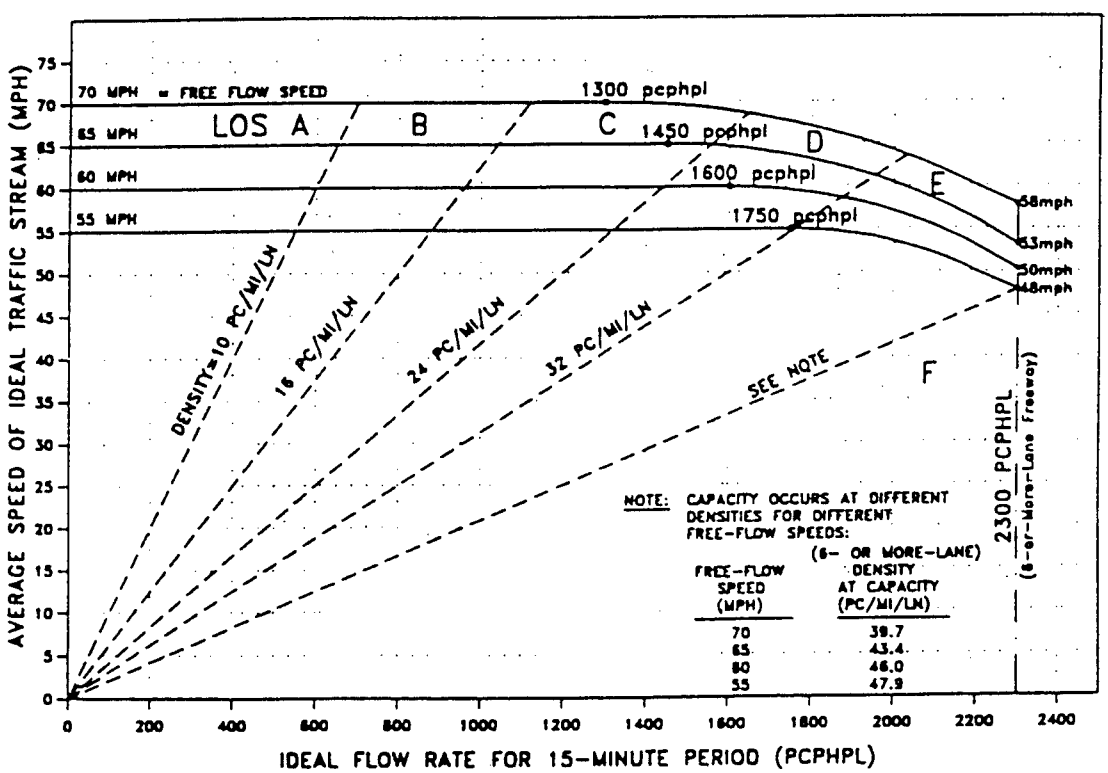


Figure 5.4. Speed-volume relationships for 6-or-more-lane freeways (1).

types of highway links including freeway segments (Chapter 3), weaving areas (Chapter 4), ramps (Chapter 5), multilane and rural 2-lane highways (Chapters 7 and 8), urban and suburban arterials (Chapter 11), and bicycle facilities (Chapter 14). The reader is referred to the HCM for comprehensive and detailed procedures for determining the capacity of these facilities. Some examples are provided below.

5.4.1.2 Nodal Capacity

In highway capacity analysis, point impedances such as signalized and unsignalized intersections, ramp junctions, and toll facilities are analyzed separately from uniform sources of impedances such as speed limits. These components are treated as nodes, and the HCM contains detailed procedures for calculating their capacities under varying conditions (including ideal conditions as shown in Table 5.1). For example, the capacity of a signalized intersection is a function of the number of legs; configuration of the intersection; signal settings (green, red, and yellow times); number of through, right-turn, and left-turn lanes; and types of vehicles on the stream. The free or "saturation" flow of signalized intersections used in the HCM under ideal conditions is 1,900 passenger cars per hour of green per lane (pcphgpl) and is adjusted based on the prevailing conditions (see Table 5.1 above and Chapter 9 of the HCM). Other procedures can be found in the HCM in Chapter 10, Unsignalized Intersections, and Chapter 5, Ramp Junctions. The capacity of toll plazas and other nodal traffic servers is simply equal to the processing rate of these servers expressed in number of vehicles processed per unit time.

5.4.1.3 Person and Freight Capacity

In determining the person-capacity or freight-capacity of highway links and nodes, one needs to know the composition of traffic (e.g., cars, vans, buses, trucks, and tractor-trailers). Since the maximum modal capacity or throughput is expressed in passenger car units (pcu) or vehicles, the actual number of specific types of vehicles is determined from the equivalent pcu. Average person-occupancy and/or freight handling rates of specific vehicle types are used to calculate the person and freight capacities of the highway components. Compared with passenger movements, which can be estimated directly, calculation of goods movement on the highway is complicated because of the different types of goods carried by freight vehicles and the variety of units by which these goods are measured (e.g., weight, volume, dimensions, and dollar value). Section 5.5 explains some of the procedures that can be used to estimate goods movement on corridor components (including highway facilities) for different types of commodity vehicles and carriers.

5.4.1.4 Highway Capacity Examples

Example 1: Link capacity (passenger vehicles). An interstate highway with a 70 mph design speed has 2 HOV lanes for cars, vans, and buses. The highway is on a level terrain, and the width of each lane is 11 ft. There is sufficient lateral clearance and shoulder width on both sides of the road.

Question: What is the capacity of the HOV lanes in vehicles per hour, assuming there are no buses in the traffic stream?

Answer: The traffic volume at capacity of the HOV lanes is equal to the following.

$$V_{HOV} = V_{max} * \text{no. of lanes} * \text{adjustment factor}$$

From the HCM, V_{max} = 2,200 pcphpl for a freeway (with two lanes in each direction). Sources of impedance include restricted lane widths. From the HCM, the adjustment factor for a lane width of 11 ft is 0.95. Therefore, the vehicle capacity of the HOV lanes is

$$= 2 \text{ lanes} * 2{,}200 \text{ pcphpl} * 0.95$$
$$= 4{,}180 \text{ vph}$$

If the traffic stream consists of slow-moving vehicles such as trucks and buses, the capacity should be adjusted to account for their presence. The HCM provides a table of capacity adjustment factors for various percentages of bus and trucks in the traffic stream.

Example 2: Link capacity (passenger and freight vehicles)

Question: What is the vehicle capacity of the HOV lanes in the above example when the HOV restriction is lifted and light trucks can use the lanes? Assume that light trucks constitute 10 percent of the overall traffic stream.

Answer: The adjustment factor to account for the presence of light trucks can be calculated using the procedures in the HCM. The passenger car equivalent (pce) of a light truck on level terrain is 1.5. The capacity adjustment factor is equal to the following.

$$\begin{aligned}\text{adjustment factor} &= 1/[1 + \text{proportion of trucks} \\ &\quad (\text{pce of light trucks} - 1)] \\ &= 1/[1 + 0.1(1.5 - 1)] \\ &= 1/1.1 \\ &= 0.952\end{aligned}$$

The vehicle capacity is equal to the following.

$$\begin{aligned}\text{vehicle capacity} &= 4{,}180 \text{ pcu per hour} * \text{adjustment factor} \\ &= 4{,}180 \text{ pcu per hour} * 0.952 \\ &= 3{,}979 \text{ vph}\end{aligned}$$

Example 3: Link capacity (freight vehicles). Suppose pavement engineers are advocating that the right lanes in both directions of a 9-mi, 8-lane (4 lanes in each direction) highway corridor heavily traveled by trucks be reconstructed to support a 40-year design life and that the right lane be reserved exclusively for vans and trucks. The speed limit on this corridor is 65 mph. There are no impedances to truck flow other than the speed limit and 3 percent vertical gradients less than 0.25-mi in length. Data are available on the type of trucks and average fraction in the traffic stream. This information, along with the estimated pce of the vehicles, is given below.

Vehicle Type	*Fraction of Traffic*	*PCE (3 percent upgrade)*
Vans and pickups	0.27	1.5
Light trucks	0.30	2.5
Heavy trucks	0.43	4.0

Question: What is the vehicle capacity of the exclusive truck lane?

Answer: The free-flow capacity of a single lane in a multilane highway with unrestricted widths and sufficient lateral clearance is 2,200 pcph. To determine the adjusted vehicle capacity, the percentages and pce of the vehicles are used as follows.

$$\begin{aligned}\text{adjustment factor} &= 1/[1 + 0.27\,(1.5 - 1) + 0.30\,(2.5 - 1) \\ &\quad + 0.43\,(4 - 1)] \\ &= 1/3.59 \\ &= 0.3478 \\ \text{vehicle capacity} &= 2{,}200 \text{ pcphpl} * 0.3478 \\ &= 765 \text{ vph}\end{aligned}$$

Individual vehicle capacities follow:

$$\begin{aligned}\text{van and pickup capacity} &= 765 \text{ vph} * 0.27 \\ &= 207 \text{ vans and pickups per hour} \\ \text{light truck capacity} &= 765 \text{ vph} * 0.30 \\ &= 229 \text{ light trucks per hour} \\ \text{heavy truck capacity} &= 765 \text{ vph} * 0.43 \\ &= 329 \text{ heavy trucks per hour}\end{aligned}$$

Example 4: Combined link and node capacity (person and freight). A 2-lane rural road with a maximum speed limit of 50 mph runs between Town A and Town B and carries all types of passenger vehicles and trucks. There are four intersections along the way. Two have stop lights with a cycle length of 120 sec each and an effective green time of 75 sec for the primary road. There are also two 4-way stop signs that each cause an average stop time of 5 sec per light vehicle and 10 sec per heavy vehicle. The road is on a level terrain, and the lane width is 12 ft in both directions with adequate shoulder. Assume that there is a 60-40 traffic split in both directions and that an LOS E is maintained.

Question: What are the person and freight capacities of the links and nodes of this corridor, and what is the total corridor capacity if (1) passenger cars constitute 90 percent of the traffic stream, with the rest single-unit trucks, or (2) passenger cars make up only 30 percent of the traffic stream, single-unit trucks are 60 percent, and buses are the remaining 10 percent? What are the capacities if the at-grade intersections are removed and replaced with overpasses?

Answer: From Chapter 8 of the HCM, the maximum capacity of a 2-lane rural highway under ideal, uninterrupted conditions (LOS E) is 2,800 pcph for both lanes. Single-directional capacity is therefore equal to 1,400 pcph.

Link Capacity. Segments of the 2-lane highway with ideal conditions could achieve the maximum capacity. This ideal capacity can be adjusted to account for the prevailing roadway and traffic conditions as follows:

$$\text{capacity}_{\text{2-lanes}} = 2{,}800 \text{ pcph} * f_d * f_w * f_{HV}$$

where

2,800 = maximum flow rate under ideal conditions (passenger cars per hour),
f_d = adjustment factor for directional distribution of traffic,
f_w = adjustment factor for narrow lane and restricted shoulder width, and
f_{HV} = adjustment factor for presence of heavy vehicles.

1. For 90 percent passenger cars and 10 percent single-unit trucks composition, the adjustment factor f_{HV} can be calculated using the pce of light trucks (2.0):

$$\begin{aligned}f_{HV} &= 1/[1 + \text{proportion of trucks (pce of light trucks} - 1)] \\ &= 1/[1 + 0.1\,(2 - 1)] \\ &= 1/1.1 \\ &= 0.91 \\ f_d &= 0.94 \\ f_w &= 1 \\ \text{capacity}_{\text{2-lanes}} &= 2{,}800 \text{ pcph} * 0.94 * 1 * 0.91 \\ &= 2{,}395 \text{ vph}\end{aligned}$$

2. For 30 percent passenger cars, 60 percent trucks (pce = 2.0), and 10 percent buses (pce = 1.6), the adjustment factor f_{HV} is as follows:

$$\begin{aligned}f_{HV} &= 1/[1 + 0.6\,(2 - 1) + 0.1\,(1.6 - 1)] \\ &= 1/[1 + 0.6 + 0.06\,] \\ &= 1/1.66 \\ &= 0.6 \\ f_d &= 0.94 \\ f_w &= 1\end{aligned}$$

$$\text{capacity}_{2\text{-lanes}} = 2{,}800 \text{ pcph} * 0.94 * 1 * 0.6 = 1{,}586 \text{ vph}$$

Nodal Capacity. There are two types of nodes on the highway—signalized and unsignalized intersections. For the signalized intersection, the adjusted saturation flow rate is equal to the ideal saturation flow (1,900 pcphgpl), adjusted for the impacts of nonideal conditions, and expressed as the following (from Chapter 9 of the HCM):

$$\text{saturation}_{\text{sig}} = 1{,}900 \text{ pcphgpl} * N * f_w * f_{HV} * f_g * f_p * f_{bb} * f_a * f_{RT} * f_{LT}$$

where

N = number of lanes in the lane group,
f_w = adjustment factor for narrow lane and restricted shoulder width,
f_{HV} = adjustment factor for presence of heavy vehicles,
f_g = adjustment factor for approach grade,
f_p = adjustment factor for presence of parking lane,
f_{bb} = adjustment factor for blocking effect of buses,
f_a = adjustment factor for the area type,
f_{RT} = adjustment factor for right turns in the lane group, and
f_{LT} = adjustment factor for left turns in the lane group.

The capacities of the signalized intersections for the two scenarios are as follows:

1. 90 percent of passenger cars and 10 percent single unit trucks

$f_{HV} = 1/(1 + 0.1) = 0.909$
$N = 1$
all other adjustment factors = 1

$$\text{saturation}_{\text{sig}} = 1{,}900 \text{ pcphgpl} * 0.909 = 1{,}727 \text{ vph}$$

$$\text{capacity}_{\text{sig}} = \text{saturation}_{\text{sig}} * \text{green time/cycle length (effective green ratio)} = 1{,}727 * 75/120 = 1{,}079 \text{ vph one direction} = 2{,}158 \text{ vph both directions}$$

2. 30 percent passenger cars, 60 percent trucks, and 10 percent buses (i.e., 70 percent heavy vehicles, pce = 2)

$$f_{HV} = [1/(1 + 0.7 * (2 - 1)] = 0.588$$
$$N = 1$$
all other adjustment factors = 1
$$\text{saturation}_{\text{sig}} = 1{,}900 \text{ pcphgpl} * 0.588 = 1{,}117 \text{ vph}$$
$$\text{capacity}_{\text{sig}} = \text{saturation}_{\text{sig}} * \text{green time/cycle length} = 1{,}117 * 75/120 = 698 \text{ vph one direction} = 1{,}396 \text{ vph both directions}$$

For the unsignalized intersection, the capacity can be estimated as the total number of vehicles that can pass the intersection over a given time period. Knowing that one car needs 5 sec to clear the intersection, and one heavy vehicle needs twice as much time (10 sec), the capacities of the intersection under the two scenarios are as follows:

1. 90 percent of passenger cars and 10 percent single-unit trucks

$$\text{capacity}_{\text{unsig}} = [0.9 * 1 \text{ car/5 sec} + 0.1 * 1 \text{ truck/10 sec}] * 3{,}600 \text{ sec/hr} = 3{,}600/5.26 = 684 \text{ vph one direction} = 1{,}368 \text{ vph both directions}$$

2. 30 percent passenger cars, 60 percent trucks, and 10 percent buses

$$\text{capacity}_{\text{unsig}} = [0.3 * 1 \text{ car/5 sec} + 0.7 * 1 \text{ heavy vehicle/10 sec}] * 3{,}600 \text{ sec/hr} = 3{,}600/7.7 = 468 \text{ vph one direction} = 936 \text{ vph both directions}$$

Corridor Capacity. The capacity of the entire highway corridor is governed by the link(s) or node(s) with the lowest throughput. In both cases, the unsignalized intersection limits the movement of vehicles along the corridor to 1,368 vph both directions (10 percent heavy vehicles) and 936 vph both directions (70 percent heavy vehicles).

If the at-grade intersections were replaced with overpasses, the conditions along the corridor would become uniform and the capacity of the entire highway would be equal to 2,395 in vph both directions for Case 1 and 1,586 vph (both directions) for Case 2.

5.4.2 Rail Transit

Discussions of rail transit capacity determination procedures were mostly taken from the HCM (*1*) and the book *Urban Rail Transit*, by Lang and Soberman (*3*).

Rail transit encompasses a variety of modes—each with distinctive service and performance characteristics. It includes commuter rail lines (both electric and diesel), urban rapid transit (both city and suburban systems), street car, and light-rail transit with both on- and off-street running. Rail transit modes differ not only in rail type but also in station spacing and design, fare structure and collection method, train length and propulsion, degree of access control, and the markets served.

Chapter 12 of the HCM contains guidelines and procedures for estimating rail and bus transit capacities. It describes procedures for calculating passenger flows on rail transit lines for varying car sizes, train lengths, service frequencies, and loading conditions—for both rapid and light-rail transit lines.

According to the HCM, the general capacity of a rail line is determined by station (node) or line haul (link) capacity, whichever is smaller. In many cases, capacity is governed by the station or stop. Capacity depends on the following:

- Car size and train station length,
- Allowable standees as determined by scheduling policy, and
- Minimum spacing (headway) between trains.

The minimum headway is a function not only of dwell times at major stations but also of train length, acceleration and deceleration rates, and train control systems. Time space diagrams can be used to estimate the "safe separation" or minimum headway between trains. Theoretical approaches to estimating the minimum spacing are sometimes used. A more common practice is to obtain the minimum spacing between trains based on actual experience, station dwell times, and signal control systems.

Passenger capacity in the peak direction during the peak hour can be estimated from the following equations:

passengers/hour = trains/hour * cars/train * seats/car * passengers/seat

or

passengers/hour = cars/hour * seats/car * passengers/seat

Based on allowable pedestrian space levels, the following equation may be used:

passengers/hour = trains/hour * cars/train * area/car * passengers/unit area

The latter formulation derives a passenger capacity that is independent of the seating configuration and that directly relates to the area of each car. Cars that maximize total passenger capacity generally minimize the number of seats. The basic values for these equations will vary among individual transit properties and depend on the type of equipment used and the operating policies.

The HCM provides summary ranges of rapid rail transit capacities for U.S. and Canadian operating experiences. If rail car lengths are 50 ft and 75 ft and trains have 6, 8, and 10 cars and operate at a minimum headway of 2 min (30 trains per hour), they have total person capacities ranging from 9,000 passengers per hour (50 ft, 6 cars per train, 0 percent standees) to 101,250 passengers per hour (75 ft, 10 cars per train, 25 percent standees).

Crush load capacities, however, cannot be used in determining the capacity of the rail system. A density of 5 ft^2 per passenger represents a transit LOS D and should be used in planning and capacity analysis. This LOS corresponds to transit capacities ranging from 18,000 passengers per hour (50-ft car, 6 cars per train, 30 trains per hour) to 30,000 passengers per hour (50-ft car, 10 cars per train, 30 trains per hour). Pushkarev formulated comfortable peak-hour capacities ranging from 20,000 to 34,000 passengers per hour (*4*).

The HCM also states that current operating experiences for light-rail systems in the United States and Canada suggest maximum realizable capacities of 12,000 to 15,000 persons per track per hour. However, the European experience shows up to 20,000 persons per hour.

5.4.2.1 Theoretical Rail Transit Capacity

Lang and Soberman (*3*) determined the capacity of a single track by the number of trains that can pass a given point during 1 hr and the number of passengers carried in each train. This relationship is expressed by the following equation:

$$Q = 60k'L/H = 60k'nl/H$$

where

Q = capacity (in passengers per hour passing any given point on a single track),
H = headway (in minutes, 2-min headways are equal to 30 trains per hour),
k' = loading coefficient (in passengers per foot of train length),
l = length of each car (in feet),
n = number of cars per train, and
L = total train length = nl.

The above equation shows that the running train of the longest possible length at minimum headways would theoretically maximize capacity. In the limiting case one would obtain maximum capacity with a continuous, conveyor-type system in which headways were effectively zero, and train lengths were equal to the total length of the route. As a practical matter, limitations on the available supply of equipment and on minimum standards in the quality of service provided render this solution unacceptable. These factors thus have an important bearing on the capacity question.

The general relationship between headway, equipment requirements, and average speed may be inferred from the following equation:

$$N = 60n/HV$$

where

N = approximate number of cars required per mile of single track,
n = number of cars per train,
H = headway in minutes, and
V = average train speed in miles per hour.

The above equation shows that reducing headways to increase capacity can usually be accomplished only at the expense of an increase in equipment requirements. The alternative would be to increase average train speed. However, a reduction in headway usually requires a decrease in speed (for safety reasons). The problem of capacity, then, is not merely one of determining the maximum number of passengers that can be carried past a point in a given amount of time. Rather it is one of determining this number for a given quantity of equipment and with an acceptable quality of service (average speed). Some of the more important factors in analyzing this problem are as follows.

Headway. The basic alternatives in selecting a desirable headway are to use short, slow trains at frequent intervals or longer, faster trains at less frequent intervals. The optimum solution depends on many factors, of which station spacing is probably the most significant. Greater station separations allow higher average speeds and fewer trains. In many cases, this adjustment of train speed, length, and headway to maximize equipment utilization may not be practical. For example, traffic demand may require the use of the longest possible trains (usually determined by the station platform lengths), whereas performance capabilities of the train itself (acceleration, deceleration, and maximum speed) will dictate the average speeds that can be attained. In such cases, the reduction of headways between trains of given length and performance characteristics becomes the major problem.

The problem of reducing headways has always been of interest in the transit industry. It has provided much of the incentive for the development and subsequent improvement in transit signaling systems. Of course, modern block signaling is also designed to maintain a safe distance (that is, headway) between the successive trains in any section of line. This distance is some function of the maximum train speed that will be reached in that section.

In sections containing no stations, for example, the equation relating minimum safe headway to train speed is given by the following:

$$H = t + L/V + 2.03V/d$$

For sections with stations,

$$H = T + L/V + V/2a + 5.05V/2d$$

where

H = headway (in seconds),
t = time required for motorman reaction and brake operation (in seconds),
L = total train length (in feet),
T = station stop time (in seconds),
V = maximum train speed (in feet per second),
a = rate of acceleration (in feet per second^2), and
d = rate of deceleration (in feet per second^2).

These equations show that when block signal systems are in use, smaller headways will be obtained largely at the expense of average speed. With the more sophisticated block signal systems, particularly those using speed control wayside signals or cab signals, this reduction in average speed may not be too significant.

Train length. The time required for a train to travel its own length, denoted by L/V, may be a significant factor in operating with short headways and slow-moving trains. Therefore, if train length is increased, a corresponding increase in train speed is usually necessary if capacity is not to be reduced.

Loading coefficient. The effect of car dimensions and seating and door arrangements on the value of k' used in the equation above are as follows:

- Car length. On most existing rail transit properties, car dimensions (length, width, and height) are fixed by the clearance limits for existing structures and alignments. Where new lines are being constructed, moreover, it may be advisable to adhere to the car dimensions required for other lines, so as to maintain flexibility in the interchange of equipment. Even where this is not the case, length in particular may be limited to that which can be handled by existing repair and maintenance facilities.
- Car width. The same considerations concerning existing clearances apply here as well. Past experience indicates that two-across seating using 38-in. seats provide adequate comfort. For newer equipment using this arrangement, car widths of about 10 ft are common. Again, existing clearance limitations can rule out such widths.
- Seat door and arrangement. The number of seats that should be provided in a car of given dimensions depends on whether one is maximizing comfort or capacity. Floor space use in one locale may be totally unacceptable in another. It is admittedly difficult to approach this question analytically, but its importance cannot be overstated. Utilization of floor space to maximize the number of seats may result in intolerable overcrowding of standees. However, if standing capacity is maximized at the expense of seating, many pas-

TABLE 5.2 Rail line engineering capacity (*6*)

	Automatic Block Signal System		Traffic Control Centralized	
Number of Tracks	Trains per Day*	Gross Tons per Year** (Millions)	Trains per Day*	Gross Tons per Year** (Millions)
Single	40	62	60	93
Double	120	186	160	250

* Total both directions
** Gross tons per route mile; total both directions

sengers for whom this capacity has been provided may not use the facility because they cannot get a good seat. In addition to considerations of passenger comfort and car capacity, the effect of seating arrangement on loading and unloading time (and thus on line capacity) is also important.

5.4.2.2 Rail Transit Capacity Example

Example 1: Rapid rail. A 15-mi segment of a transit line connecting the downtown of a city and a suburban community has two parallel tracks. Operating policies require the train not to exceed 50 mph. Safe operating policy requires that time headways be no less than 2 min, which translates into a minimum distance headway of 1.67 mi, assuming that the speed limit is consistent with operating policy. Trains are composed of two power units 80 ft long at each end, and six passenger cars in between are each 75 ft long. Each power unit has a maximum occupancy of 160 persons, and each passenger car has an average maximum occupancy of 180 persons. There are 12 stations, each requiring 2-min stops. The train accelerates at a rate of 2.9 ft/sec^2 from the station and decelerates at 4.3 ft/sec^2 toward the station. There are two sections with curves along the 10-mi segment, each section requiring the train to slow down to an average of 40 mph for 0.5 mi.

Question: What is the one directional capacity of the transit?

Answer: Since the rail system has transit stations, the minimum time headway between trains is equal to the following.

$$H = T + L/V + V/2a + 5.05V/2d$$

From the given parameters,

T = 2 min = 120 sec (station time),
L = 80 ft/car $*$ 2 cars + 75 ft/car $*$ 6 cars = 600 ft (total train length),
V = 50 mph = 73.33 ft/sec (maximum speed),
a = 2.9 ft/sec^2 (acceleration rate), and
b = 4.6 ft/sec^2 (deceleration rate).

Therefore,

$$\begin{aligned} H &= 120 + 600/73.33 + 73.33/(2 * 2.9) \\ &\quad + (5.05 * 73.33)/(2 * 4.6) \\ &= 120 + 8.2 + 12.6 + 40.2 \\ &= 181 \text{ sec } (\sim 3 \text{ min}) \end{aligned}$$

The capacity can be calculated as follows:

$$\begin{aligned} \text{capacity}_{\text{rail}} &= [2 \text{ cars/train} * 160 \text{ passengers/car} + 6 \text{ cars/train} \\ &\quad * 180 \text{ passengers/car}]/(3 \text{ min/train}) \\ &= 1{,}400 \text{ passengers per train} * 20 \text{ trains per hour} \\ &= 28{,}000 \text{ passengers per hour in one direction} \end{aligned}$$

5.4.3 Rail Freight[1]

Although trains per hour is a useful measure for transit systems, the appropriate modal capacity measure for freight rail is trains per day (*5*). Compared with traffic lanes on highways, railroad tracks provide a more constraining environment. Trains meeting on a single track cannot simply pull off on the shoulders. Instead, they first must look for a sidetrack that is long enough to hold the entire train where it can wait until the second train has passed. If the sidings of a single track are fairly close together, the two-way capacity of the track can approach one-fourth of the capacity of a double track.

The Federal Railroad Administration (FRA) has defined the ultimate capacity of a railway system component under ideal conditions as the engineering capacity (*6*). For rail lines, a fixed capacity is assumed for a given route segment based on one or two simple variables such as signal type and number of tracks. Ideal operating conditions in the lines imply the absence of all the factors that affect or limit their throughput capability. Those conditions include enough yard facilities and evenly spaced traffic throughout the day. They also presume that sidings are long enough to accommodate trains of optimum length. Table 5.2 shows the engineering capacity of rail lines.

[1]The explanations of rail freight capacity determination procedure are mostly taken from a Peat, Marwick and Mitchell Co. parametric study for the Federal Railroad Administration (*5*).

Centralized traffic control increases track capacity by allowing train operations to be controlled more precisely. Two-way operations on a single track always lower its capacity. If high-speed passenger traffic is intermixed with low-speed freight trains, the passenger trains overtake the freights and are delayed if sidings are not available for them to pass (based on the viewpoint that capacity occurs when all trains are proceeding at the same speed).

Other components of the freight rail system that are capacity constraints in the system include rail interchanges (interlockings) and rail yards. It may be desirable to use a different capacity measure for a rail yard than those used on the mainline. Cars classified per day in a classification yard may be more appropriate than trains per day. As in the highway example, it is possible to translate from one set of units into another with knowledge of the situation. That is, if the average number of cars per train is 80, then a yard capable of classifying 800 cars per day can assemble 10 trains per day. It may be more complicated, however, if the classification tracks can hold only 60 cars. In that case it may be necessary to build several groups of cars and then assemble them into a full train only as the train departs. Typically, a train will consist of several groups of cars, so the capacity constraint in a yard may be established by the number of cars that can be handled in one classification run. It could be necessary to reclassify one group into additional separate groups, reducing the throughput capacity of the yard.

Operational and cost analyses of railway systems require an intimate knowledge of their physical and service parameters, including the following:

- Route length,
- Track-mile,
- Track type,
- Communication and control,
- Geometry (curvature, grade, etc.),
- Yard and terminal type and configurations,
- Capacity and associated running times or speeds, and
- Delays for system components as well as overall system and fixed plant operations.

Change-of-mode terminals for handling intermodal trailers, maritime containers, and bulk carloading pose special capacity measurement problems. The capacity constraints are likely to be caused by the number of cranes or other lifting devices such as piggybackers or in the availability of specialized unloading equipment such as vacuum unloaders.

Like highways, many intercity railroads (Class 1) are shared by passenger and freight traffic (the Amtrak's northeast corridor is all passenger traffic). Ownership of these mainline tracks is by freight railroads. Urban rail networks are mostly for passenger mass transportation. Rail passenger capacity, as explained in the previous section, is likely to be constrained by number of stops, maximum number of cars per train, and other factors.

In 1975, Peat, Marwick, Mitchell and Co. (PMMC) developed a train-dispatching computer simulation model for the FRA that simulated the operation of a rail line with up to four tracks for a specified schedule and set of circumstances. The model was used to simulate several hundred different combinations of track, signal, and train configurations and operating policies (*5*). Various mathematical and statistical analysis techniques were used to analyze the simulation results. The application of these techniques was used to develop the mathematical relationships between capacity and various parameters.

In the above study, railway line capacity under ideal conditions presumes that adequate receiving and departure yard/terminal facilities in the system are present. Capacity of railway line is influenced by the following line and operating characteristics:

- Speed limit,
- Distribution of train speeds,
- Siding spacing (single track),
- Distribution of siding spacing (single track),
- Siding capacity (number of trains per siding),
- Siding length versus train length,
- Signal spacing,
- Proportion of multiple track,
- Crossover spacing (multiple track),
- Line profile,
- Train power,
- Train weight,
- Train priorities,
- Traffic imbalances,
- Traffic peaking patterns, and
- Incidence of disruption.

The PMMC study indicated that the occurrence of a rail system lockup (when the volume of trains exceeded the ability of the train dispatching model's logic) could not be used to estimate line capacity. Since true line capacity can be as much a function of the amount of time a dispatcher can devote to bottleneck areas as of the line and train characteristics, true line capacity cannot be defined as the ultimate logical ability to move trains. Therefore, the report defined capacity as a function of delay. To eliminate the element of available dispatcher time, it is implicit in the analysis that a reasonable number of dispatchers be assigned for the traffic to be handled. Parametric analysis of rail line capacity using simulation reveals the sensitivity of delay measured in hours per 100 mi per train per day to the above parameters.

Using regression techniques, these relationships were developed as a function of each parameter. The resulting factors were a measure of the relative sensitivity of average delay per train to the various parameters. The measure of sensitivity similar to the concept of inverse additives used to combine parallel resistances in electronics was particularly meaningful for parameters, such as siding spacing or average

speed, which could easily be represented as continuously variable.

A set of equations was developed to estimate the combined effects of several parameters simultaneously. The equations can be applied to analyze the impact of different line or operating characteristics such as proportion of double track, signal spacing, train priorities, and uniformity on train speeds.

The measure of modal capacity, C, of a railway line (link) in terms of maximum permissible delay was estimated to be as follows:

$$C = A_c/K * (100/L) \text{ trains per day}$$

where

A_c = average delay per train at capacity (in hours, exclusive of scheduled delays),
K = delay slope (for a 100-mi line)
= $f(a - p)$ above, and
L = length of line (in miles).

The value of A_c depends on the number of tracks and operational characteristics of the systems as follows:

Single Track

$$A_c = [-b + \sqrt{b^2 - 4ac}]/2a \text{ (quadratic formula)}$$

where

$a = 973{,}125 * S/L^2$,
$b = (67.2765 * P + 151.7085 * D)/L$, and
$c = 1.41432 - M(150/L) + 150/S + I$.

Double Track

$$A_c = 0.031274 * L * \sqrt{1/S\,(M * 150/L - 150/S - I - 1.84636)}$$

where

M = maximum allowable total running time (12 hours less allowance for terminal time);
S = speed of the slowest class of through freight trains (in miles per hour);
P = dispatch peaking factor
= (trains per peak hour during peak/trains per peak hour during off-peak) − 1;
D = directionality factor
= (trains in dominant direction/trains in opposite direction) − 1; and
I = amount of imposed delays on regular freight trains (such as required stops, including the start and stop time).

The basic relationship between average delay per train and the number of trains per day is as follows:

$$A = K_o * n$$

where

A = average delay per train,
K_o = delay slope, and
n = number of trains per day.

Table 5.3 summarizes the values for the delay slope and other pertinent numerical results of simulation using the base cases and single modification runs on a case-by-case basis. In each line of the table, following the case number and description, are the number of tracks (1 or 2) and a designation of double-running (D) or single-running operation for double-track cases. The next column specifies the number of cases used as the base in the calculations. Most often, the base used is the appropriate primary base case (No. 1, 26, or 43); however, sometimes another base case is chosen as a more appropriate base. In these instances, the fractional slope modification coefficients and related values pertain only to the net modification between the case at hand and the specified base. For example, when the 32.5 mph case (Case 7) is used as the base for the 50 mph modification (Case 8), only the overall speed level is changed. The change from mixed speeds by class to uniform speeds that would have also been involved if the primary single-track base case were used as base has thus been excluded and the change represents only a speed change.

The columns headed K and K_s represent the linear and square slope coefficients for the various cases tested, adjusted for a 100-mi line. K_s may be approximated as $0.05K$, which has been demonstrated to be empirically valid for the values of K below 0.09 The specific line cases in the table can be extended so that delay slopes can be estimated as a function of the base case K for other magnitudes or modifications from a base case and for combinations of modifications. To estimate the effects on delay slopes of changes in parameter values, a fractional approach can be adopted. Using this approach, delay slopes for modified cases were developed as fractions of the base case delay slope. The fractions were normalized to a unit fractional modification by taking the P_ith root of the fraction, as follows:

$$f_{oi} = (K_i/K)^{-P_i}$$

where

f_{oi} = delay slope adjustment factor (obtained from simulations),
K_i = delay slope for the change in parameter i,
K = delay slope for the base case,
P_i = percent change in parameter i
= $(V_i - V_o)/[0.5 * (V_i + V_o)]$,
V_o = value of the parameter in the base case, and
V_i = changed value of the parameter.

TABLE 5.3 Case summary of simulation results—Single modifications (5)

Case No.	Modifications From Primary Base	No. of Tracks D: Double Runs S: Single Runs	Base Case No.	K_i	K_s	P_i	f_{oi}
1	Single Track Base Case	1	--	0.04538	0.001867	-1	0.9450
2	5-mile Segments	1	1	0.03108	0.001324	-0.561	1.7752
3	15-mile Segments	1	1	0.06026	0.003825	+0.510	1.9486
4	21.4-mile Segments	1	3	0.08728	0.004935	+0.353	2.8558
5	Uniform Segments	1	1	0.03387	0.001360	+1	0.7897
6	33% Decrease in Speeds	1	1	0.06421	0.004277	-0.395	0.4154
7	40% Increase in Speeds	1	1	0.02228	0.000713	+0.333	0.1395
8	8 mph Uniform Speed	1	9	0.43867	*	-1.030	0.1124
9	25 mph Uniform Speed	1	10	0.04592	0.002761	-0.270	0.2140
10	32.8 mph Uniform Speed	1	1	0.03029	0.001119	+1	0.7062
11	50 mph Uniform Speed	1	10	0.01288	0.000435	+0.415	0.1221
12	70 mph Uniform Speed	1	11	0.00991	0.000281	+0.333	0.4799
13	1-mile Blocks, 4 Aspects	1	1	0.03515	0.001423	-0.462	1.5379
14	3-mile Blocks	1	1	0.04663	0.001919	+0.609	1.1475
15	1 Block Between Stations	1	1	0.12203	0.006365	+1	2.6890
16	Double Siding Lengths	1	1	0.03932	0.001317	+1	0.9170
17	1.5 Length Trains	1	1	0.04681	0.002020	+0.400	1.0806
18	Double Train Lengths	1	17	0.05609	0.004409	+0.286	1.8823
19	Double Length, One Way	1	1	0.05694	0.003516	+0.667	1.4053
20	Coincident Peaks	1	1	0.04179	0.002345	+0.824	0.9049
21	Separate Peaks	1	1	0.03328	0.002077	+0.824	0.6866
22	1:2 Directional Imbalance, No Rare Events	1	25	0.03169	0.001039	+0.667	0.7834
23	1:4 Directional Imbalance, No Rare Events	1	22	0.02563	0.000870	+0.667	0.7273
24	No Priorities	1	1	0.02981	0.001183	+1	0.6569
25	No Rare Events	1	1	0.03730	0.001540	+1	0.8219
26	Double Track, Double Run Base	2 D	43	0.01067	0.000137	-1	0.6029
27	2 in 3 Segments Single	2 D	28	0.04179	0.001235	-0.424	0.7438
28	1 in 2 Segments Single	2 D	29	0.03685	*	-0.271	0.3438
29	1 in 3 Segments Single	2 D	26	0.02759	*	-0.353	0.0677
30	5-mile Segments	2 D	28	0.00858	*	-0.561	1.4819
31	15-mile Segments	2 D	26	0.00840	0.000162	+0.510	0.6260
32	Uniform Station Spacing	2 D	26	0.00913	0.000164	+1	0.8563
33	33% Decrease in Speed & Uniformity	2 D	26	0.01645	*	-0.395	0.3343
34	40% Increase in Speeds & Uniformity	2 D	26	0.00547	0.000100	+0.333	0.1349
35	1-mile Blocks, 4 Aspects	2 D	26	0.00856	*	-0.462	1.6122
36	3-mile Blocks	2 D	26	0.00958	*	+0.609	0.8346
37	Coincident Peaks	2 D	26	0.01022	*	+0.824	0.9498
38	Separate Peaks	2 D	26	0.00767	*	+0.824	0.6898
39	1:4 Directional Imbalance, No Rare Events	2 D	41	0.00752	0.000092	+0.667	0.9716
40	No Priorities	2 D	26	0.00767	*	+1	0.7168
41	No Rare Events	2 D	26	0.00767	*	+1	0.7187
42	Alternate Direction Crossovers	2 D	26	0.01338	0.000306	+1	1.2520
43	Double Track, Single Run Base	2 S	26	0.00643	0.000052	+1	0.6029
44	2 in 3 Segments Single	2 S	45	0.05574	*	-0.875	0.3286
45	1 in 3 Segments Single	2 S	43	0.02630	*	-0.353	0.0185
46	40% Increase in Speeds and Uniformity	2 S	43	0.00278	*	+0.333	0.0804
47	1-mile Blocks, 4 Aspects	2 S	43	0.00522	*	-0.462	1.5695
48	3-mile Blocks	2 S	43	0.01011	*	+0.609	2.1023
49	Coincident Peaks	2 S	43	0.00856	*	+0.824	1.4139
50	No Rare Events	2 S	43	0.00487	*	+1	0.7257

* Not Calculated.

Table 5.4 presents the policy variables that correspond to the modifications tested and the units in which V_o and V_i were expressed.

Knowing f_{oi} and P_i, the value of K_i can be obtained by rearranging the above equation as follows:

$$K_i = K * (f_{oi})^{P_i}$$

To combine the individual fractional factors, $(f_{oi})^{P_i}$, in multiple modification cases, the method is more complicated. Two components are multiplied, one from all of the individual slope-increasing modifications and the other from all of the slope-decreasing modifications. The product is multiplied by the base case slope to obtain the slope, K_m, for the modified case. For an observed multiple modification, a factor f_{om} can be calculated as follows:

$$f_{om} = K_m/K$$

An estimate of f_{om} from the individual component modifications is as follows:

$$f_{om} = C_I * C_D^{-1}$$

where

C_I = component of factors that increase the slope and
C_D = component of factors that decrease the slope.

Therefore, the multiple modification delay slope is equal to the following:

$$K_m = K * C_I * C_D^{-1}$$

Yard and terminal (e.g., node) operations and capacity are difficult to model because of the individualistic nature of yard designs, operations, and configurations. These transfer facilities provide access to other modes of transportation

TABLE 5.4 Policy variable units (5)

Type	Modification	Policy Variable	Unit (V_1)	Base Value (V_0)
A	Change block size	Average block size	Miles	1.8 mi
B	Change train priority	Train priority	No Priority: 3/2 Base Priorities: 1/2	1/2
C	Change station spacing	Average segment size	Miles	8.82 mi
D	Select uniform or non-uniform speed	Train speed uniformity	Base Speeds by Class: 1/2 Uniform Speeds: 3/2	1/2
E	Change uniform speed	Uniform Train Speed	mph	32.8 mph
F	Change proportional speed	Average Train Speed	mph	32.8 mph
G	Change siding capacity	Siding Capacity	Base Capacity: 1/2 Double Capacity: 3/2	1/2
H	Select uniform or non-uniform segments	Segment uniformity	Non-Uniform: 1/2 Uniform: 3/2	1/2
I	Select dispatch peaking or non-peaking	Fraction daily volume in peak/ Fraction of day in peak	Peaking Fraction	1
J	Select rare events or non-rare events	Presence of rare events	Rare events: 1/2 Non-rare events: 3/2	1/2
K	Change train length	Train length as fraction of base length	Train length as fraction of base length	1
L	Change directional imbalance	No. of trains in heavy direction/ No. of trains in light direction	Directional Imbalance Fraction	1
M	Select base blocks or 1 block between stations	Same as modification	Base block configuration: 1/2 1 Block between stations: 3/2	1/2
N	Select full cross-over or alternate directional cross-overs	General double-track crossover flexibility	Full: 1/2 Alternate: 3/2	1/2
P	Change fraction double track	Fraction of line mileage with double track	Double: 1 1-in-3 Single: 0.7 1-in-2 Single: 0.533 2-in-3 Single: 0.3467 Single: 0	0 or 1

such as buses, cars, trucks, barges, and airplanes. Yard operations that affect capacity are arrival and inbound inspection, train break up and classification, waiting to make connections, train marshaling or assembly, and outbound inspection and departure. Other parameters include geometry, yard crews, and class track assignments.

Rail freight capacity of a yard or terminal can be calculated using the following expression:

ton-capacity = trains/hour ∗ cars/train ∗ ton/car

5.4.3.1 Rail Freight Capacity Example

Example 1: Mainline capacity. A rail mainline 50 mi long with one track in each direction is in a mountainous region and supports an operating speed of only 25 mph. There are eight highway at-grade crossings along the route that cause the train to slow down to 10 mph on each ½-mi segment. The average block length for the track is 2 mi and the side spacings are 7 mi. Traffic moves evenly on both directions.

Question: What is the capacity of the mainline?

Answer: There are three modifications from the base case (see Table 5.3).

1. Average speed is equal to (25 mph ∗ 46 mi + 10 mph ∗ 4 mi)/50 mi = 23.8 mph, compared with the baseline value of 32.8 mph;

2. Average block length is 2 mi, compared with base value of 1.6 mi; and
3. Average side spacing is 7 mi, compared with 8.82-mi base value.

Using the fractional approach to delay slope adjustment, the fractional changes in parameters are as follows:

$$P_{speed} = (23.8 - 32.8)/[0.5 * (23.8 + 32.8)] = -0.318$$

$$P_{block} = (2.0 - 1.6)/[0.5 * (2.0 + 1.6)] = 0.222$$

$$P_{siding} = (7 - 8.82)/[0.5 * (7 + 8.82)] = -0.230$$

Changes in average speed are slope-decreasing modifications, whereas changes in block length and side spacing are slope-increasing modifications.

From Table 5.3 (single modifications), the adjustment factors are as follows:

$f_{o,speed} = 0.3343$ (Case 33),

$f_{o,block} = 0.609$ (Case 36), and

$f_{o,siding} = 1.4819$ (Case 30).

Using these factors, the components of factors that change the slope are as follows:

$$\begin{aligned} C_{Inc} &= 0.6090^{0.222} + 1.4819^{-0.230} - (2 - 1) \\ &= 0.896 + 0.914 - 1 \\ &= 0.81 \end{aligned}$$

$$\begin{aligned} C_{Dec} &= 0.3343^{-0.318} - (1 - 1) \\ &= 1.42 \end{aligned}$$

Then, the multiple modification factor is calculated as follows:

$$\begin{aligned} f_{om} &= C_I * C_D^{-1} \\ &= 0.81 * 1.42^{-1} \\ &= 0.57 \end{aligned}$$

The modified delay slope is equal to the following:

$$\begin{aligned} K_m &= K * 0.57 \\ &= 0.01067 * 0.57 \ (K = 0.01067 \text{ from Table 5.3, Case 26}) \\ &= 0.0061 \end{aligned}$$

The average delay per train at capacity (for double track) can be calculated using the following parameters:

$M = 11$ hr (assuming terminal time of 1 hr),

$S = 25$ mph,

$P = 1 - 1 = 0$,

$D = 1 - 1 = 0$,

$L = 50$ mi, and

$I = 1.233$ (assumed equal to base case).

$$\begin{aligned} A_c &= 0.031274 * 50 \\ &\quad * \sqrt{1/25 * (11 * (150/50) - 150/50 - 1.233 - 1.84636)} \\ &= 0.031274 * 50 * 1.0377 \\ &= 0.1622 \text{ hr per train.} \end{aligned}$$

The capacity of the track is equal to the following:

$$\begin{aligned} C &= A_c/K * (100/L) \text{ trains per day} \\ &= 0.1622/0.0061 * (100/50) \\ &= 53 \text{ trains per day} \end{aligned}$$

5.4.4 Air Transportation

Growth in demand for air transportation requires the addition of new facilities or better use of existing facilities or both. The airspace practically has infinite capacity to handle air traffic between any two locations. Airport facilities and operations are the major determinants of the capacity of air transport systems and are primary sources of congestion. An airport may be divided into two parts: the *airside* (runways, taxiways, and air traffic control systems used by aircraft and pilots) and the *landside* (aircraft parking positions and gates, terminal buildings, baggage services, access roadways, and automobile parking structures used by passengers).

From the standpoint of corridor analysis the most appropriate measure of air transport capacity is the volume of passengers and tonnage of freight that can be handled by air from one location to another. Both the airside and landside components of airports are restricted in terms of the maximum number of passengers or amount of cargo that can be serviced at a given point in time.

Airside capacity is defined by the Federal Aviation Administration as the maximum number of aircraft operations (i.e., arrivals and departures) that can take place in an hour. This modal capacity is expressed as the maximum throughput rate. Service volume is the volume of traffic with particular demand characteristics that can be accommodated by a functional component or group of components during an analysis period at a given service level. Service level is measured in terms of delay, crowding, and availability of passenger amenities for comfort and convenience.

The dominant factors that affect airside capacity are as follows:

- Configuration and number of runways, taxiways, and aprons;
- Availability of aids to air traffic control facilities (approach and landing aids);
- Aircraft size, speed, ground maneuverability, and braking capability;
- Visibility, winds, and weather;
- Runway surface conditions;
- Noise abatement requirements;
- Operating strategy for runway; and
- Air traffic control rules.

Runway capacity has been defined in two ways: (1) practical capacity that corresponds to a tolerable level of average delay and (2) ultimate capacity, which is the maximum number of aircraft that can be handled during a given period under conditions of continuous demand (there are always aircraft ready for takeoff or landing) (*7*). Maximum runway capacity is reached when the total runway occupancy time is equal to the time headway between landing aircraft as follows:

$$C = 7{,}200/(t_a + t_d)$$

where

C = runway capacity (operations per hour),
t_a = runway occupancy time of arriving aircraft (seconds)
= $a * v + b$,
v = approach speed of landing aircraft (100 mph $\leq v \leq$ 170 mph),
a, b = positive constants, and
t_d = runway occupancy time of departing aircraft (seconds)
= 60 (heavy aircraft), 50 (others).

Landside capacity is the capability of the landside or its functional components to accommodate passengers, cargo, ground transport vehicles, and aircraft. Service volume is the principal indicator of landside capacity (*8*). Components of landside facilities that are critical for capacity determination are as follows:

- Aircraft parking position and gate,
- Passenger waiting area,
- Passenger security screening,
- Terminal circulation (stairs, corridors, etc.),
- Ticket counter and baggage check,
- Terminal curb,
- Parking area,
- Ground access,
- Baggage claim,
- Customs and immigration, and
- Connecting passenger transfer.

The capacity of the landside system of a particular airport taken as a whole is more difficult to assess than that of an individual component. LOS of the terminal system as a whole includes total processing time for the enplaning and deplaning passenger, which is the sum of the service time at each component, the wait time at each component, and the travel time between components that make up the system.

Air passenger and freight transportation usually involve long distances and demand short trip times. The modal capacity of an airport to serve demand for transportation between two cities can be measured by determining the number of flights made per hour or per day from the city of origin to the destination. The number of landings and takeoffs (airside) on the O-D pair of airports can be multiplied by the maximum person occupancy, freight occupancy, or both to determine the multimodal capacity. For each airport the total handling capacity corresponds to the maximum hourly or daily service volume at the landside/terminal facilities and the maximum total number of landings and takeoffs in the runways (regardless of aircraft destinations) multiplied by the maximum person/freight occupancy of each aircraft.

Performance and LOS measures for air transportation include terminal processing and waiting time (parking, security, check-in, baggage claim, etc.), in-flight time, transit time, total trip time, noise, and comfort.

5.4.4.1 Air Transport Capacity Example

Example 1: Intercity air corridor. Two cities, A and B, both have an airport that serves passenger and freight aircraft. The airports have the following characteristics:

Airport A
percentage of daily flights to City B = 5 percent of total flights
passenger flights = 85 percent of total flights

Airport B
percentage of daily flights to City A = 8 percent of total flights
passenger flights = 90 percent of total flights

Question: What is the ultimate intercity corridor capacity between Cities A and B, assuming that the average runway occupancy time of departure is 60 sec and the average runway occupancy time of landing is 65 sec? Assume that the capacity of landside facilities exceeds airside capacity.

Answer: Each airport has an ultimate capacity as follows.

$$C = 7{,}200/(65 + 60)$$
$$= 57.6 \text{ aircraft per hour}$$

Following are the maximum numbers of passenger and freight aircraft that can be served by the corridor:

$$C_{pass} = 57.6 \text{ aircraft per hour} * 0.85 * 0.05 + 57.6 \text{ aircraft per hour} * 0.9 * 0.08$$
$$= 6.6 \text{ passenger aircraft per hour}$$
$$= \sim 1 \text{ passenger aircraft every 10 min}$$

$$C_{frei} = 57.6 \text{ aircraft per hour} * 0.15 * 0.05 + 57.6 \text{ aircraft per hour} * 0.1 * 0.08$$
$$= 0.9 \text{ freight aircraft per hour}$$
$$= \sim 1 \text{ freight aircraft per hour}$$

5.4.5 Waterway Transportation

Waterway transportation is a very broad term that refers to the movement of goods and people between two points by means of vessels operating between ports that make up a part of the total door-to-door movement. Within this broad context, waterway transportation serves as a key link in a truly intermodal system. In a great majority of cases, goods in waterway transportation are neither produced at the port of origin nor consumed at the port of destination. Therefore, a need almost always exists for movement by surface modes to and from ports.

Waterway transportation consists of two major components: (1) the body of water (link) across which vessels carry goods and people and (2) the ports (nodes), which permit vessels to berth in order to load and unload cargo and passengers.

5.4.5.1 Vessels

A large variety of vessels are in use in water transportation service depending on the nature of the commodity (liquid/dry-bulk, neo-bulk, containerized, etc.) and water route characteristics (trip distance, channel depth, lock size, trade route, etc.).

Vessels carrying passengers range from large ocean-going liners and cruise ships capable of overnight on-board accommodation to much smaller ferries in local service and specialized vessels such as car ferries, which cater to trucks, buses, and automobiles. Although most passenger ferries are equipped with conventional propeller drives, light air-cushion vessels are increasingly being used for passenger transport at higher speeds.

The type and capacity of vessels carrying freight are more numerous than passenger ships and ferries. Bulk liquid goods not packaged in barrels, drums, or other containers are carried by tankers across open waters and tank barges in rivers and inland waterways. Barges are not self-propelled and, therefore, must be towed in groups by towboats. Barge sizes are restricted by lock dimensions in inland waterways. A typical tank barge operating in the Mississippi River system measures 290 by 50 by 12 ft and can carry 2,900 tons of petroleum products (*9*). Tanker sizes, on the other hand, range from 26,000 dead weight tons (dwt) generally used in intracoastal trades to ultralarge crude carriers of nearly 600,000 dwt used in long distance crude oil trade.

Dry-bulk goods such as granular commodities (grain, ore, and coal) are carried by bulk carriers ranging in capacity from 2,500 tons for barges to 370,000 dwt in ocean transportation. A variation known as ore-bulk-oil (OBO) carriers are adaptable for use either as a liquid or dry-bulk carrier in order to reduce the share of ballast (empty) trips.

Conventional vessels are used to carry general break-bulk goods, which are in small packages, bags, or boxes and generally unitized on small pallets. Automobiles, a type of neo-bulk cargo, and containers on chassis are best handled by roll-on/roll-off (ro/ro) vessels. Containerized cargo stowed in standard 20- or 40-ft-long shipping containers are mostly handled by container ships with a capacity range from 750 TEUs for first-generation container ships of 14,000 dwt to 3,000 TEUs for third-generation ships of 40,000 dwt.

Special container ships that do not require installation of expensive shore-based handling equipment have been developed. One example is lighter aboard ship (LASH), which consists of a barge-carrying type of container vessel to which barge containers are towed and lifted aboard by the ship's large gantry cranes of 500-ton capacity. Another type of vessel is an ocean going catamaran design in which the bow section opens like a bear trap to admit 10 barges into the space between its hulls. Once inside, the barges are lifted mechanically and locked into place (*10*).

5.4.5.2 Ports

Direct and Indirect Cargo Transfer. Ports provide the intermodal interface between waterway and surface modes of transport. The port's primary function is the transfer of cargo and passengers between the water and inland carriers. To accomplish this function, the port must provide berthing space for the vessel to dock so that cargo and passengers can be loaded/unloaded.

In the past, many ports provided direct transfer at the apron, which minimized the need for storage areas and sheds. Although direct transfer is still in use in private piers exclusively dedicated to handling only one type of bulk cargo, its use in general cargo terminals is allowed only for heavy loads and large cargo. The more common transfer operation is between ship and transit area, allowing onward transport from transit area to ultimate destination by inland carrier.

Because of the need to provide indirect transfer, adequate storage areas are needed at the port. In addition to storage, the ports also perform auxiliary functions such as vessel servicing, cargo marketing and processing, customs, etc.

Types of Ports. Ports can be grouped in a number of ways depending on classification criteria. With respect to ownership of port facilities, a distinction can be made between private and public ports. Private ports or terminals are owned and operated privately; they are generally small and used for a specific or a very limited number of goods. Public ports are larger, can handle a variety of cargo types, and offer their services to the general public.

With respect to functional complexity, ports can be classified as integrated versus specialized ports. A specialized port handles only one, or a limited number, of goods; is equipped with special cargo handling equipment that is capable of efficiently handling a limited variety of goods; and is operated by a private company as part of its transportation/distribution system. Its hinterland is limited to the location of manufac-

turing or processing centers to and from which the cargo is shipped and received. An integrated port, on the other hand, has berths and facilities to handle a variety of goods and different types of vessels. Most public ports are integrated and serve a larger hinterland with many shippers or consignees of cargo.

Ports can also be classified by the types of trades they serve. Inland waterway ports are geared toward domestic trades, mostly by barge; they can handle a limited variety of bulk goods; and because of limited water depth, cannot accommodate large ships. Some coastal ports are geared toward intracoastal trades with small vessels. Deepwater ports can handle ocean-going vessels in intercoastal and international trades and offer integrated facilities serving a large hinterland. Great Lakes ports constitute a special case because they serve smaller vessels (because of the size restriction of locks in the St. Lawrence Seaway system) in international trades; operate only 8 months a year (because of winter ice conditions); and display characteristics of inland, intracoastal ports while operating in overseas trade.

5.4.5.3 Waterway Transportation Capacity

Differences between waterway link (river, channel, or coast) and node (port) operations make it is necessary to distinguish between the two major components of waterway transportation when estimating capacity. Capacity for individual components is described first, then the interrelationship between the two components at the berth where the vessel meets landside facilities is established.

Capacity of Vessels. In marine trade, the capacity of a vessel is generally defined in terms of the maximum cargo weight that can be loaded aboard its hulls. Dead weight tons (dwt) of the vessel is commonly used as an indicator of this capacity. Assuming unitary cargo density and full space utilization, the vessel should be loaded up to the dwt under conditions of ideal operation such as no wave, wind, or other environmental factors that affect the safety of the vessel and its cargo. However, such favorable conditions can never be attained. Therefore, using dwt as a capacity figure would have no more than an academic purpose.

In addition to this limitation, using dwt as an indicator of vessel capacity is conceptually wrong because it does not allow an expression of capacity based on deliverability of a physical quantity per unit of time such as tons per day. A large vessel carrying 50,000 tons of cargo to a port once a month has a lower capacity than a smaller vessel carrying 20,000 tons three times a month to the same port. When capacity is expressed within this context, it becomes a function of voyage length, speed, time at port, weight of cargo loaded, number of days vessel remains in service, and the ratio of laden trip length to voyage length:

$$Q = [(365 - I) * 24 * B * (T_o + T_d)]/[(L/V) + O + D]$$

where

Q = vessel capacity (in tons per year);
I = number of days per year the vessel is laid up for repairs and maintenance;
B = percent of the two-way trip length the vessel is laden; $0.00 \leq B \leq 1.00$ (when B = 1.00 the vessel is always loaded; when $B = 0.00$ the vessel is always empty);
T_o = tons loaded aboard at origin port;
T_d = tons loaded aboard at destination port;
L = two-way voyage length (in miles);
V = average vessel speed under steam (in miles per hour);
O = hours at port of origin to load; and
D = hours at port of destination to unload.

The value of Q can be expressed in tons per day by dividing the computed annual value by 365. The above equation implies that a vessel operates year round between two ports in a specific trade route. In cases of multiple port operations, the equation can still be applicable by treating each port called as the port of origin for the next leg of the ship's voyage; computing a weighted average value for B, which represents a vessel load capacity utilization rate; and defining L as a one-way distance.

Ship operators view the value of Q as revenue tons because liner freight rates between two ports are generally established on the basis of either weight ton (for goods with high density) or measurement ton (for low-density goods). The higher the value of Q per year, the higher the gross revenue the ship owner realizes. It is, therefore, natural to expect that the following developments in the past in vessel technology and operations will continue in the future:

1. Size of vessels has increased allowing the ship owners to carry more tons per trip. This is especially true with tankers and bulk ore carriers. Increase in vessel size is possible only by increasing the length, beam, and draft. The relationship between ship size and draft for tankers and dry-bulk carriers of 10,000 to 500,000 dwt can be represented by the following rule of thumb taken from *Port Development: A Handbook for Planners in Developing Countries* (*11*):

   $$DWT = (D - 5)^2$$

   where

   DWT = vessel dwt (in thousands) and
   D = vessel draft (in meters).

   Using the above rule, a bulk carrier of 400,000 dwt has a draft of 25 m when fully loaded. Increasing ves-

sel dimensions make it increasingly difficult for most ports to accommodate large ships at shore-based berths. This pressure results in development of artificial islands and platforms in offshore areas where deep water is available. In some cases these offshore structures include storage facilities to support transshipment operations by barges and coastal tramps. Another recent development for offshore liquid cargo loading and discharge is the single-point mooring system allowing the tanker to take up the most favorable position with regard to sea currents and winds by rotating around the buoy.

2. Vessel speed has increased. This is especially true with container ships. In the case of tankers, increasing vessel size provided a better tradeoff than increasing speed. Therefore, tanker speeds have not changed appreciably. However, in the case of container ships, the ship owners were able to achieve increased load capacity as well as speed.
3. Pressure at ports to reduce port time (which is not revenue time for ship owners) resulted in increased investments in specialized cargo handling equipment and facilities; more berths to reduce average ship waiting time for berth space; improvements in shore-based terminal operations to remove congestion; guaranteeing berth space or assignment of dedicated terminals and berths to liner operators calling the port on a regular schedule; and developing specialized vessel technology alternatives such as LASH, ro/ro, Seabee, catamaran straddlers, etc., to minimize port time.
4. A tendency to call as many ports as possible in order to increase the value of B in the expression for Q above has been offset by the increase in the percent of ship's time spent at ports. New vessels were developed (such as OBOs) to improve the ship's capability to carry a wider variety of bulk goods.

Capacity of an Inland Waterway. If one watched a waterway, one would see an occasional tow steaming between locks and a number of tows queued at each lock awaiting service. If the number of tows were increased, the principal effect would be an increase in the number of tows queued at locks. Bottlenecks determine capacity, and it is the lock that determines the capacity of a waterway (*12*).

More precisely, an inland waterway may be described as a serial processing system since a tow must traverse the waterway in prescribed order to move from origin to destination. Under these conditions, the capacity of a system is determined by the slowest-serving facility (the narrowest bottleneck). For a waterway, the service rate of the lock determines capacity.

The physical capacity of a waterway might be measured in terms of the number of barges that could be locked through in the course of a year. These barges arrive in tows, and the rate at which tows can be served is inversely related to the number of barges in tow. Thus, the number of tows that could be served in a year depends on the size of the tow. If all tows were the same size, the capacity could be calculated as follows:

$$K = 8{,}760 * m(b)$$

where

K = waterway capacity (in tows per year);
8,760 = number of hours in a year;
$m(b)$ = service rate of the most constraining lock (in tows per hour) [note: the inverse, $1/m(b)$, is the service time for each tow]; and
b = average number of barges in each tow.

Using the above equation, the number of barges that can be serviced in a year is equal to $K * b$. The equation is based on the assumption that there is always a tow ready for service when the previous tow is through the lock. Thus, tows must be scheduled to arrive at the proper time.

Capacity of Ports: Intrinsic Versus Practical Capacity. Any method used to estimate the capacity of ports must recognize that practically every port is unique in terms of its facility configuration, operation, cargo types, and service parameters. In addition, the capacity of a port may be viewed as its intrinsic capacity, a level of throughput that can be attained under ideal conditions of berth utilization and zero bottleneck at various sections of the port used for cargo storage and transfer. As opposed to intrinsic capacity, an actual attainable throughput level computed by taking into account realistic operating conditions at the port would represent practical capacity. In this sense, practical capacity represents typical cargo throughput based on actual working conditions. The following illustration represents the distinction between intrinsic and practical capacity.

A break-bulk general cargo terminal with one berth operates two 16-hr shifts per day for 240 days per year (excluding weekends, federal holidays, and downtime for repair and maintenance). The berth is used exclusively on liner trades with a predictable schedule of call and minimal time between ship arrivals. Given these favorable conditions, the terminal is able to maintain an average berth occupancy of 80 percent and a ratio of 0.90 for work time to total ship time at berth. In other words, the berth is occupied 80 percent of the time and the vessel is worked 90 percent of the time while at berth during operating hours. Each vessel is served by six longshoreman gangs at the apron with a productivity rate of 15 tons per hour per gang. The ideal conditions represented by these assumptions will yield a daily berth capacity of 1,440 tons or 248,832 tons per year at $0.80 \times 0.90 = 72$ percent berth utilization. This estimate would represent intrinsic capacity for the berth.

Assumptions of more realistic berth conditions reduce the berth utilization rate considerably. To begin with, about 45

percent of oceanborne foreign trade through U.S. ports is handled by vessels in unscheduled (tramp) service (*13*). Therefore, uniform and predictable interarrival rates between vessels with minimum interarrival times is highly improbable. A more realistic berth occupancy suggested by United Nations Conference on Trade and Development (UNCTAD) is a maximum of 40 percent (*14*). Assuming a vessel work ratio of 0.75 yields a berth utilization of 30 percent. In addition, typical gang productivity rates in U.S. general cargo terminals is 14 tons per hour with 12 working hours per day (*15*). Given these operating conditions, the practical berth capacity is 72,576 tons.

Types of Cargo. Another consideration in developing methods to estimate port capacity is to recognize the vast variety of cargo types in water transportation. Goods in liquid and solid form packed in different ways and sizes require different types of vessels and port facilities.

For example, liquid-bulk goods not packed into barrels or containers are shipped by tankers and require surge storage tanks and pipeline facilities on shore to affect transfer between water and land transport modes. Tankers generally spend about 10 percent of their total trip time in port. The same liquid cargo packed in barrels shipped either as individual units or on pallets generally arrive at the port aboard conventional cargo liners. These vessels spend 30 to 50 percent of their total round trip time at port and require cargo transfer equipment and facilities to accommodate ship to apron, apron to storage yard, and yard to inland transport transfers. Liquid cargo packed in barrels that are stowed in 20-ft containers is another type of cargo. It generally arrives at port aboard container ships, which require container-handling equipment such as gantry cranes to allow transfer. Dry-bulk goods in granular form (grains, ores, and coal) arrive at port aboard bulk carriers, which require specialized bulk-handling, storage, and transfer equipment.

It is neither possible nor meaningful to develop a capacity formula that is applicable to all types of cargo. A distinction is made for the following types of cargo:

1. Bulk cargo either in liquid or dry form, is homogeneous in its composition and is predominantly handled in large quantities. For most bulk cargo, the transportation vehicle (vessel, tank truck, railroad car, barge, etc.) is the container. Because of its uniformity, highly mechanized handling equipment with high productivity has been developed to load/unload bulk cargo at ports. Because of differences in shipping and handling equipment, bulk cargo is further divided into two types:
   - Liquid-bulk cargo, such as crude oil, petroleum products, and vegetable oils not packaged in barrels, drums, or similar containers; and
   - Dry-bulk cargo, such as grains, metallic ores, and coal not packaged in barrels, drums, or similar containers.
2. General cargo consists of goods packaged in separate units of various sizes, weights, and shapes. Different equipment needs also further divide general cargo as follows:
   - Break-bulk. Miscellaneous goods in small packages, bags, or boxes. Break-bulk goods are not containerized and are usually loaded and unloaded on small pallets by ships' gear.
   - Neo-bulk. Miscellaneous goods shipped packaged and transferred at port as units. Automobiles, bundled steel products, lumber in stacks, and heavy machinery are examples of neo-bulk.
   - Containerized. Miscellaneous goods shipped in standard International Organization for Standardization (ISO) containers with or without chassis. In the chassis case, goods remain stowed in the container, which is moved through the yard on wheeled trailer chassis suitable for highway transport.

Terminal Modules. When a port's capacity is estimated it is necessary to distinguish between the facilities used to perform different functions in the overall cargo transfer cycle. This is an important distinction because cargo transfer rates are a function of different parameters for different port functions. For example, annual cargo throughput capacity at the yard is a function of the yard size, yard storage capacity, average number of days in storage, and throughput density. On the other hand, annual cargo transfer capacity at the apron is a function of the number of gangs assigned per ship, gang productivity, total number of ship arrivals per year, and average cargo loaded/unloaded per ship.

In the *Port Handbook for Estimating Marine Terminal Cargo Handling Capability* (*16*), the U.S. Department of Transportation uses the following modules for estimating cargo throughput:

- Ship size and frequency,
- Ship/apron transfer capability,
- Apron/storage transfer capability,
- Yard storage capability,
- Storage/inland transfer capability, and
- Inland transport unit processing capability.

Port Capacity Versus Berth Capacity. One final distinction in estimating port capacity pertains to the berth system configuration. It is logical to estimate capacity at the individual berth detail. The berth is supported by shore-based facilities (transfer sheds, storage yards, materials handling equipment, port entry/exit gates, etc.) and labor. In ports with multiple berths the annual port capacity will be derived by adding capacities at individual berths. However, this additive relationship must be interpreted with care because backland areas generally serve multiple berths. For example, when all berth capacities are added together, the port's throughput capacity may be restricted by the gate processing capacity if

gate processing facilities end up being the bottleneck in the entire cargo transfer cycle.

Principal Capacity Studies. One of the earliest attempts to establish a mathematical framework for estimating port capacity was undertaken by T. J. Fratar in 1960, set forth in the article Prediction of Maximum Practical Berth Occupancy (*17*). Fratar applied queuing theory to analyze the interrelationship between berth occupancy and ship waiting time and established that berth occupancy strongly influenced terminal capacity. However, increasing berth occupancy must be critically interpreted. The cause for such an increase may be lower productivity, which does not result in increased berth capacity. On the other hand, a reduction in berth occupancy may increase capacity if it is accomplished through improvements in productivity.

In 1978, UNCTAD published a comprehensive manual (*18*). The manual includes detailed procedures for estimating capacity for different port modules and terminals. UNCTAD also published other manuscripts dealing with more specialized cases of port capacity (*19*). All UN studies, however, cover ports in developing and developed countries with a wide range of technology. Although applicability of equations to U.S. ports is limited, some UN publications, such as *Berth Throughput: Systematic Methods for Improving General Cargo Operations* (*19*), include comprehensive coverage of the elements that influence berth capacity.

A more recent and valuable source of reference for estimating capacity in U.S. ports is the *Port Handbook for Estimating Marine Terminal Cargo Handling Capability* initially published by the U.S. Department of Commerce in 1979 and updated in 1986 by the U.S. DOT, Maritime Administration (*15*).

Types of Terminals. In developing capacity estimates, the U.S. DOT uses the following types of terminals:

- Break-bulk general cargo terminal with covered storage;
- Neo-bulk general cargo terminal;
- Container terminal with yard chassis operation;
- Container terminal with grounded container operation;
- Multiple-berth container terminal with grounded container operation;
- Dry-bulk terminal module with silo storage;
- Dry-bulk terminal with open storage, low-density cargo;
- Dry-bulk terminal with open storage, high-density cargo;
- Liquid-bulk terminal other than petroleum;
- Bulk petroleum terminal serving up to 50,000 dwt tankers; and
- Bulk petroleum terminal serving 50,000 to 200,000 dwt tankers.

In the following section, capacity equations are presented for a one-berth break-bulk general cargo terminal and a container terminal with yard chassis operation. Capacity equations are given for each module in the port, and typical values in U.S. ports are given for independent variables based on data reported in the U.S. DOT port handbook. The capacity equations presented below are developed from the U.S. DOT handbook, with some adaptations from UNCTAD publications. Similar functional relationships can be developed for other types of terminals and cargo from the U.S. DOT handbook and UNCTAD's port development manual.

Break-Bulk General Cargo Terminals. Average berth length in a break-bulk general cargo terminal is 712 ft with a mean lower low water depth of 35 ft. Assuming a berthing gap of 180 ft, the maximum length of ship that can be safely accommodated is 532 ft. These dimensions translate to a maximum ship size of 18,000 dwt.

On the average, 33 ships dock at berth per year to load or unload 2,000 tons per call. In other words, 66,000 tons of break-bulk cargo is handled through the berth. Each ship stays 2 days at berth. Therefore, annual berth occupancy is 26.4 percent for a 250-workday year.

Cargo transfer between the ship and apron is accomplished by six gangs of 15 longshoremen, each using ship gear (booms and winches) and forklifts. Cargo transfer between the apron and storage yard is accomplished by 12 forklift trucks (two per gang), each pulling a train of small cargo cars to be loaded or unloaded in the working area of the apron.

Cargo storage area consists of a 100,000-ft^2 transit shed and a 18,000-ft^2 open storage area. In addition, another 143,000-ft^2 of area is used as auxiliary space for driveways, equipment storage, office space, and truck loading area.

Three-fourths of the cargo is transported by truck with the remaining volume transplanted by rail. Although 30 loading docks are available to provide transfer of cargo from the shed to inland carrier, cargo loading/unloading bays are underutilized. On the average, each bay can handle one truck per hour, which translates to a maximum capacity of 240 truck loads per 8-hr day. Assuming a cargo weight of 17 tons per truck, this capacity translates into 1 million tons per 250-day work year, which is 15 times the volume of cargo handled through the berth (a capacity utilization of 6.6 percent).

Inland transfer processing (interface between the port and highway) is performed through a gate that can process five trucks per hour. An open space of 42,000 ft^2 is used for truck queues. Functional relationships to estimate capacity for the six port modules are given in Table 5.5.

Container Terminals. A variety of methods now exist to handle containers in and through ports. More recent advancements made in this area, commonly known as roll-on/roll-off (ro/ro) systems facilitate faster ship turnaround at port. In the ro/ro system, the vessel carries the container on a trailer that is driven on or off the ship. In the load-on/load-off (lo/lo) system containers are loaded on or off the ship by use of shore-based cranes or ship gear. The lo/lo systems require

TABLE 5.5 Break-bulk cargo berth capacity by module

Port Module and Functional Relationship	Description of Variable	Typical value in U.S.
(1) SHIP SIZE AND FREQUENCY:		
Q1 = (A x T) / 365	Q1 = Berth throughput (tons/day).	180
T = TU + TL = DWT x L	A = Number of ship arrivals per year.	33
A = 365 / I	T = Average cargo transfer per ship arrival (tons).	2,000
DWT = $(D - 5)^2$	TU = Tons unloaded per arrival.	1,300
D = MLLW - 1 for MLLW <= CD	TL = Tons loaded per arrival	700
D = CD - 1 for CD <= MLLW	I = Average inter-arrival time (days).	11
	DWT = Maximum dwt size ship (000).	18
	D = Maximum draft allowed at berth (meters).	9.2
	MLLW = Mean lower low water depth at berth (meters).	10.2
	CD = Controlling depth of channel (meters).	10.2
	L = Load factor per ship call (0.00 <= L =< 1.00).	0.11
(2) SHIP/APRON TRANSFER:		
Q2 = (G2 x H2) / 365	Q2 = Ship/Apron transfer capacity (tons/day).	190
	G2 = Ship/Apron transfer unit hours per year.	4,950
	H2 = Transfer rate per gang (tons per hour).	14
G2 = N2 x W2 x Y2 x B	N2 = Number of gangs per ship.	6
	W2 = Gang working hours per day.	12
B = O2 / Y2	Y2 = Gang working days per year.	250
	B = Berth occupancy rate.	0.275
	O2 = Number of days per year berth is occupied.	66
(3) APRON/STORAGE TRANSFER:		
Q3 = (G3 x H3) / 365	Q3 = Apron/storage transfer module capacity (tons/day).	190
	G3 = Apron/storage transfer unit hours per year.	9,900
	H3 = Transfer rate per transfer unit (tons per hour).	7
G3 = N3 x W3 x Y3 x U3	N3 = Number of transfer units.	12
	W3 = Transfer unit working hours per day.	12
	Y3 = Work days per year for transfer units.	250
U3 = O3 / Y3	O3 = Number of days per year berth is occupied.	66
	U3 = Apron/storage transfer module utilization rate.	0.275
(4) TERMINAL STORAGE: *(20)*		
Q4 = QY/365	Q4 = Average cargo volume handled in storage/day (tons).	182
	QY = Annual tonnage handled through storage (tons).	66,500
	HC = Cargo handling capacity (tons).	2,370
QY = (HC x 365) / TA	TA = Average transit time in storage (days).	13
	GH = Gross holding volume (cu ft).	474,000
HC = (GH x SF) / 2000	SF = Stowage factor (lbs/cu ft).	10
	NH = Cargo net holding volume (cu ft).	423,000
GH = NH x (1 + SB)	SB = Broken stowage factor (% of smaller unit cargo)	0.12
	AA = Average stacking area (sq ft).	52,875
NH = AA x AH	AH = Average stacking height (ft).	8
	AS = Regular storage area (sq ft).	117,500
AA = AS x SP	SP = % of total storage area used for stacking.	0.45
	TS = Total storage area (sq ft).	261,000
AS = TS x (1 - DS)	DS = Reserve factor for demand surge.	0.55
(5) STORAGE/INLAND TRANSPORT:		
Q5 = (G5 x H5) / 365	Q5 = Storage/inland transport module capacity (tons/day).	186
	G5 = Module transfer unit hours per year.	4,000
	H5 = Transfer rate per transfer unit (tons per hour).	17
G5 = N5 x W5 x Y5	N5 = Number of transfer units.	2
	W5 = Transfer unit working hours per day.	8
	Y5 = Work days per year for transfer unit	250
(6) INLAND TRANSFER PROCESSING:		
	Q6 = Inland transfer processing module capacity (tons/day).	466
	G6 = Transport units per year.	10,000
Q6 = (G6 x H6) / 365	H6 = Average load per transport unit (tons).	17
	N6 = Number of traffic lanes or rail tracks.	1
	W6 = Gate working hours per day	8
G6 = N6 x W6 x Y6 x U6	Y6 = Gate working days per year.	250
	U6 = Productivity/lane; no. of units served/hour.	5

more investment in shore-based container handling equipment than ro/ro systems.

Both ro/ro and lo/lo systems are used for port-to-port and door-to-door containerized shipping operations with ro/ro offering the best possible reduction in transit time and cost when used in conjunction with door-to-door operations. The advent of just-in-time logistic strategies provides the principal impetus to taking maximum advantage of transit time savings offered by ro/ro systems. Because of the basic differences between ro/ro and lo/lo systems, typical terminal operations are separately discussed below.

Ro/Ro Operations. Three different kinds of ro/ro operations can be distinguished. In the first type, both the trailer and tractor remain on ship during its voyage and are driven off at the other end. This type of service can be economical on short sea voyages such as cargo or mixed cargo/passenger ferry service. No shore-based special facilities are required except sufficient land for parking and prepositioning vehicles while waiting for the next ship's arrival.

In the second type, the trailer unit remains on ship and the tractor unit is used to tow trailers between the ship and trailer storage area on shore. In the third type, neither the trailer nor tractor remains on ship. A straddle type carrier is used to drive the container onto the ship and to stack it, or the ship's lifting gear is used to stack containers. In this type of ro/ro operation, the apron width ranges from 60 to 90 ft, with ship loading and unloading capacity between 150 and 200 tons per hour.

Lo/Lo Operations. In lo/lo operations, containers are usually loaded on or off ship by use of container cranes, ranging from the ship's own gear to specially designed, rail-mounted gantry cranes. Two variants of this type of operation follow:

1. The yard chassis operation where transfer to storage yard and inland carrier are effected by keeping the container on the trailer and
2. The grounded operation where containers are stacked on the ground in the yard and apron to yard transfer is accomplished by a shuttle chassis.

Table 5.6 presents the functional relationships to estimate capacity by port modules for a yard chassis operation. The relationships included in the table represent a single 1,000-ft berth configuration with a water depth of 41 ft, allowing berthing to a typical second-generation container ship of 30,000 dwt with an 800-ft length and 38-ft draft and a capacity of 2,000 TEUs.

The typical U.S. container berth averages 75 to 80 ship calls per year, with 1,500 TEUs loaded or unloaded per call. The standard berth time for container ships is 24 hours. This translates into an average berth utilization of 20.5 percent. At 75 calls per year, the average interarrival time is slightly less than 5 days. Therefore, the time elapsed between a ship's departure and arrival of the next ship is 4 days, which is considered to be average.

When yearly ship calls reach 100 (berth utilization of 27 percent), the average time elapsed between a ship's departure and the arrival of the next ship is reduced to 2.6 days. This is generally considered a tight operation, even for regular liner service, not allowing a sufficient margin for scheduling errors, trip variation, and changes in cargo transfer time. Therefore, when ship calls approach 100 per year, a second berth is usually added to avoid excessive queuing of ships.

Especially in cases of random ship arrival rates, the two-berth operation can effectively handle more ship calls per year than twice the number per berth in single-berth operations. Stated differently, given the same number of annual ship arrivals per berth, the average ship waiting time for a multiple-berth configuration is considerably less than for a single-berth operation.

The ship to apron transfer module capacity is a function of the type of crane system used. Shipboard equipment is the least productive and almost never used in container ports. A widely used system is two rail-mounted gantry cranes. Although up to 36 crane moves (cycles) per hour have been reported for some U.S. ports (*21*), the effective maximum rate of a gantry crane is 25 cycles per hour after accounting for stoppages and idle times (*22*). Assuming a typical operation of 20 cycles per hour per gantry, the total number of containers that can be handled per 24-hr day with two gantry cranes is 960.

In order to convert the daily containers handled into tons per day, it is necessary to compute the average cargo weight per container, which is a function of container size and stowage factor. TEU represents a standard ISO 20-ft equivalent container, which has a gross volume of 1,280 ft^3 (20 by 8 by 8 ft). In a typical container port, about 25 percent of containers are TEUs, with the remaining 75 percent represented by the double-size ISO container with a gross volume of 2,560 ft^3 (40 by 8 by 8 ft). This size represents the standard size trailer used in interstate commerce, whereas the TEU is akin to a delivery van used in short hauls and in urban goods movement. The double-tandem tractor-trailer operations in interstate commerce use two TEUs in tow.

The stowage factor represents the cargo weight-to-volume relationship as shown below:

Stowage factor (cu ft/ton)	*Cargo TEU(*)*	*Net Weight (Tons) Per 40-ft ISO(**)*
50	18.0(***)	36.0(***)
60	17.1	34.1
70	14.6	29.3
80	12.8	25.6
90	11.4	22.8
100	10.2	20.5
110	9.3	18.6
120	8.5	17.1
130	7.9	15.8
140	7.3	14.6

(*) 1,024 ft^3 net.
(**) 2.048 ft^3 net.
(***) Maximum cargo weight limit.

TABLE 5.6 Container cargo terminal capacity in lo/lo yard chassis operations

Port Module and Functional Relationship	Description of Variable	Typical value in U.S.
(1) SHIP SIZE AND FREQUENCY:		
Q1 = (A x T) / 365	Q1 = Berth capacity (tons/day).	3,700
T = N x S = DWT x L	A = Number of ship arrivals per year.	75
A = 365 / I	T = Average cargo transfer per ship arrival (tons).	18,000
DWT = $(D - 5)^{1.83}$	N = Number of containers handled/arrival.	1,500
D = MLLW - 1 for MLLW <= CD	S = Average cargo weight per TEU (tons).	12
D = CD - 1 for CD <= MLLW	I = Average interarrival time (days).	4.9
	DWT = Maximum dwt size ship (000).	30.7
	D = Maximum draft allowed at berth (meters).	11.5
	MLLW = Mean lower low water depth at berth (meters).	12.5
	CD = Controlling depth of channel (meters).	12.5
	L = Load factor per ship call (0.00 <= L =< 1.00).	0.59
(2) SHIP/APRON TRANSFER:		
Q2 = (G2 x H2) / 365	Q2 = Ship/Apron transfer capacity (tons/day).	3,630
	G2 = Ship/Apron transfer unit hours per year.	3,450
	H2 = Transfer rate per unit (tons per hour).	384
G2 = N2 x W2 x Y2	N2 = Number of transfer units per ship.	2
CW = [N x TEUP x STE +	W2 = Hours transfer units work per working day.	23
[N(1 - TEUP)/2] x STF]/	Y2 = Transfer unit working days per year.	75
[N x TEUP + N(1-TEUP)/2]	CY = Cycles per hour per transfer unit.	20
	CW = Average weight per transfer unit cycle (tons).	19.2
	TEUP = Percent of TEU containers in mix.	0.25
	STE = Average cargo weight per TEU (tons).	12
	STF = Average cargo weight per 40-foot container (tons).	24
(3) APRON/STORAGE TRANSFER:	SAME AS MODULE (2)	
(4) TERMINAL STORAGE:		
Q4 = QY/365	Q4 = Max. cargo volume handled in storage per day (tons).	19,200
	QY = Max. annual weight handled through storage (tons).	7 mil
	HC = Max. yard storage capacity (tons).	44,100
QY = (HC x 365) / TA	TA = Average transit time in storage (days).	2.3
	SD = Storage density (Number of chassis per acre).	42
HC = SD x AS x AW	AS = Yard storage area (acres).	50
	AW = Weighted average weight per chassis (tons).	21
AW = TEUP x STE + (1 - TEUP) x STF		
(5) STORAGE/INLAND TRANSPORT:	CONTINUOUS OPERATION COMBINED WITH MODULE (6)	
(6) INLAND TRANSFER PROCESSING:		
Q6 = (G6 x AW) / 365	Q6 = Inland transfer processing capacity (tons/day).	4,142
	G6 = Transport chassis units per year.	72,000
	N6 = Number of lanes (gates).	12
	W6 = Gate working hours per day	8
G6 = N6 x W6 x Y6 x U6	Y6 = Gate working days per year.	250
	U6 = Productivity/gate; no. of chassis units served/hr.	3

Stowage factors for specific types of commodities and packaging have been computed and are regularly used in containerization. In the absence of specific cargo stowage factors, it is customary to assume a net cargo weight of 12 tons per TEU.

Apron to storage transfer is affected by yard tractors and transtainers, which work in perfect synchronization with the gantry cranes in the apron. They work when gantry cranes operate and clear the apron area at the completion of ship loading or unloading. Therefore, their daily capacity is equal to the ship to apron transfer module. The typical equipment configuration to achieve this capacity consists of seven yard tractors to pull chassis containers or seven straddle carriers to move containers loaded on trailers. Typical transfer rate per yard of a tractor or straddle carrier is six cycles or 115 tons per hour.

The terminal storage consists of only an open storage area because containers do not require undercover protection from inclement weather. In an operation characterized by 75 ship calls per year, the average interarrival time of 4.9 days

appears to provide sufficient leeway to clear the yard before the next ship's arrival assuming that the average time in storage is 2.3 days. However, the average time in storage represents a value that is the mean of a distribution of days. If the distribution is assumed to be uniform, then the average of 2.3 days means that all containers will be removed from storage in 4.6 days. In this case, assuming 18,000 tons per ship call, the average removal rate from storage per day will be 3,913 tons.

Therefore, during the day of ship's arrival 18,000 tons of cargo will be moved into the storage area and 3,913 tons will be moved out by the end of the first day. Assuming that no cargo existed in storage when the ship arrived, at the end of the first day 14,087 tons will remain in storage. During the second, third, and fourth days, 3,913 tons will be moved out of storage per day, and by the 14th hour of the fifth day the remaining 2,348 tons will be removed.

Unfortunately, events in real life do not follow this type of uniform and predictable pattern. First, withdrawals from or deliveries to storage are highest 2 days before and 2 days after ship arrivals. Outgoing cargo is staged in the yard in anticipation of a ship's call. Since interarrival time is 4.9 days, 2.9 days after arrival of a ship, cargo to be loaded onto the next ship starts to pile up in the storage yard while some cargo unloaded from the first ship is still in storage.

Another complication stems from the behavior of ship interarrival times, which are best described by the Poisson probability function. With a total of 75 arrivals per year, the Poisson probability distribution shows that for each of 60 days out of 365, one ship will arrive at port; for each of 6 days, two ships will arrive; and for 1 day, three ships will arrive. There will, therefore, be some time periods when as many as four ships will be berthed during 4 consecutive days. At a uniform withdrawal rate of 3,913 tons per day and a mean transit storage time of 2.3 days, there will still be leftover cargo in the yard from the first three ships by the time the fourth ship's cargo is moved into the storage yard. Given this pattern, as much as 32,870 tons of cargo space is needed (see Figure 5.5).

Because of the additional storage requirement for peak demand and other contingencies, the typical storage yard capacity for a one-berth container terminal handling 75 ship calls per year is 2.3 times the average volume of cargo handled per ship call or 42,000 tons. The standard yard design for a single-berth container terminal includes 50 acres of net storage area excluding auxiliary areas and maintains a storage density of 42 chassis per acre.

In the chassis operation, the storage/inland transport transfer operation is accomplished by the tractor, which picks up the chassis from the storage yard without assistance of any other equipment. When the chassis is hooked, the tractor proceeds to the gate for processing. Therefore, the storage/inland transport transfer module is integrated with the gate processing module as a continuous operation.

The gate processing operation in a container terminal involves checking in the tractor through the gate when it arrives for pickup and checking out of the tractor-trailer unit when it departs from the port area. In delivery of a chassis to the port for outbound cargo the reverse of this procedure is followed. The typical two-way processing time is 20 min. With 12 gates each operating 8 hr, the maximum number of chassis processed in a day is 288. With an average weight of 21 tons per chassis, 6,048 tons of cargo can be processed through the gates per day.

Implications of waterway capacity on intermodal corridors. It is generally agreed that vessels cost more than port facilities. To the extent that port facilities are built to reduce the average waiting time of vessels, the investment is justified. However, a reduction in total vessel time and, therefore, cost does not necessarily mean an optimum investment if the vessel-related savings are more than offset by port-related costs. The optimum investment level for port facilities is where the total of vessel and port costs are minimum.

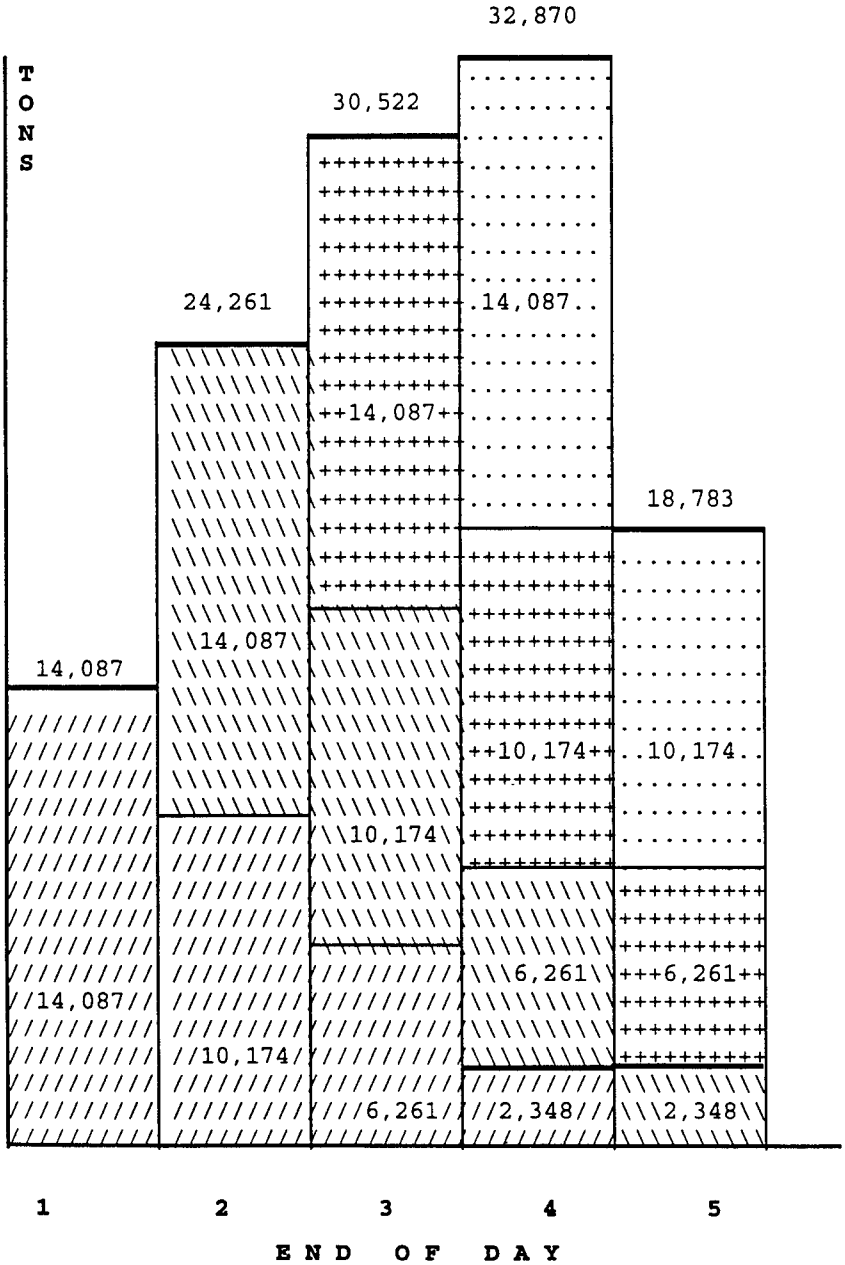
The optimum level is always below the intrinsic capacity of the port. Therefore, the procedures described in the preceding sections to estimate practical (as opposed to intrinsic) port capacity provide a valuable perspective of the detail required in defining relevant parameters of facility configuration and operation so that intelligent estimates can be made.

When practical capacity is considered in light of intermodal implications, a shortcut solution to estimate the port's intermodal impact along its primary transportation corridors is to convert the annual tonnage handled by the port into ton-miles of intermodal traffic by use of the following simplified procedure:

- Break down the cargo handled by the port into cargo types (break-bulk, neo-bulk, etc.) and direction of flow (outbound versus inbound).
- Define the hinterland for each cargo type (at the minimum, represent hinterland with one inland point of origin or destination) and define modal split.
- Compute ton-miles along the corridor represented by the link between the port and the hinterland points.
- For traffic impact analysis, compute the number of vehicles by assuming load factors per vehicle.

The simplified procedure requires only the actual cargo volumes handled by the port, which are extensively reported for past years and can be (and are regularly) projected with confidence by individual ports.

An important input for corridor analysis is to estimate the number of port-related vehicles entering the transportation corridor during a certain time interval (preferably every 15 min). Gates at ports usually work for 8 hr per day and release/receipt of traffic does not follow a uniform distribution throughout the day. In addition, daily traffic volumes



/// First ship's cargo \\\ Second ship's cargo +++ Third ship's cargo .... Fourth ship's cargo

Figure 5.5. Tons remaining in storage yard.

vary depending on the ship arrival schedule. Simulation models can be used to generate traffic release/receipt patterns to and from the corridor by assuming known probability distribution functions for vehicle arrival and gate processing rates under different service rules.

The impact of port-generated traffic on the intermodal transportation corridor is directly related to the port's hinterland. A regional port with a large hinterland generates a significantly larger corridor load expressed in ton-miles than a smaller port handling local traffic. The difference between the two ports stems not only from the difference in the total tonnage but also from the size of hinterland expressed by the average length of haul. The regional port serves a much larger geographic area than a local port, which serves a few (and most likely a handful of bulk cargo) customers in the immediate vicinity. This difference in average distance between the two ports results in a much wider difference in ton-miles than suggested by a difference only in the volume of cargo.

Sources of Delay in Waterway Transportation. By definition, a delay occurs when the transport infrastructure and

equipment become inadequate for handling demand. In waterway transportation, causes of delay are similar to other modes of transport; therefore, at some point in time, demand simply exceeds the capacity of the system. The result is congestion and increased costs for shippers and operators.

The functional relationships described in the preceding section demonstrate clearly the effect of specific parameters on the cargo handling capacity in waterway transportation. For example, adding additional gates, berths, storage areas, cranes, and other cargo handling equipment will result in increased capacity. If such improvements are made in critical bottleneck areas, then the overall capacity of the facility will be increased.

The principal concern of ship operators is delay caused by lack of berthing to load and unload at ports. For inland waterways, an additional concern for ships is waiting time in queue at locks. Although there is a general consensus that there are adequate port facilities in the United States to handle the demand of ship operators, delays frequently occur because it is impossible to accommodate all ships with berthing space as soon as they arrive. Especially in unscheduled tramp and trip charter trades, delays are unavoidable because of the difficulty of planning for berthing requirements sufficiently in advance to build adequate facilities.

On the land side, a frequent source of delay cited by port officials is the congestion of highways connecting the port facilities with shippers and consignees inland. This congestion is especially acute in ports in large metropolitan areas where chronic urban traffic congestion precludes effective cargo operations, including port-related movements. The ability of port operators to alleviate these bottlenecks is limited because the authority for making improvements often resides with local, state, and federal transportation agencies rather than with the ports.

In spite of these limitations, there are areas where significant improvements can be achieved without a large investment in additional facilities. To the extent permitted by labor contracts, extended work hours allowing movements to and from ports during noncongested times will improve intermodal transport efficiency. In some highly congested urban areas, use of feeder ports to transfer cargo by water to and from the primary port, as opposed to shipping overland along already overburdened highways, offers an attractive solution.

Another alternative for mitigating urban congestion is to locate at an inland point a general and container cargo distribution center served by a dedicated rail or highway from the port. This alternative eliminates the use of congested urban corridors by shippers located inland.

5.4.5.4 Waterway Capacity Example

Example 1: Barge throughput. An inland waterway connecting two ports has a lock and dam on it. Based on statistics gathered throughout the years, suppose the average service rates for tows of different sizes are as follows:

Tow Size (No. of Barges)	*Service Rate (Tows/Hour)*
1	3
5	2
10	1.3
15	1
20	0.5

Question: What is the maximum capacity on the waterway, assuming the barges in each tow are identical in dimensions and handling rates?

Answer: Using the above information, the number of barges per hour for each tow size are as follows.

Tow Size	*Service Rate (Tows/Hour)*	*No. of Barges/Hour*
1	3	3
5	2	10
10	1.3	13
15	1	15
20	0.5	10

Therefore, the capacity of the waterway is equal to 15 barges per hour or 131,400 barges per year. The freight capacity can be calculated based on the type of commodity transported and the unit for measuring this commodity.

Question: How would the results change in the above example if there are two locks on the waterway? Assume that both locks are identical but independent.

Answer: The capacity of the waterway with more than one lock is governed by the lock with the least capacity (assuming that locks are independent, and are the main source of interruption to barge movement on the waterway). Hence, the capacity of the waterway is still equal to 15 barges per hour.

5.4.6 Pipeline Transportation

The U.S. pipeline network is one of the most advanced transportation systems in the world capable of moving large volumes of crude oil, liquid petroleum products, and natural gas, as well as smaller volumes of more exotic commodities such as liquid natural gas, coal slurry, carbon dioxide, and ammonia. Of the many products that can be handled by pipelines, crude oil, petroleum products, and natural gas are the most prominent in intercity transportation/transmission and in local distribution. Other liquid products are carried by pipelines mostly in local operations and rarely enter into interstate trades (*23*).

The total tonnage carried by crude oil, petroleum products, and natural gas pipelines in 1990 amounted to 1.54 billion tons (*24*). This tonnage level places the pipeline mode in the third place following trucks (2.6 billion tons) and railroads

(2 billion tons) and followed by domestic waterborne commerce (1.1 billion tons) (*25*).

The determinants of pipeline capacity and procedures to estimate it are different for liquid and gas products. Therefore, any discussion on capacity must distinguish between these two physical states. Although this distinction is necessary, a capacity section on gas pipelines is not needed simply because there is no intermodal interface in gas transmission and distribution lines. Collection of gas from producing fields, its intercity and/or interstate transmission, and local distribution and delivery to end users are all accomplished through an interconnected pipeline system with no need for intermodal interface. Therefore capacity of only liquid pipelines will be discussed in this section.

Pipeline capacity is generally defined as the flow rate or throughput. To be meaningful, the flow rate must relate a specific physical quantity (barrels, tons, gallons, etc.) to a time unit such as per second, minute, hour, day, and year. The physical quantity in the flow rate expression depends on the physical state of the product such as barrels or gallons for liquid hydrocarbons, cubic feet for natural gas, and tons for coal slurry.

The estimation of pipeline flow rate (capacity) is the subject matter of fluid mechanics, a well-defined and developed area of engineering science. Formulas have been developed and are being used to express interrelationships between a multitude of factors that affect pipeline capacity.

Among all the factors that determine pipeline capacity, the two most important are the pipeline size (diameter) and velocity. The fundamental relationship between flow rate and these variables is established by the following:

$$Q = V * A$$

where

Q = flow rate (capacity) expressed in volume units per time period;
V = velocity expressed in linear distance traversed per time period; and
A = area of the cross section of the flow.

A simple rule of thumb that is widely used to estimate capacity, expressed in barrels per day, is to multiply the square of the nominal pipe size (inches) by 500 (*26*).

Although the rule of thumb is very simple and straightforward, it is asserted that "almost all of the oil and products lines now in operation have throughput capacities which will be given by the above rule, with the constant (given as 500) ranging between 300 and 600" (*27*). For light products with high viscosity and low density and pump outlet pressures near the pipe design pressure, the constant will be closer to 600.

Since nominal pipe size represents the outside diameter of the pipe, expressing this relationship in terms of radius and substituting it in the equation above implies a flow rate of 318.47 barrels per day per inch^2 of the circular cross section of the pipe. However, this implied flow rate (barrels/day/inch^2) does not contribute to a true expression of velocity (distance/time period). A more direct empirical relationship between velocity and capacity is provided by the following:

$$Q = (V * D^2)/0.0081$$

where

Q = flow rate (barrels per day);
V = velocity (miles per hour);
D = inside diameter of pipe (inches); and
0.0081 = the constant that represents the viscosity and density of a typical oil (*28*).

Neither the rule of thumb nor the above equation adequately describes the effects of a multiplicity of factors that affect pipeline capacity. In order to evaluate the effects of alternative measures to improve pipeline capacity, it is important to describe the empirical relationships between these factors and the velocity of the liquid column.

The general approach to estimating capacity in a more formal manner takes into account the interrelationships between important parameters. The conceptual framework recognizes capacity determinants in the following three areas:

The Product. Product characteristics such as density, viscosity, gravity, and other chemical and physical properties determine a range of allowable operating conditions. These conditions include pressure, temperature, usability of drag-reducing agents, need for batch segregation, and type of flow (turbulent versus viscous or laminar). All of these product characteristics affect pipeline capacity.

The Pipe. Internal design pressure of the pipe is a major determinant of the maximum pump outlet pressure. The type of steel used in the construction of the pipe is an important determinant of yield strength. This strength is important in specifying allowable stress, which in turn establishes the allowable working pressure. The horsepower of pumps and spacing of pumping stations are two important determinants of pressure loss between stations. Finally, when pressure loss between stations is used in conjunction with physical properties of the product the flow rate can be estimated. The types and configuration of the pipeline and pump stations are determined by the yield strength, pipe diameter, wall thickness, weld joints, and design safety considerations. In addition, horsepower, distance between pumping stations, and other factors related to the pressure in the system are important determinants of capacity.

The Route. A third set of properties are defined by terrain, ambient temperature, topography including elevation, curvature, crossings across water, and other obstructions. Although these characteristics do not directly affect the pipeline capacity, their importance is recognized in the design of the

overall system in terms of the type of pipe, pump capacity, spacing of pumping stations, operating conditions, and other parameters that have a direct impact on capacity.

A comprehensive treatment of all the above listed determinants of pipeline capacity and derivation of numerous formulas showing their interaction would require the inclusion of the entire field of fluid mechanics in this section. On the other hand, some important empirical relationships must be described here for use by pipeline transportation analysts.

The allowable working pressure for a pipeline can be determined by the following (*29*):

$$P = 1.75\, S(t - 0.057)/(D + 0.04 - 0.7t)$$

where

P = allowable working pressure (psi);
D = pipe outside diameter (inches);
t = pipe wall thickness; and
S = allowable stress (psi).

The American Society of Mechanical Engineers specifies allowable stress values for reference use in liquid petroleum pipelines (*30*). Different types of pipe construction such as seamless, furnace butt welded, and furnace lap welded are assigned a weld joint factor ranging from 0.6 to 1.00. A design factor that is typically equal to 0.72 to represent the maximum percent of specified minimum yield strength of the pipe as a safety factor for onshore liquid pipelines is used along with the weld joint factor to compute S (*31*):

$$S = Y * E * 0.72$$

where

Y = specified minimum yield strength (psi) and
E = weld joint factor.

The maximum allowable working pressure, computed by the equation for P above, is one of the key determinants of pump station sizing and spacing. There would be no engineering or economic justification for installing pumping horsepower that would be capable of exceeding the maximum working pressure allowed for the pipeline. On the other hand, inadequate pumping horsepower for a certain size pipeline would result in less than optimum velocity and, therefore, underutilization of the system.

Once the pumping configuration is established, it will be possible to compute pressure loss per mile. This variable, together with pipe size and product characteristics, determines pipeline capacity. A number of empirical formulas have been developed to establish this relationship (*32*).

The Shell/MIT formula to compute pressure loss per mile uses a friction factor (f), which requires use of the Reynolds number (r), which, in turn, is determined by daily flow. Since daily flow must be kept as the dependent variable in the computation of capacity, the utility of the Shell/MIT formula for purposes of computing pipeline capacity is considerably diminished. Attempts were made in the past to estimate pipeline capacity within the context of investment requirements wherein flow rate was used in an iterative manner and the effect of incremental changes in flow rate upon pipeline size and pumping configuration was analyzed (*33*). However, these algorithms require simulation of many iterations with different configurations of product type, distance, pipe diameter and wall thickness, pump horsepower, looping, elevation, and number of booster stations so that it is impractical at this point to implement such rigorous software.

Another empirical relationship between pressure drop and flow rate expressed in barrels per hour is developed by T. R. Aude. The only limitation of the Aude formula is that it is based on data related to pipes between 6 and 8 in. in diameter. The applicability of Aude's formula to a wider range of pipe sizes is severely restricted. The well-known Hazen-Williams flow rate-pressure loss relationship is typically used for water system hydraulic calculations.

The Benjamin Miller formula establishes a general relationship of flow rate to pressure drop and other variables in crude oil and petroleum product pipelines:

$$B = (0.1692) * (d^5 * P/S)^{0.5} * [\log(d^3 * S * P/Z^2) + 4.35]$$

where

B = flow rate (barrels per hour);
d = inside diameter of pipe (inches);
P = pressure loss (psi per mile);
S = specific gravity; and
Z = absolute viscosity (centipoises) − 1 centipoise = 0.000672 lb/(ft)(sec) or 2.42 lb/(ft)(hr)].

Specific gravity is the ratio of the weight density of a liquid to the weight density of pure water. Weight density is the weight of a substance per unit of volume at a given temperature and under atmospheric pressure. Table 5.7 gives the weight density and specific gravity equivalents for various products and crude oil at 60°F, the base temperature generally used for liquid hydrocarbons.

Absolute viscosity is the force required to move a unit plane surface over another plane surface at a unit velocity when the two surfaces are separated by a layer of fluid of unit thickness. Absolute viscosity and pressure are directly related.

5.4.6.1 Pipeline Capacity Example

Example 1: A 20-in. nominal size pipeline with a wall thickness of 0.3125 in. is pumping 40° API crude oil with an absolute viscosity of 0.65. The pipeline consists of 500 mi with five booster pump stations with 800 psi discharge pressure and 20 psi suction pressure.

TABLE 5.7 Weight density and specific gravity of liquid hydrocarbons at 60°F

Product	Weight Density (lbs/cu.ft.)	Specific Gravity
Bunker C Fuel	63.25	1.014
Distillate	52.99	0.850
Fuel 3 Max.	56.02	0.898
Fuel 5 Min.	60.23	0.966
Fuel 5 Max.	61.92	0.993
Fuel 6 Min.	61.92	0.993
Gasoline	46.81	0.751
Kerosene	50.85	0.815
Residual Fuel Oil	58.32	0.935
SAE 10 Lube	54.64	0.876
SAE 30 Lube	56.02	0.898
SAE 70 Lube	57.12	0.916
32.6° API Crude	53.77	0.862
35.6° API Crude	52.81	0.847
40° API Crude	51.45	0.825
48° API Crude	49.16	0.788

Source: E.W. McAllister, Op. Cit., p.521, Courtesy of Crane Co. (Technical Paper #410).

Question: What is the maximum throughput of the pipeline?

Answer: To compute the flow rate it is first necessary to derive the average pressure loss per mile. Since five stations operate over a 500-mi distance, the average spacing between stations is 100 mi. The total pressure drop over this distance is 780 psi, which results in an average pressure loss of 7.8 psi per mile.

From the pipe size data given in the example, the inside diameter of the pipe is computed as $20 - 2 * 0.3125 = 19.375$ in. From Table 5.7 the specific gravity for this type crude oil is 0.825.

Using the Miller formula, the capacity of the pipeline B is calculated as follows:

$$B = (0.1692) * (19.375^5 * 7.8/0.825)^{0.5} * [\log(19.375^3 * 0.825 * 7.8/0.65^2) + 4.35]$$

$$B = 0.1692 * 5080.7 * (\log 110{,}776 + 4.35)$$

$$B = 859.65 * (5.044 + 4.35) = 8{,}076 \text{ barrels per hour.}$$

5.5 MULTIMODAL CORRIDOR CAPACITY ANALYSIS (STEP 3)

As explained earlier in this manual, a corridor may consist of just one relatively short link carrying one type of vehicle between two points (e.g., a busway), or it may be a combination of links and nodes with different types of vehicles/carriers and movements and covers long distances (e.g., intercity highway/rail corridor). Breaking up the corridor into individual components (links and nodes) and determining the capacity of each component separately, as described in Steps 1 and 2, would allow one to analyze any type of corridor including those identified in Chapter 4.

Calculation of vehicle/carrier capacity of an individual corridor component for the most part is rather straightforward, as shown in the examples above. However, these components are usually not independent, and in many cases they are physically and functionally connected. Hence, the capacity of one component may depend upon the capacity of another. For example, intercity rail corridors consist of a combination of rail segments, classification yards, train stations, and other intermodal transfer facilities/terminals. Similarly, most urban highways are made up of different types of highway links and nodes as described in Section 5.4. If a corridor consists of a series of components through which traffic flows in a successive manner, the corridor capacity is simply equal to the capacity of the most constraining element (least capacity component). If the corridor, however, consists of independent components (e.g., parallel links), the overall capacity is the sum of the individual capacities. On the other hand, if the components of the corridor form a network (with possible cyclic traffic flows), the capacity of the entire corridor is indeterminate, because no specific origins and destinations exist unless specific components are chosen.

Table 5.8 shows a matrix of various links and nodes that can be found in multimodal corridors. To determine component capacity, the maximum number of specific types of vehicles and carriers that each component can carry (e.g., vehicular/modal capacity) is calculated. These modal capacities can correspond to various traffic compositions (percentage of specific types of vehicles) on the component. The modal capacities can also be calculated for each type of vehicle/carrier assuming that only this vehicle will use the component (e.g., unimodal). Average person-occupancy and/or freight-handling rates are used to convert these modal capacities into equivalent passenger and/or freight capacities.

The following sections describe the procedures for calculating the person and freight capacities of multimodal corridors.

5.5.1 Person Capacity

If the vehicular capacity of the corridor and its components are known, the person capacity can be easily calculated by multiplying this capacity with the maximum passenger occupancy rates of these vehicles. The approximate passenger-occupancy rates of vehicles and carriers are shown below:

Vehicle	*Maximum Person-Occupancy (No Standing)*
Bicycle	1
Motorcycle	2
Car	5
Van	~5-12
Bus	~15-75
Light-Rail Train	~100-130
High-Speed Rail Car	~500
Commuter Rail Train	~1000
Commercial Aircraft	~10-500
Ferry	~50-500

TABLE 5.8 Multimodal corridor capacity analysis matrix

CORRIDOR COMPONENTS	Modal Capacity (Vehicle or Carrier per Hour)							Handling Rate (Person and/or Freight Tonnage/Volume/$)							Multimodal Capacity (Person and/or Freight per Hr.)						
	Component No.							Component No.							Component No.						
	1	2	3	4	5	6	N	1	2	3	4	5	6	N	1	2	3	4	5	6	N
LINKS																					
Interstate Highway																					
Freeway																					
Expressway																					
Primary System																					
Arterial Road																					
Inland Waterway																					
Commuter Rail																					
Rapid Rail																					
Intercity Rail																					
Intercity Air																					
HOV Lanes																					
etc.																					
NODES																					
Ramps/Intersections																					
Airports																					
Inland Port																					
Railroad Yard																					
Seaport																					
Commuter Train Stations																					
Bus Stations																					
Kiss and Ride																					
Park and Ride																					
Truck Dock																					
etc																					

Notes:
1. Corridors can have multiple links and nodes of the same type.
2. There can be more than one vehicle/carrier type on each component.
3. The spreadsheet is generic but can be adjusted to reflect actual/specific conditions.
4. Nodes cannot be part of a defined link.
5. Links have to be homogenous, otherwise averages are used.

The total passenger-carrying capacity of a multimodal corridor is simply the sum of person-capacities of all independent components or component-group (links, nodes, or combinations). Determination of whether or not two or more components are interdependent in terms of passenger movements requires knowledge of their physical and operational connectivity, as stated above.

Example 1: Person capacity

Question: What is the person capacity of the 2-lane HOV highway in Example 1 (Section 5.4.1)? The capacity of the highway was calculated at 4,180 vehicles per hour at 100 percent passenger cars.

Answer: The person-capacity of the facility, assuming that each car has a carrying capacity of five people, is $4{,}180 * 5 = 20{,}900$ persons per hour.

One may argue that perhaps the highest person throughput can be attained when the HOV traffic consists of all fully loaded buses. In reality this scenario will probably never occur except maybe in exclusive busways. If the highway is

indeed a busway, the pce of buses is determined and used to calculate the equivalent bus capacity of the highway. From the HCM, the pce of a bus is equal to 1.5 for level terrain. The bus capacity of the busway is equal to the following:

bus capacity = 4,180 vehicles per hour/1.5 vehicles per bus
= 2,786 buses per hour

Assuming a maximum bus occupancy of 40 persons (no standees), the person capacity is equal to the following:

person capacity = 2,786 buses per hour * 40 persons per bus
= 111,440 persons per hour

5.5.2 Freight Capacity

The freight capacity methods described in this manual require a measure of vehicle capacity from which goods capacity can be calculated. Freight vehicle capacity can be calculated in terms of a single freight vehicle, for instance a particular type of barge or a composite of several types of vehicles. It can also be calculated in terms of a consist such as a freight train composed of engines, cars, and containers. Either a single freight vehicle or a consist, regardless of the mode to which it pertains, can be converted into equivalent freight movements expressed in terms of either one of the following:

1. Link or node throughput of equivalent pieces of equipment per unit time (i.e., number of vehicles or containers of a particular type, such as truckloads, boxcars, and 60-ft containers); or
2. Link or node throughput of commodities per unit time expressed in terms of quantities, weight, cubic volume, or dollar value.

If the goods movement capacity is expressed in terms of vehicles or consists, then the multimodal freight capacity is equal to the vehicle/carrier capacity. If goods movement is expressed in other units, such as equivalent pieces of equipment movement, weight, cubic volume, or dollar volume, then specific conversion factors are needed. The following describes these procedures.

5.5.2.1 Equivalent Equipment, Weight, Cubic Volume, and Dollar Conversion Factors

A link or node may carry a huge number of commodities with widely varying characteristics that vary in terms of weight, cubic volume, and value per unit transported. To convert goods movement into movements of equivalent pieces of equipment, weight, cubic volume, or dollar value, two tables have been developed (see Table 5.9 and Table 5.10).

For any vehicle, equipment, or other movement, the kind of information in Table 5.9 can be used for conversion into traffic volumes, expressed in terms of equivalent pieces of equipment, cubic volume, or weight. Denote the corresponding conversion factors for vehicles and containers as follows:

r_j^w = the conversion factor expressed in terms of maximum weight for vehicle type j;
r_k^w = the conversion factor expressed in terms of maximum weight for container type k;
r_j^v = the conversion factor expressed in terms of maximum cubic volume for vehicle type j; and
r_k^v = the conversion factor expressed in terms of maximum cubic volume for container type k.

Equivalent Equipment Movements. Using the factors above, freight movements can be converted into units of equivalent movements of Type e equipment (e.g., equivalent

TABLE 5.9 Conversion factors for freight movements

	Cubic feet available	Car/bogie Tare Wt. (lbs)	Trailer/ Container Wt. (lbs)	Payload (lbs) tract = 15,400	Length of unit (ft)
Type of Equipment					
Regular Highway Trailers, 48'-102'	3,847	80,000	14,500	50,100	48.0 - 93.0
Hi-cube Highway Trailers, 53'-102'	3,847	140,000	14,500	50,100	186.0
Conventional 53' Highway Plate Trailers	4,100	0	14,500	50,100	53.0
Piggyback Refers, 48'-96'	3,477	35,000	17,000	47,600	58.1
Domestic Containers, 48'-102'	3,847	60,000	9,500	47,100	76.8
ISO Containers, 40'-96'	2,890	41,500	9,500	47,100	61.5
60' Box Car	6,600	60,000	9,500	100,000	

Source: Transmode Consultants Inc.

TABLE 5.10 Input and output values for commodity classes

		Input Values		Output Values	
STIC	Description	Density lbs/cu ft.	Values $/lbs.	Density lbs/cu ft.	Values $/lbs.
AGRI, FORESTRY & FISH					
7	Ag Services	10	0.32	30	na
8	Forestry	10	2.65	10	na
9	Fish, Hunting, Trapping	30	3.00	30	0.93
MINING					
10	Metal Mining	20	3.00	100	4.00
11	Anthracite Mining	20	3.00	100	.50
12	Lignite & Coal Mining	20	3.00	100	.50
13	Oil & Gas Extraction	20	3.00	60	.89
14	Nonmetallic Mining	20	3.00	100	.04
CONSTRUCTION					
15	Gen. Bldg. Construction	10	2.30	100	na
16	Heavy Construction	10	2.10	100	na
17	Specialty Trade Contractors	10	2.40	100	na
19	Ordinance	150	100.00	150	100.00
MANUFACTURING					
20	Processed Foods	40	0.17	40	0.37
21	Tobacco Products	18	3.00	18	7.51
22	Textile Mill Products	15	6.00	15	8.00
23	Clothing	20	5.00	15	7.13
24	Wood Products	25	0.13	25	0.32
25	Furniture	10	3.00	10	5.73
26	Paper Products	20	0.09	20	0.17
27	Printed Matter	32	0.80	32	1.63
28	Chemical Products	50	0.81	50	1.20
29	Petroleum Products	52	0.40	52	1.20
30	Rubber Products	13	0.85	13	1.90
31	Leather Products	12	7.00	12	2.30
32	Glass Products	70	0.04	40	17.07
33	Primary Metals	150	0.30	150	0.09
34	Metal Products	100	1.70	25	0.83
35	Machinery	70	2.60	60	4.15
36	Electric Equipment	10	1.50	6	3.74
37	Transport Equipment	30	0.05	6	0.11
38	Instruments	20	30.00	13	66.62
39	Misc. Mfg. Products	20	0.36	15	0.82
TRANS. & PUBLIC UTILITY					
40	Railroads	20	na	1	na
41	Local Busses	20	na	1	na
42	Truck Transportation	20	na	1	na
43	U.S. Postal Service	20	na	1	na
44	Water Transportation	20	na	1	na
45	Air Transportation	20	na	1	na
46	Pipeline Transport	20	na	1	na
47	Transport Services	20	na	1	na
48	Communication Services	20	na	1	na
49	Elec., Gas, Water, & Sant.	20	na	1	na

(continued)

truckloads, boxcars, or containers), where the maximum weight that can be carried by the equipment is r_e^w and the maximum volume that can be carried by the equipment is r_e^v. Then the freight conversion factor for vehicle type j expressed in terms of equivalent movement of Type e equipment by weight is

$$r_{je}^w = r_j^w / r_e^w$$

and the freight conversion factor for container type k, expressed in terms of equivalent movement of Type e equipment by weight, is

$$r_{ke}^w = r_k^w / r_e^w$$

Similarly, the freight conversion factor for vehicle type j, expressed in terms of equivalent movement of Type e equipment by volume, is

TABLE 5.10 *(continued)*

		Input Values		Output Values	
STIC	Description	Density lbs/cu ft.	Values $/lbs.	Density lbs/cu ft.	Values $/lbs.
WHOLESALE TRADE					
50	Wholesale Durables	25	na	25	na
51	Wholesale Nondurables	15	na	15	na
	Admin. & Aux.				
RETAIL TRADE					
52	Building Materials	35	na	35	na
53	General Merchandise	25	na	25	na
54	Food Store	15	na	15	na
55	Automobile Dealers	10	na	10	na
56	Apparel Stores	10	na	10	na
57	Furniture Appliances	15	na	15	na
58	Eating Places	15	na	15	na
59	Misc. Retail (Drugs, Liqr.)	10	na	10	na
	Admin. & Aux.				
FINANCE, INS. & REAL EST.					
60	Banking	1	2,000.00	1	2,000.00
61	Credit Agencies	1	2,000.00	1	2,000.00
62	Security Brokers	1	2,000.00	1	2,000.00
63	Insurance Carriers	1	2,000.00	1	2,000.00
64	Insurance Agents	1	2,000.00	1	2,000.00
65	Real Estate	1	2,000.00	1	2,000.00
67	Holdings & Invest. Offices	1	2,000.00	1	2,000.00
SERVICES					
70	Hotels	5	1,000.00	5	1,500.00
72	Personal Services	1	1,000.00	1	5,000.00
73	Business Services	1	1,000.00	1	3,000.00
75	Auto Repair Services	1	100.00	1	400.00
76	Misc. Repair	1	100.00	1	500.00
78	Motion Pictures	1	50.00	1	200.00
79	Amusements/Recreation	1	1,000.00	1	2,000.00
80	Health Services	1	1,000.00	1	1,562.00
81	Legal Services	1	1,000.00	1	4,000.00
82	Educational Services	1	1,000.00	1	5,000.00
83	Social Services	1	1,000.00	1	5,000.00
84	Museums	1	1,000.00	1	1,000.00
86	Membership Organizations	1	1,000.00	1	5,000.00
87	Engr. & Mgt. Services	1	1,000.00	1	4,000.00
89	Industries NEC	10	1,000.00	10	2,500.00

Source: Transmode Consultants based upon Association of American Railroads Data.

$$r_{je}^{v} = r_j^{v}/r_e^{v}$$

and the freight conversion factor for container k, expressed in terms of equivalent movement of Type e equipment by volume, is

$$r_{ke}^{v} = r_k^{v}/r_e^{v}$$

To give a simple example, suppose the maximum weight that Type e equipment can carry is $r_e^{w} = 10{,}000$ lb, and the maximum weight that vehicle type j can carry is 20,000 lb. Then the factor for converting movements of vehicle type j into equivalent movements of Type e equipment by weight is as follows:

$$r_{je}^{w} = r_j^{w}/r_e^{w} = 20{,}000/10{,}000 = 2$$

Conversion Factors for Vehicles or Containers Carrying Only One Type of Commodity. The first four conversion factors listed above (r_j^W, r_k^W, r_j^V, r_k^V) when combined with information on the density and the dollar value per pound of different commodities allows one to determine factors for converting freight movements of different types of commodities into equivalent weight, cubic volume, and dollar value.

Table 5.10 presents input (inbound) and output (outbound) values for key attributes—density and value expressed in dollars per pound—for different commodity classes represented by two-digit Standard Transportation Industry Codes

(STIC). More detailed information is available at the five- and six-digit STIC from the Association of American Railroads.

If vehicle type j or container type k is used exclusively to carry commodity type c, and the density of commodity c in weight per unit volume (e.g., pounds per cubic foot) is x_c, then the conversion factors in terms of weight or cubic volume of commodity c are as follows:

r^w_{jc} = min $\{r^v_j x_c, r^w_j\}$, the conversion factor expressed in terms of weight of commodity c carried by vehicle type j;
r^w_{kc} = min $\{r^v_k x_c, r^w_k\}$, the conversion factor expressed in terms of weight of commodity c carried by container type k;
r^v_{jc} = min $\{r^w_j(1/x_c), r^v_j\}$, the conversion factor expressed in terms of cubic volume of commodity c carried by vehicle type j; and
r^v_{kc} = min $\{r^w_k(1/x_c), r^v_k\}$, the conversion factor expressed in terms of cubic volume of commodity c carried by container type k.

The reason each of the conversion factors is expressed as a minimum of two terms is that the density of a commodity may result in the weight of a commodity that uses the maximum volume capacity of a vehicle exceeding the weight capacity of the vehicle. Therefore, the lowest maximum allowable weight the vehicle can carry, versus the lowest maximum weight associated with the maximum volume the vehicle can hold of commodity c, determines the maximum weight a vehicle can carry. Similar reasoning applies to the maximum weight of a commodity a container can carry and the maximum volume that a vehicle or container can hold.

If the value of commodity c is b_c dollars per unit weight (e.g., pound), then the conversion factor for vehicle type j in terms of the dollar value is calculated as follows:

$$r^{\$}_{jc} = r^w_{jc} b_c$$

Similarly, the conversion factor for container type k in terms of dollar value of commodity c is as follows:

$$r^{\$}_{kc} = r^w_{kc} b_c$$

Example 1: Freight capacity. A 2-lane, two-way road with a restricted shoulder of 2 ft and 11-ft lanes was built on a rolling terrain to connect a large furniture manufacturing plant and an interstate highway 5 mi away. Each truck leaving the plant must stop for 2 min at a gate outside the plant where the contents are checked against credentials. The posted speed limit on the road is 45 mph.

Question: What is the maximum hourly freight capacity (assuming no passenger vehicles) in both directions expressed in terms of each of the following (assume that the directional split is 60-40)?

1. 63-ft semi-tractor trailer pulling hi-cube highway trailers (53 ft-102 in.),
2. Tons of freight based on trailer weight capacity,
3. Cubic volume based on trailer volume capacity,
4. Boxcar equivalents by weight,
5. Boxcar equivalents by volume,
6. Tons of furniture,
7. Cubic volume of furniture, and
8. Dollar value of furniture.

Answer: From Chapter 8 of the HCM, the maximum capacity of a 2-lane highway under ideal/uninterrupted conditions (speed = 45 mph, LOS E) is 2,800 pcph for both lanes. This ideal capacity can be adjusted to account for the prevailing roadway and traffic conditions as follows.

$$\text{capacity}_{\text{2-lanes}} = 2{,}800 \text{ pcph} * f_d * f_w * f_{HV}$$

where

2,800 = maximum flow rate under ideal conditions (passenger cars per hour),
f_d = adjustment factor for directional distribution of traffic,
f_w = adjustment factor for narrow lane and restricted shoulder width, and
f_{HV} = adjustment factor for presence of heavy vehicles.

Using the tables in Chapter 8 of the HCM:

f_d = 0.94 (for 60-40 distribution),
f_w = 0.92 (4-ft shoulder, 11-ft lanes, LOS E), and
f_{HV} = 1/[1 + 1(5 − 1)] (100 percent heavy trucks on rolling terrain)
= 1/5 or 0.20.

Therefore, the two-way capacity of the highway is as follows:

capacity = 2,800 pcph * 0.94 * 0.92 * 0.20
= 484 heavy trucks per hour (both directions)

The maximum flow in one direction is 0.60 * 484 = 290 vph. The following parameters will be used to convert this movement into other freight capacity measures:

$x_c = x_{furn}$ = 10 lb per cubic foot, furniture density
$b_c = b_{furn}$ = dollars per pound of furniture = \$5.73 per pound
$r_{trailer}$ = 1
$r^w_j = r^w_{trailer}$ = 50,100/2,000 lb/lb per ton
= 25.05 tons, maximum semi-trailer capacity in tons
$r^v_j = r^v_{trailer}$ = 3,847 ft^3, maximum semi-trailer capacity in cubic feet
e = boxcar, equivalent equipment unit
r^w_e = maximum weight capacity of boxcar by weight
= 100,000lb/2,000 lb = 50 tons

r^v_e = maximum volume capacity of boxcar
= 6,600 ft^3

$r^w_{trailer,e} = r^w_{trailer}/r^w_e$
= 25.05/50 = 0.501 boxcar by weight

$r^V_{trailer,e} = r^V_{trailer}/r^V_e$
= 3,847/6,600 = 0.583 boxcar by volume

$r^w_{jc} = \min\{r^v_j x_c, r^w_j\} = \min\{r^v_{trailer} x_{furn}, r^w_{trailer}\}$
=min {(3,847 ∗ 10)/2,000 lb per ton, 25.05 tons}
= min {16,235 tons, 25.05 tons}
= 19.235 tons of furniture per trailer

$r^v_{jc} = \min\{r^w_j(1/x_c), r^v_j\}$
$= \min\{r^w_{trailer}(1/x_{furn}), r^v_{trailer}\}$
= min {(25.05 tons ∗ 2,000 lb per ton)(1/10 ft^3 per pound), 3,847 ft^3 per trailer}
= 3,847 ft^3 of furniture per trailer

$r^\$_{jc} = r^w_{jc} b_c$ = 19.235 tons ∗ 2,000 lb per ton ∗ $5.73 per pound
= $220,433 worth of furniture per trailer

The capacity of the segment in terms of each of the measures asked for is as follows:

1. *Semi-tractor trailers* are classified as heavy trucks; therefore, the capacity of the highway in terms of these vehicles is as follows:

   vehicle capacity = 484 semi-tractor trailers per hour

2. *Tons of freight based on maximum trailer weight capacity—*

   vehicle capacity ∗ $r^w_{trailer}$ = 484 vph
   ∗ 25.05 tons per vehicle = 12,124.2 tons per hour

3. *Cubic volume based on maximum trailer volume capacity—*

   vehicle capacity ∗ $r^v_{trailer}$ = 484 vph
   ∗ 3,847 ft^3 per hour = 1,861,948 ft^3 per hour

4. *Boxcar equivalents by weight—*

   vehicle capacity ∗ $r^w_{trailer,e}$ = 484 vph
   ∗ 0.501 boxcars per trailer by weight = 242 boxcar equivalents by weight per hour

5. *Boxcar equivalents by volume—*

   vehicle capacity ∗ $r^V_{trailer,e}$ = 484 vph
   ∗ 0.583 boxcars per trailer by volume = 282 boxcar equivalents by volume per hour

6. *Tons of furniture—*

   vehicle capacity ∗ $r^w_{trailer,furn}$ = 484 vph
   ∗ 19.235 tons = 9,309.74 tons per hour

7. *Cubic volume of furniture—*

   vehicle capacity ∗ $r^v_{trailer,furn}$ = 484 vph
   ∗ 3,847 ft^3 per vehicle = 1,861,948 ft^3 per hour

8. *Dollar value of furniture—*

   vehicle capacity ∗ $r^\$_{trailer,furn}$ = 484 vph
   ∗ $220,433 per vehicle = ~ $107 million per hour

Average Conversion Factors Across All Commodity Types When One Type of Vehicle Carries Only One Type of Commodity. Suppose vehicles in the traffic stream carry more than one type of commodity but no vehicle of type j carries more than one type of commodity. Suppose further that the number of vehicles carrying commodity c is known. There is then a one-to-one correspondence between vehicle type and the commodity contents of a vehicle. The number of vehicles carrying a particular commodity is denoted by p_j, where j represents the vehicle type. Then the conversion factors for all commodity types expressed in terms of weight, cubic volume, or dollars are as follows:

$r^w = \Sigma_j Sp_j r^W_{jc}$, the conversion factor for all commodity types in terms of weight j

$r^v = \Sigma_j p_j r^V_{jc}$, the conversion factor for all commodity types in terms of cubic volume j

$r^\$ = \Sigma_j p_j r^\$_{jc}$, the conversion factor for all commodity types in terms of dollar value j.

Example 1: Multiple commodities. A 2-lane rural highway with a 45 mph speed limit connects an industrial park to an interstate 3 mi away. Suppose the factories in the industrial park produce two types of commodities: (1) electric equipment and (2) wood products. Panel trucks with a weight capacity of 16,000 lb and a cubic volume capacity of 1,800 ft^3 are used to carry electric equipment and semi-trailers with a weight capacity of 50,100 lb and a cubic volume capacity of 3,847 ft^3 is used to carry wood products. Assume that the relative fraction of trucks in the traffic stream is 60 percent panel trucks and 40 percent semi-trailers. There is a railroad at-grade crossing along the way where there is a rail yard. Switching operations disrupt highway traffic every 2 hr for a period of 2 min. Furthermore, a load-restricted and narrow bridge requires the semi-trailers to detour around it on a route with a 35 mph speed limit. The lanes on the bridge are 11 ft wide and the shoulder width is 2 ft.

Question: What is the one-directional freight capacity of the 2-lane highway expressed in terms of tons of throughput per hour for all types of commodities? Assume that roadway conditions are ideal unless stated otherwise.

Answer: The highway can be broken down into the following components with their respective vehicle capacities.

LINKS
2-lane, two-way rural highway segments
45 mph speed limit, uninterrupted flow (LOS E)
traffic = 100 percent truck (40 percent semi-trailers, 60 percent panel trucks)

$$\text{capacity}_{\text{2-lanes}} = 2{,}800 \text{ pcph} * f_d * f_w * f_{HV}$$

where

f_d = 1 (50-50 directional split),
f_w = 1 (adequate road width and lateral clearance),
f_{HV} = 1/[1 + 1(2 − 1)] (100 percent trucks on level terrain, at full freight capacity)
= 1/2
= 0.5, and
capacity = 2,800 pcph * 1 * 1 * 0.5
= 1,400 trucks per hour (both directions)
= 700 trucks per hour (one direction: 280 semi-trailers, 420 panel trucks).

NODES

- Railroad at-grade crossing: This node functions like a traffic light with a green time of 2 hr and a red time of 2 min. The adjustment factor for heavy vehicles, saturation flow after each switching operation, and capacity are calculated as follows:

f_{HV} = 0.50 (from Table 9-6 of the HCM, 100 percent heavy vehicles)
saturation flow = 1,900 * f_{HV}
= 1,900 * 0.5
= 950 trucks per hour
capacity = saturation flow * green time per cycle length
= 950 trucks per hour * (120 min/122 min)
= 934 trucks per hour (both directions)
= 467 trucks per hour (one way)

- Bridge: 2-lane, two way
- 45 mph speed limit, uninterrupted flow (LOS E)
- Traffic = 100 percent truck (100 percent panel trucks)

$\text{capacity}_{\text{2-lanes}}$ = 2,800 pcph * f_d * f_w * f_{HV}
f_d = 1 (50-50 directional split)
f_w = 0.88 (11-ft lanes, 2-ft shoulders)
f_{HV} = 1/[1 + 1(2 − 1)] (100 percent trucks on level terrain, at full freight capacity)
= 1/2
= 0.5

capacity = 2,800 pcph * 1 * 0.88 * 0.5
= 1,232 trucks per hour (both directions)
= 616 trucks per hour (one way, all panel trucks)

The one-directional vehicular capacity of the entire corridor is equal to the minimum component capacity, which is that of the railroad at-grade crossing, 467 trucks per hour = 280 panel trucks per hour + 187 semi-trailers per hour.

The values for the input parameters for calculating the equivalent freight capacity of the highway follow:

$r_j^w = r_{panel}^w$
= 16,000 lb/2,000 lb per ton = 8 tons, maximum panel truck capacity by weight
$r^v j = r_{panel}^v$
= 1,800 ft^3, maximum panel truck capacity by volume
$r_j^w = r_{trailer}^w$
= 50,100 lb/2,000 lb per ton = 25.05 tons, maximum semi-trailer capacity by weight
$r_j^v = r_{trailer}^v$
= 3,847 ft^3, maximum semi-trailer capacity by volume
x_{elec} = 6 lb/ft^3, density of electronic products
x_{wood} = 25 lb/ft^3, density of wood products
$r_{panel,elec}^w = \min\{r_j^v x_c, r_j^w\}$
$= \min\{r_{panel}^v x_{elec}, r_{panel}^w\}$
= min {(1,800 * 6) lb/2,000 lb per ton, 8 tons}
= min {5.4 tons, 8 tons}
= 5.4 tons
$r_{trailer,wood}^w = \min\{r_j^v x_c, r_j^w\}$
$= \min\{r_{trailer}^v x_{wood}, r_{trailer}^w\}$
= min {(3,847 * 25) lb/2,000 lb per ton, 25.05 tons}
= min {48.09 tons, 25.05 tons}
= 25.05 tons

Therefore, the ton-capacity of the corridor is as follows:

freight capacity = 280 panel trucks per hour * 5.4 tons per panel truck + 187 trailers per hour * 25.05 tons per truck
= 6,196 tons per hour

5.5.3 Combined Person and Freight Capacity

From a physical standpoint, there is no single capacity measure of a component carrying traffic consisting of both persons and goods or, for that matter, more than one mode. The analyst has two basic options for calculating physical capacity of persons and goods. The first is to calculate person and freight capacities separately and interpolate between the two in order to make tradeoffs. Similarly, if more than one mode is involved, the capacity of each mode can be calculated separately, and then some form of interpolation can be performed.

The second approach is to make a prior assumption about the fraction of traffic that is made up of person or freight movement. If the fractions of freight or passenger traffic are known, the formula for calculating multimodal person or freight capacity follows:

$$\text{capacity}_m = R_m * f_m * N$$

where

m = index representing persons or goods;
R_m = the occupancy rate for persons if m = persons or the goods conversion factor for freight if m = freight;
f_m = the fraction of the traffic that carries persons if m = persons or freight if m = freight; and
N = total number of vehicles in the traffic stream.

From an economic standpoint, the relative prices (costs) of freight versus person movement are a major determinant of the mix of traffic that uses a particular facility. These prices (costs) result from supply and demand of transportation that are a consequence of the more fundamental supply and demand for various types of goods and services and needs of individuals to take different types of trips. In theory, there is a production possibility curve that describes the rate at which society in a given locale trades off the production of freight and person transport. The relative prices of freight and person transport determine what mix is actually produced in the locale. Chapter 9 provides additional discussions of economic issues in capacity determination.

5.5.4 Additional Examples

Example 1: Independent/parallel links. A corridor is 10 mi long and has a highway, bicycle lane, and commuter rail line. The two-way bicycle lane begins at Mile 2 and runs only to Mile 7, the only bicycle segment. The highway is composed of two segments consisting of three lanes in each direction from Mile 0 to Mile 5 and two lanes in each direction from Mile 5 to Mile 10. The commuter rail line is a single segment running on two tracks along the entire length of the traveled way. The person capacity of a single track of the commuter rail line is 24,000 persons per hour. The person capacity of each lane of the highway is 11,000 persons per hour per lane. The person capacity of each bicycle lane is 2,150 persons per hour. The person capacity of the 0- to 0.5-mi highway portion is 3 lanes ∗ 11,000 persons per hour per lane = 33,000, and the person capacity of the 0.5- to 1-mi portion is 2 lanes ∗ 11,000 persons per hour per lane = 22,000.

Question: What is the total person-capacity of the corridor in one direction?

Answer: The corridor is logically divided into four component segments. Each segment has one or more links. Segment 1 is from Mile 0 to Mile 2 where the bicycle lane begins. Segment 2 is from Mile 2 to Mile 5 where the highway changes from three to two lanes in each direction. Segment 3 runs from Mile 5 to Mile 7 where the bicycle lane ends, and segment 4 runs from Mile 7 to Mile 10. The capacity of each segment of the corridor is the sum of the capacities of component links:

	Segment 1 (0-2 mi)	*Segment 2 (2-5 mi)*	*Segment 3 (5-7 mi)*	*Segment 4 (7-10 mi)*
Highway	33,000	33,000	22,000	22,000
Rail	24,000	24,000	24,000	24,000
Bike	0	2,150	2,150	0
TOTAL	57,000	59,150	48,150	46,000

The corridor capacity is 46,000 persons per hour, which is the capacity of Segment 4, the smallest of the sum of the link capacities within each segment of the corridor.

Example 1a: Suppose in the above example that the two center lanes of the highway from Mile 5 to Mile 10 were reversible.

Question: What is the one-directional capacity of the corridor for the direction in which one of the reversible lanes is added to the capacity?

Answer: The person capacity per lane of highway in the example is 11,000 persons per hour. Thus the one-directional person capacity of Segment 3 and Segment 4 should be increased by 11,000 to account for the addition of a reversible lane.

	Segment 1 (0-2 mi)	*Segment 2 (2-5 mi)*	*Segment 3 (5-7 mi)*	*Segment 4 (7-10 mi)*
Highway	33,000	33,000	22,000	22,000
Rail	24,000	24,000	24,000	24,000
Bike	0	2,150	2,150	0
Rev. Lane	0	0	11,000	11,000
TOTAL	57,000	59,150	59,150	57,000

Segments 1 and 4 have the smallest capacities of 57,000 persons per hour, which determine the capacity of the entire corridor.

Example 2: Combined links and nodes. An intercity corridor connecting City A and City B has three major paths composed of links and nodes. The nodes of Path 1 for the highway represent locations of freeway interchanges. The nodes for Paths 2 and 3 for the rail line and intercity air travel, respectively, are passenger terminals. Capacity is presented in thousands of persons per hour:

Path 1 (Highway) Link/ Node	*Capacity*	*Path 2 (Rail) Segment/ Node*	*Capacity*	*Path 3 (Air) Link/ Node*	*Capacity*
Link 1	10	Node 1	12	Node 1	17
Node 1	9	Link 1	6	Link 1	6
Link 2	8	Node 2	10	Node 2	5
Node 2	7				
Link 3	8				

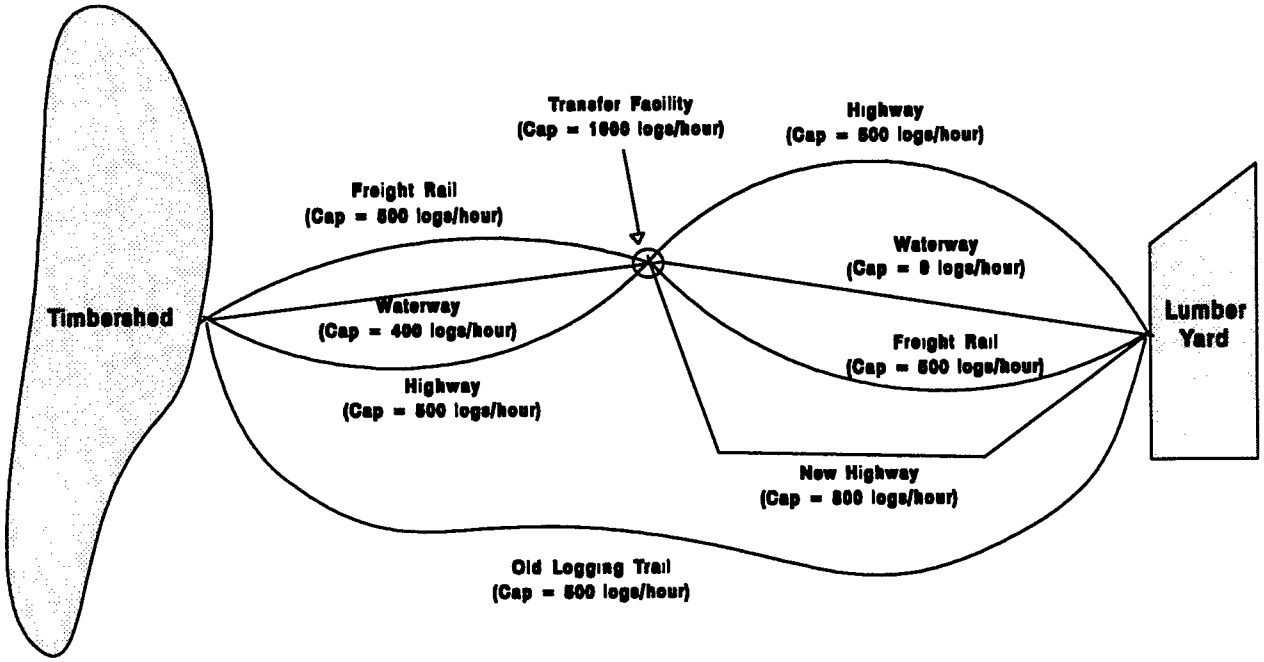


Figure 5.6. Multimodal freight corridor.

The capacity of Path 1 is 7,000 persons per hour, the capacity of the smallest of the links or nodes comprising the path, which is Node 2 comprising the freeway interchange between Segments 2 and 3 of the highway. The capacity of the intercity rail line is 6,000 persons per hour, the capacity of Segment 1, which is smaller than the capacity of the rail passenger terminals at either end of the path. However, the capacity of Path 3 is determined by the air passenger terminal represented by Node 2, which has a capacity of 5,000 persons per hour, which is less than either the link capacity or the capacity of the air passenger terminal at the other end.

Question: In the above example, what is the corridor capacity?

Answer: None of the paths share the same links or nodes and therefore can be treated as independent. The one-directional corridor capacity is the sum of each of the paths, which is 7,000 + 6,000 + 5,000 = 18,000 persons per hour.

Example 3: Multimodal freight corridor. A freight corridor between a timber shed and a lumber and paper pulp processing center has several alternative paths consisting of links and nodes (see Figure 5.6). Three links connect the timber shed with an intermodal transfer facility. The first is a river channel. Fifty-foot logs can be floated down the river. The other two links are rail and highway, which run next to the river. The capacity of the river is 400 logs per hour. The capacity of the road along the river is 500 logs per hour. The capacity of the railroad is also 500 logs per hour. The transfer facility is located on the side of the river. The handling capacity of this transfer point is 1,000 logs per hour. From the transfer facility to the processing center, the logs can be transported by using three links, two using either rail or truck along the river, which has the same capacity as above. The other link is a recently constructed highway that veers away from the river but eventually leads to the processing center. The capacity of this road segment is 800 logs per hour. A completely independent link connects the timber shed and processing center, one that follows a sequence of old logging roads whose capacity is the same as the road along the river, 500 logs per hour.

Question: What is the total freight capacity of this corridor?

Answer: Figure 5.6 shows that the corridor consists of many possible paths. Only one path—the portion of waterway—is dependent on the loading/transfer facility. The other two links next to the river, the highway and rail, can move the logs from the timber shed to the processing center without loading or unloading. The transfer facility has sufficient capacity to process the logs coming through the waterway. These logs can move only through the newly constructed highway, which has a greater capacity than the waterway. The sequence of old logging roads is independent of these paths. Therefore, the four independent paths and their capacities are as follows:

Path	Links and Nodes	Maximum Throughput
1	Rail	500 logs per hour
2	Highway (along waterway)	500 logs per hour
3	Waterway-Transfer-New Highway	400 logs per hour
4	Old Logging Road	500 logs per hour
TOTAL CORRIDOR		1,900 logs per hour

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CHAPTER 6

LEVEL OF SERVICE AND PERFORMANCE MEASURES

Performance measures are used to evaluate the effectiveness of a transportation system and its individual components. Performance can be approached from a variety of perspectives. Users and nonusers view system performance differently. Users want frequency of service, speed, consistent progress, infrequent delays, reliability, safety, and low cost. Nonusers value low levels of pollution, reduction in noise, lack of visual impact, and minimal effect on adjacent land uses. Both viewpoints can be accommodated by picking a proper set of performance measures.

6.1 OBJECTIVE

The objective of this chapter is to identify various measures of link/node/corridor performance and explain how they are related to capacity (supply) and traffic volume (demand). Computational strategies for the estimation of performance measures for both passengers and freight have also been developed. Comparisons of observed or projected performance levels with desired/acceptable levels will enable planners and analysts to identify the location, manifestation, and extent of current and potential capacity problems.

6.2 STEPS IN THE PROCESS

The following steps will help explain the performance aspects of segments and nodes of a multimodal transportation corridor or network and where the problems are.

1. **Identify important unimodal or multimodal corridor performance measures.** Specify units for each measure (e.g., hours, probabilities, etc.).
2. **Stipulate the time periods for which performance measures are to be determined.** This step is crucial because the performance measures of each link and node vary over time.
3. **Identify major capacity constraints in the corridor of interest** and select links and nodes to define a simplified network that represents the major segments.
4. **Develop the capacity on each segment** using the techniques described in Chapter 5.
5. **Determine the flows that are likely on each segment during each time period** for which the performance assessment is being developed.
6. **Calculate existing and/or future performance measures for key segments** using available traffic volume data and capacity figures from Step 4. Traffic volumes should correspond to the time periods identified in Step 2.
7. **Develop summary performance for typical trips** using the corridor by summing the performance for each trip for use in utility assessment, which converts performance into a common quantitative unit, preferably dollars.
8. **Identify locations of significantly poor performance levels** within the corridor, both existing and potential. Identify the causes of poor performance and the extent of the problems and suggest possible actions that can be taken to alleviate them.

6.3 ROLE OF PERFORMANCE MEASURES

Performance measures, or LOS measures as they are sometimes called, can take a wide variety of forms. They can be quantitative and objective, such as travel time or cost. They can be qualitative and subjective, such as the level of service measures adopted by the HCM, which are used as shorthand for the deterioration of traffic performance with increasing volume-to-capacity (v/c) ratio. It is also useful to note that the objective measure, travel time, which applies to a single trip made by a single tripmaker, might be termed *disaggregate*, whereas measures such as average travel time of persons and average speed of vehicles are *aggregate*, applying to all of the traffic using a specific facility at a given point in time. Both disaggregate and aggregate measures of performance will continue to find usefulness in the future as they have in the past. It is also important to differentiate between those performance measures that apply to the user of the transportation system and those of interest primarily to the nonuser.

6.3.1 User Performance Measures

The ultimate purpose of a performance measure is to measure the utility of transportation service to individuals. Consequently, we will start by suggesting a set of performance measures that will allow us to evaluate single trips. In the introduction above, a number of possible candidate performance measures were suggested. Users want frequent ser-

vice, speed, consistent movement, infrequent delays, reliability, safety, and low cost. These phrases translate into the following list of qualitative and quantitative performance measures:

- Service frequency,
- Travel time,
- Travel comfort,
- Travel time reliability,
- Probability of loss and/or damage, and
- Cost.

Other measures can be devised, and other names given to the measures above, but these are the most important. Some discussion of each is appropriate.

Service frequency is related to the amount of time that a traveler or a shipper might have to wait to make the trip. A common example is the number of sailings of ships to a particular foreign port during a given week or the number of departures of an aircraft to a given destination during a day. Service frequency could be referred to as "interarrival time," the average time one would have to wait to get the service, which is the same as the time headway. For freight, service frequency could be called equipment availability, since the availability of a freight car or a trailer in which to carry the freight is typically the source of delay at the start of a trip. One of the principal virtues of single-passenger automobiles is that the driver can leave whenever he or she is ready. There is no waiting time to begin the trip. Quantitative measures of service frequency are therefore: (1) interdeparture time (time headway, h_t) for person transport, which is typically zero for automobile travel, and (2) delay in obtaining freight vehicles or equipment.

Travel time is clearly one of the most important performance measures for any type of trip. Both freight and passengers will compare the desirability of one trip versus another in terms of its total travel time. The possible exception is vacation travel. A longer cruise may be preferred over a shorter one. Travel time may be measured in seconds, minutes, hours, or days. Travel time is typically correlated negatively with high values of all of the other performance measures identified above. Travel time can also be decomposed into sources of delay. Sources of delay, for the individual traveler or shipment, can be broken down into non-congestion- and congestion-related delay. The magnitude of each non-congestion- and congestion-related delay can be identified, and delay sources can be further categorized as recurring or nonrecurring.

Travel comfort is clearly important, but it is difficult to measure objectively. If an airline flight is crowded, the seats are small, the air conditioning is functioning poorly, or the food is of low quality, this measure could be important. Likewise for a driving trip, if the road is crowded, the traffic is stop-and-go, and the road signs are difficult to see and understand, the trip is less comfortable compared with a similar trip on an uncongested freeway on which travelers can set their own speed without interference from other traffic. Potential quantitative measures of comfort are space capacity per person (i.e., square or cubic feet of area per person) and a measure of space capacity per vehicle, for which distance headway is a partial measure. One might argue that there is no equivalent performance measure for freight since freight is not aware of comfort. The need for a special environment, such as refrigeration or a nitrogen gas atmosphere, however, is not totally dissimilar. At the same time, finding a variable for comfort, which can serve as a performance measure, is difficult for passengers and freight alike.

Travel time reliability is a measure of the variability in travel time (see Figure 6.1). If one had the travel time distribution for the same trip made on numerous occasions one might think of reliability as the "standard deviation" of travel time. For many shippers and travelers, travel time reliability is as important as travel time, perhaps even more important.

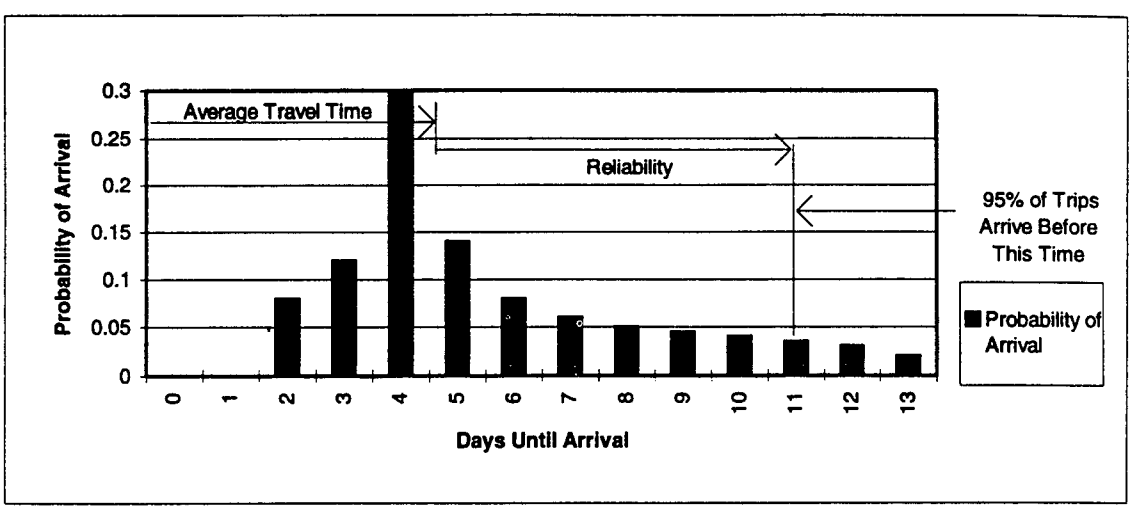

Figure 6.1. Definition of time reliability.

If travel time varies from trip to trip then in order to safely arrive prior to a given time it is important to schedule the departure time earlier than it would have to be if the variability did not exist. Trips to the airport to catch a flight must allow for the contingency that there could be a tie-up on the freeway. Consequently, many travelers will leave early to be sure that they have enough time. For freight transportation, a variant of travel time distribution, lead time (which includes travel time), can be shown to be a determinant of the "safety stock" that must be carried to prevent stockout.

Probability of loss and/or damage is a performance measure for safety. There are several possible dimensions that need to be covered. For passenger travel, safety can include probability of an accident, probability of property damage, probability of personal injury or probability of a fatality. For property damage or injury there is the level of damage or injury. At one extreme there may be damage to a fender. At the other extreme the entire vehicle may be "totaled." Likewise, for freight there is the probability of a loss, the level of loss, and the probability that at least some of the product can still be used. Sorting all of this out will need to be done for the particular case at hand.

Cost of transportation would appear to be an unambiguous measure, but even here the question of exactly which costs are covered and which are left uncovered poses a problem. For example, is drayage covered? What about demurrage or equipment rental? Is the figure that is presented the total cost, the variable cost, or the price of transportation service? Do the costs cover interlined service? Ultimately we note that higher LOSs may have to be traded off against higher cost.

6.3.2 Facility Performance Measures

If the performance measure needed is for the cost of a single trip by a user, the measures above appear satisfactory. On the other hand, to examine the performance of traffic consisting of the trips of many individual travelers over a single facility in the system, the measures of greatest interest will be point measures on the facility. The use of aggregate measures could include

- v/c ratio for vehicles;
- v/c ratio for persons;
- v/c ratio for goods expressed in any of the following units—weight, cubic volume, and equivalent equipment movements (e.g., truckloads, boxcars, and containers);
- Speed on facilities and through nodes—time mean speed, space mean speed, and variability;
- Travel time on facilities and through nodes—mean and variability;
- LOS—for facilities (e.g., A, B, C, D, E, and F for highways) and for key sources of delay (e.g., frequency of service and drayage);
- Cumulative vehicle-hours of delay for vehicles;
- Cumulative person-hours of delay for persons;
- Cumulative hours of delay for freight (e.g., ton-hours, cubic volume-hours, and container-hours);
- Dollar value of cumulative delay for persons and freight;
- Cumulative delay by most important delay sources—non-congestion-related delays, congestion-related delays, recurring delays, and nonrecurring delays;
- Vehicle miles traveled on a facility—passenger and freight;
- Additional trips on facility;
- Longer trips on facility; and
- Accidents—persons (property damage only, personal injuries, and fatalities) and freight (incidents, loss, and damage).

6.3.3 Nonuser Performance Measures

As indicated above, there is a difference in the performance measures that might be employed by nonusers of a transportation facility. Increasingly, the neighbors of a transportation facility are its principal critics. Performance measures for nonusers include the following:

- Congestion costs,
- Noise,
- Fuel use,
- Emissions,
- Pavement maintenance costs, and
- Bridge maintenance costs.

Each contributes to the social cost of operating the transportation system.

Congestion costs refer to those costs imposed on the system as a whole by the addition of a single vehicle to the traffic stream. Economists have long argued that the congestion imposed on the system by the marginal vehicle exceeds the value to the individual, so that, ultimately, society is negatively affected by this marginal traveler. If a toll equal to the cost imposed by the marginal vehicle were to be imposed, the marginal vehicle could choose not to travel or to change the time of travel. The tolls collected could be redistributed so that society as a whole would be no worse off as a consequence of the toll. Whether or not society implements the toll system, recognizing congestion as a nonuser cost is a useful thing to do. Although economists regard marginal congestion costs as a nonuser cost, one can still accumulate average congestion costs experienced by each user to obtain a cumulative measure of congestion costs for facility usage as indicated above.

Noise is clearly one of the negative aspects of today's urban society. Traffic noise is of particular concern to nonusers of the transportation system. It is common to find noise barriers retrofitted to many freeways located in residential areas. A performance measure that takes into account

the decibel levels at various distances from the roadway would provide an objective measure of the size of the problem. An exposure index that would measure the number of people exposed to these particular noise levels is a possible next step.

Fuel use by automobiles has become the example by which to illustrate waste of natural resources. During severe energy crises in the past, the United States instituted public measures to estimate fuel use and proposed reduction measures. These public policies have resulted in fuel-saving engine improvements made by vehicle manufacturers through effective research and development and through reductions in vehicle weight. We now have a reasonably good methodology for estimating the fuel use associated with a particular alternative, and a performance measure on a facility can include the amount of fuel consumed to achieve certain demand levels. Providing a fuel use performance measure for an individual link in the system appears to be useful.

Emissions are the natural consequence of the burning of carbon fuels by automotive equipment. Closely related to fuel use are the emissions of noxious byproducts of the combustion of this fuel. Measures can include the amount of carbon monoxide, carbon dioxide, nitrogen oxide, hydrocarbons, and particulates emitted on alternative systems. Reliable measures have been developed for computing the changes in the amounts of each of these pollutants that will result from implementing a particular traffic scheme.

Pavement maintenance costs are of concern in part because it is difficult to assign cost responsibility to the individual vehicles using the facility. Trucks tend to cause more pavement damage than do typical passenger cars; heavy trucks cause an inordinate amount of wear and tear. Some argue that the tax recovery system built into the fuel tax levied on trucks fails to recover the full cost of road use by some of the heavier vehicles. However, some allocation studies indicate that trucks pay more than their fair share of pavement construction and maintenance costs. Still the cost to city and local governments to maintain pavements may not be fully transferred down to the lower governments from the taxing authorities. For some types of projects, therefore, it may be desirable to develop the magnitude of these pavement maintenance costs as a performance measure.

Bridge maintenance costs are of the same type as pavement maintenance. Bridges are subject to stress caused by vehicle loads. Bridge maintenance costs can be developed so as to recognize the wear and tear imposed by damage-causing vehicles. This will allow alternatives that switch these loads to rail (if the goods and market demand warrant the switch) to realize societal benefits, which are reflected in the performance measures for each of the alternatives.

These nonuser costs, reflected in the performance measures of each of the alternatives being examined, can be summed and incorporated into the direct logistics cost savings realized by the freight users of the system and the time cost savings of passenger users of the system. These direct cost savings can have a multiplier effect on the growth of the economy of the region. Cost savings by manufacturers can lead to reductions in price, to a more competitive posture vis-à-vis competitors in other regions, and to larger sales. These sales, in turn, lead to the need to enlarge the manufacturing facility, hire more workers, and secure more inputs in order to produce the additional product required to meet the larger demand. This results in increased growth in all of the service industries within the area. Therefore, direct cost savings lead to indirect growth in the economy of the region and this, of course, will result in greater traffic volumes.

6.4 CAPACITY AND PERFORMANCE

Regardless of which performance measures are chosen, the most important indicator of performance is the volume of traffic on the facility (segment or node) relative to the capacity of the facility. This is known as the volume/capacity relationship, normally referred to as the v/c ratio. This ratio should be expressed in terms of vehicles, persons, and goods movement. Each provides a different perspective. High v/c ratio for vehicles implies there is a current or projected problem regarding the accommodation of vehicle movement. However, the v/c ratio for person movement may be a fraction of the ratio for vehicles, indicating underutilization of person capacity. Similarly, the v/c ratio for goods movement may be low compared with that for vehicles. Low utilization of maximum feasible occupancy rates and maximum capacity of conveyances for freight is fundamentally a behavioral and economic issue, usually best addressed through demand management options (see Chapters 7 and 8).

The v/c ratios are indicators of the supply and demand relationships that exist on a facility. As demand approaches supply, the opportunity for congestion increases. As demand exceeds supply, delays are inevitable as well as stop-and-go operations, queues, and unsafe conditions. This produces longer travel times, lowers reliability, and increases costs and the risk of accidents. These results occur in all modes. However, the manifestation of the delay caused by congestion in each mode may be different. In railroad yards, for example, the amount of shifting of rail cars increases as the v/c ratio increases. The mode for which these relationships are most widely studied is the highway mode, and because of its importance to multimodal transportation in general, this is the mode we will use as an example.

6.4.1 Capacity As a Function of Speed and Flow

Capacity is a function of speed, and speed is a function of capacity. As the volume on a free-moving roadway approaches its speed-determined capacity it becomes unstable. This phe-

nomenon is extensively discussed in the HCM. The volume level that can be accommodated under free-flowing conditions and the maximum volume levels that are possible at lower speeds illustrate the unstable nature of traffic at the higher volume levels (see Figure 5.2 in Chapter 5). If anything disrupts the free-flowing speed at high volume levels, the capacity drops to a lower level consistent with the reduced speed. This causes a traffic jam in the road, which slows approaching vehicles and perpetuates the jam, which then propagates back through the approaching traffic. The disturbance will not die out until the volume of traffic in the approaching stream drops to a level that can accommodate the short-term delay. Frequently, on a roadway that is running close to capacity, a condition of stop-and-go traffic is produced, which can last for hours until traffic volume levels drop off.

Urban roadways with their high level of commuter traffic are particularly subject to this phenomenon, which is commonly referred to as a "traffic breakdown." Beltways and peripheral roads typically have sections on which the approaching volume exceeds the existing roadway capacity several times during the day. The usual case is where four lanes drop to three, where an input ramp feeds additional volume onto a roadway that is already running at capacity, or where the roadway narrows to go through a constricted section, such as a bridge or tunnel. These overcapacity sections can require longer-than-normal times to negotiate because the volume of vehicles that can pass is now determined by speed rather than volume level. This reduces the effective speed for the trip as a whole. Stop-and-go operations are also very annoying to the user, who must maintain constant vigilance to avoid "rear-ending" the vehicle ahead. To the user, this is clearly a poorly performing section of roadway.

In some cases, the storage capacity of the roadway is inadequate to accommodate the number of stopped or slowed vehicles, and the jam causes backups on entry ramps or backs up the main roadway to the point that it affects other interchanges. The HCM treats in some detail the design required to prevent these conditions from occurring. It also helps the designer determine the capacity at which queuing will begin to occur and the roadway will break down. On the other hand, it does very little to determine the performance of the system once the volume levels have exceeded this threshold. The manual makes no attempt to develop the travel times, or travel time reliability, once conditions have reached level E or F. The only exception is when it describes conditions as unstable, though there is a short section, Analysis of Breakdown Conditions, which treats a simple case of queue build-up graphically.

Nevertheless, the situation in many of our urban areas and particularly on the corridors addressed in this study exist at level E or F for several, if not many, hours each day. Because of the large numbers of commuters and the limited nature of the transportation system it would appear that peak-hour demand will almost always exceed peak-hour capacity of the system at several points over the system on the corridors of most interest. Therefore it is important that this manual address this problem directly, indicating the relationships between capacity and the v/c ratio that exist on the roadway and the manner in which the peak is spread, first by the absolute capacity of the facility and second by the user perceptions of what is happening and a conscious effort to adjust departure time to accommodate to the congestion anticipated in the system.

6.4.2 Capacity and Queuing

Queuing at capacity constrictions is a transient phenomenon, growing during the period for which the arrival rate of vehicles is greater than the capacity of the restricted section and shrinking as the arrival rate drops below the capacity of the constricted section. It is not unlike the standing and moving queues that develop at toll plazas and on open sections of roadway where the average rate of arrival is less than the processing rate of the server. Transient queues are caused by short-term fluctuations in the arrival and departure rates, which cause capacity to be momentarily exceeded on a probabilistic basis. The queuing associated with these "well-behaved" queuing processes can be treated by standard queuing theory to develop the average length of queue and the average delay.

Queues and their associated buffers may be found at many points in most corridors. Some queues grow during the peak period and shrink as it passes. Other queues appear only during superpeaks or as the result of an incident such as a fender bender, a slowdown caused by weather, or a major accident. The upstream queues may tend to "meter" the flow to the sites of possible downstream queues and in some cases prevent them from forming. If the upstream queues are eliminated as the consequence of remedial construction, downstream queues may begin to appear, sometimes to the consternation of the traveling public, which perceives that nothing has been accomplished by the addition of capacity upstream.

For queues where arrival rates are clearly greater than the processing rate, the length of time it will take to negotiate the queue depends on these relative rates, the length of the queue at the time the vehicle in question arrives at its rear and the storage capacity. The total travel time along a corridor depends in part on congestion delay time associated with waiting time in queues along the route. In spite of the complications, it is possible to compute the average delay experienced at each queue. Wait time associated with each queue can be summed and compared with travel time through the system when the system is uncongested, such as in the middle of the night.

6.4.3 Capacity and Peak Spreading

The entry portals of tunnels in many urban areas have multiple lanes (sometimes as many as 10 or 12) that "neck

down" into two lanes in the tunnel itself. The designers, aware of the lack of capacity inside the tunnel, have provided very large areas to allow storage of vehicles working their way to the tunnel entrance. This reduces the impact of tunnel backup on the surrounding street system. The buffer provides a way to "spread the peak in demand," so that even when traffic demand exceeds capacity for short periods the transportation system can still accommodate the flow, albeit with a delay caused by waiting to arrive at the front of the queue.

Peak spreading is clearly a necessary fact of life wherever the traffic demand along a route exceeds the capacity of the system. The point to remember is that the queues are transient and will always form and dissipate over a 24-hr period. Clearly, travelers who have sufficient experience with a particular corridor understand the tendency of a particular queue to grow and shrink at different times of the day and under different weather conditions and they know when the queue is likely to be unacceptably long. Also, the users have a working knowledge of their location, formation, and dissipation and adjust their travel patterns accordingly. In effect, they perform their own peak spreading.

This adjustment in the time of travel of individuals is facilitated by the uncertainty in travel time as volume on a facility approaches the capacity of the facility. As long as all vehicles can maintain their speed, the service flow rate of the system remains at a relatively high level. However, the least slowdown can cause a breakdown in the system. The resulting delay may increase travel time substantially. A person with a low tolerance for uncertainty in his or her arrival time must depart early to leave time for delay. Early travelers will face lower v/c ratios and less uncertainty in arrival times. The telephone switchboard operator, who must be on time to work, may decide that it is best to travel much earlier, face lower travel volumes, arrive early, and use the extra time to eat breakfast next door before starting work. This widely understood relationship between travel time, peak spreading, and the v/c ratio exists among travelers in every congested urban area.

6.5 TRACING PEAK SPREADING—AN EXAMPLE

To illustrate the problems involved in estimating travel times under peaking conditions it is useful to look at an example of peak spreading. We will examine an urban travel corridor with a major capacity deficiency. In this case we will consider it to be a bridge or a tunnel crossing a river. Potential travelers are located on the west and east sides of the river. Many trips to the other side are made on a daily basis. We have assumed the travel demand for these trips by time of day and we will use it to develop the travel conditions before, during, and after the peak hour.

6.5.1 Travel Situation

Travel demand by time of day can be thought of as travel demand without regard to traffic conditions on the route. In other words, it is the "true" demand by time of day. Table 6.1 illustrates this demand for a case in which 16,000 travelers (both freight and passenger) based on the west side of the river want to make the trip to the other side at a particular time and return several hours later and in which 12,000 travelers based on the east side of the river follow a similar diurnal travel pattern. The return trip is assumed to occur x hours after the initial trip. We have assumed a distribution for x that has most trips returning 9 to 10 hr later, with some shorter and some longer.

Note that for those persons who are domiciled west of the river, the trip tends to be a round trip when viewed over the entire working day. Thus, eastbound travelers in the morning tend to become westbound travelers in the afternoon and evening. To complete the analysis flows are needed in both directions. It becomes important, therefore, to assume the demand for trips in the westbound direction in the same manner as has been done for the eastbound trips. This has been done in a separate table that develops the trips that originate from the east side of the river. The final result is the demand for movement across the river in each direction by time of day. Figure 6.2 illustrates this demand and demonstrates the contribution of the separate parts for the eastbound travelers.

TABLE 6.1 Trips from one side of the river to the other and return trips

Hour	Volume Going	Volume Returning	Eastbound Totals
0:00	41	328	287
1:00	33	278	241
2:00	25	248	210
3:00	29	221	194
4:00	142	200	292
5:00	336	183	473
6:00	1,090	162	1,211
7:00	2,001	138	2,105
8:00	3,016	118	3,105
9:00	2,561	118	2,650
10:00	1,704	146	1,813
11:00	1,325	208	1,481
12:00	749	331	997
13:00	574	563	996
14:00	425	946	1,135
15:00	277	1,448	1,363
16:00	290	1,908	1,721
17:00	270	2,112	1,854
18:00	223	1,928	1,669
19:00	210	1,523	1,353
20:00	201	1,126	1,046
21:00	195	800	795
22:00	164	567	589
23:00	119	420	434
24-Hour Total	**16,000**	**16,016**	**28,012**

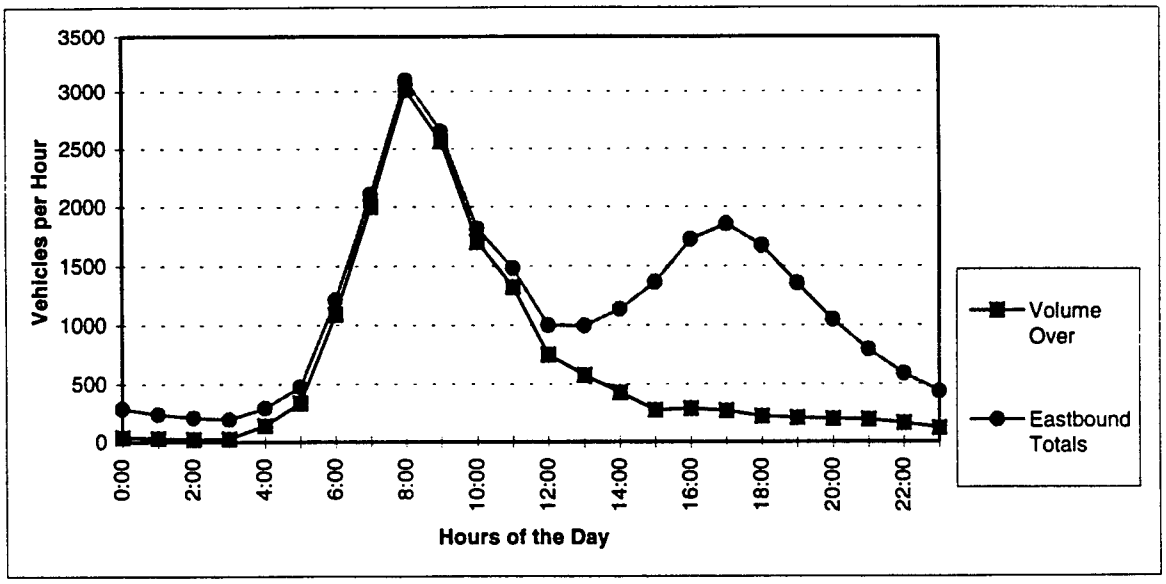

Figure 6.2. Demand for eastbound travel by time of day.

6.5.2 Unconstrained Peaking

Unfortunately, the demand in the morning peak hour exceeds the capacity of the facility. If all of these trips are to be made at the originally planned time, there will be queuing on the facility. Since the westbound trips include those returning home to the domiciles west of the river, both morning and afternoon peaks are produced in the westbound direction.

Since the facility is physically incapable of carrying the volume during the peak hour, it would appear that some adjustment to the demand by time of day must occur or substantial queuing will take place. In the real world, both probably would happen. Some travelers will adjust their tripmaking to earlier departure times, whereas others will decide to travel later. There will also be some adjustment by queuing at the crossing.

The process of peak spreading has been approximated in an adjustment process that assumes that (1) two-thirds of the travelers that represent demand in excess of capacity will move their travel time to an earlier hour and (2) one-third will delay their departure until later. The adjustment process was performed iteratively in 18 separate rounds of adjustment. The resulting peak spreading on the eastbound direction is shown in Figure 6.3.

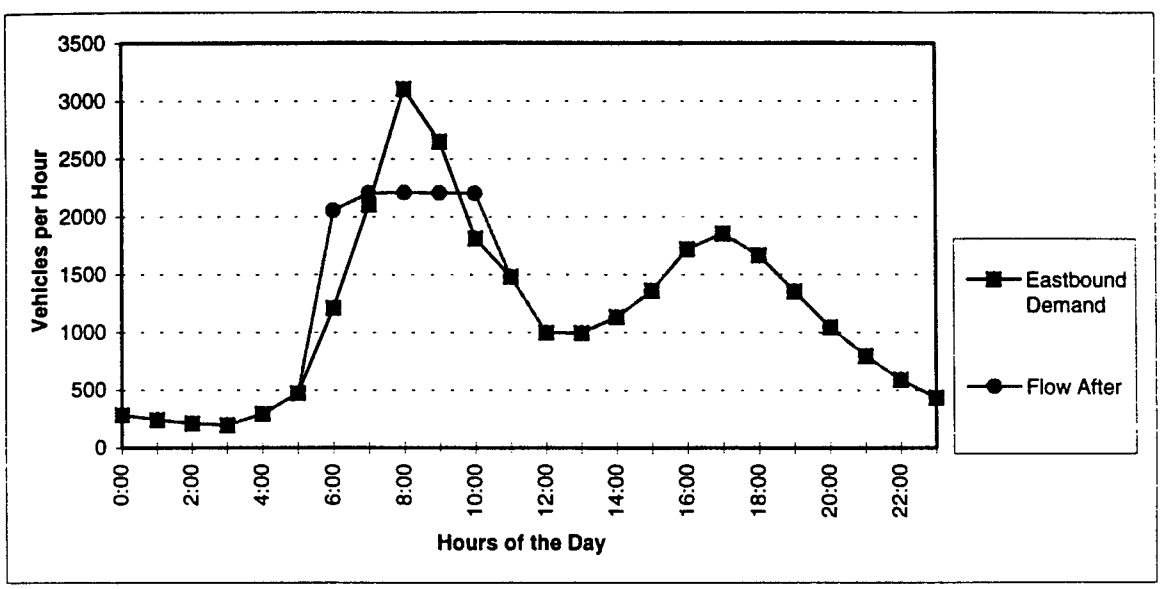

Figure 6.3. Eastbound flows before and after peak spreading.

A similar peak-spreading situation exists for westbound flows except that both morning and afternoon peaks exceed the capacity of the facility.

6.5.3 Developing the Performance Measures

The HCM identifies the LOSs that exist at different v/c ratios for free flowing traffic conditions on different types of roadways. Each produces a distinctly different operating environment with different performance characteristics. Table 6.2 shows the speed on the roadway at various v/c ratios.

For conditions involving peak-spreading, such as exists in the river-crossing example above, the v/c ratio continues at or around 1.0 throughout the duration of the peak. The speed, however, can drop to values considerably lower than the 47 mph as shown in the table above. Because of the stop-and-go nature of the traffic operations within the queue, the average speed can be computed only by dividing travel time by distance.

Nevertheless, various v/c ratios computed from the peak-spreading exercise presented above give some indication of the traffic conditions that exist on the corridor and may be useful in developing performance measures. There are a number of possible ways to measure v/c ratio:

- Peak hour,
- Peak period,
- Off-peak period,
- 12-hr v/c,
- 18-hr v/c, and
- 24-hr v/c.

Each of these v/c ratios presents clues concerning the schedule frequency, travel time, time reliability, travel comfort, and safety measures of performance, which were presented earlier.

6.5.4 Impact on Travel Time

The peak-hour figure of 1.0 is an indication that travel at this time (8:00 a.m. to 9:00 a.m.) is slow. This is not uncommon, however, since travel during the peak period is difficult in many areas. A high v/c ratio for the peak period (7:00 a.m. to 11:00 a.m.) suggests that the peak period is much longer than 1 hr. The v/c ratio for the off-peak period gives an indication of the congestion level for the corridor at the best time for movement during the workday. The 12-hr, 18-hr, and 24-hr v/c ratios show periods when travel can be scheduled without encountering serious delays.

For the peak-spreading example above, each of the v/c ratios described has been computed. These are presented in Table 6.3.

The peak period in the example lasts for 5 full hours. This is indicated by the peak-hour v/c of 1.0 followed by the peak period v/c of 1.0. The seriousness of the congestion on this corridor is shown by the 12-hr v/c of 0.76. This means that the LOS never rises above D during the entire workday. This presents extremely difficult travel conditions for commercial vehicles. There is no time during the workday at which a truck can be scheduled to make retail deliveries without encountering potentially damaging delays. The 18-hr and 24-hr v/c ratios further indicate the difficulty of travel on this corridor. The v/c ratio of 0.53 for the 24-hr v/c ratio suggests that traffic volume in the corridor will consistently average below 1,000 pcphpl and frequently will be lower than this figure. Finally, the off-peak v/c of 0.62 (LOS C) shows that the usual off-peak period in which travel can be scheduled without serious congestion does not exist in this case.

6.5.5 Impacts on Other Performance Measures

The v/c ratio is closely related to speed and consequently to travel time. It also tells something about each of the other performance measures developed above. The peak period

TABLE 6.2 Level of service criteria for multilane highways (at 50 mph)

Level of Service	Density (pc/mi/ln)	Average Speed (mph)	Max V/C	Max Flow Rate (pc/hr/ln)
A	≤ 12	50	0.30	600
B	≤ 20	50	0.50	1,000
C	≤ 28	50	0.70	1,400
D	≤ 34	49	0.84	1,670
E	≤ 43	47	1	2,000
F	Highly Unstable and Variable Traffic Flow			

Source: 1994 *Highway Capacity Manual*

TABLE 6.3 Computation of performance measures on the flow after peak spreading

Hour	Eastbound Demand	Flow After	Performance Measures
0:00	287	287	
1:00	241	241	
2:00	210	210	
3:00	194	194	
4:00	292	292	
5:00	473	473	
6:00	1,211	2,054	
7:00	2,105	2,208	
8:00	3,105	2,209	Peak-hour v/c = 1.00, 8:00 a.m.-8:59 a.m.
9:00	2,650	2,208	
10:00	1,813	2,205	Peak period v/c = 1.00, 7:00 a.m.-10:59 a.m.
11:00	1,481	1,481	
12:00	997	997	12-hr v/c = 0.76, 7:00 a.m.-6:59 p.m.
13:00	996	996	
14:00	1,135	1,135	Off-peak hour v/c = 0.62, 10:00 a.m.-3:59 p.m.
15:00	1,363	1,363	
16:00	1,721	1,721	
17:00	1,854	1,854	
18:00	1,669	1,669	18-hr v/c = 0.66, 5:00 a.m.-10:59 p.m.
19:00	1,353	1,353	
20:00	1,046	1,046	
21:00	795	795	
22:00	589	589	
23:00	434	434	
24-hr Total	**28,014**	**28,014**	**24-hr v/c = 0.53**

Note: Capacity = 2,208.

v/c gives an indication of the scheduled delay associated with travel in the corridor. Travelers seeking to avoid travel delays in the example above must leave early. The 12-hr and 18-hr v/c ratios indicate travel time reliability. Where reliability is important, as it is for most delivery vehicles, for travelers going to the airport, and for many commuters, a high v/c ratio over the extended day means that it is difficult to avoid the problem by merely leaving early. The off-peak v/c indicates likely conditions, where travelers may expect to find comfortable travel, and how likely they are to encounter stop-and-go conditions during the least congested part of the day. Finally, safety is highly correlated with low v/c ratios. Stop-and-go traffic has an extremely high incidence of accidents. Poor performance in the travel time and reliability categories usually leads to high transportation costs for the trip.

6.6 TRAVEL TIME IN QUEUING SITUATIONS

Although some indication of transportation performance in a congested corridor can be obtained using v/c ratios averaged over various periods of the day, it would be much more satisfying to be able to predict actual travel times for individual trips in a corridor under study. It was pointed out previously that the time required to negotiate a queue depends on the length of the queue at the time that the traveler joins it. It is also the case that upstream queues sometimes meter the flow of traffic to downstream queues so that there can be substantial interaction between the individual segments in the network. Nevertheless, it would appear that better predictions of queue lengths, schedule delays, travel times, and travel time reliability can be achieved.

The example Analysis of Breakdown Conditions in the 1994 HCM is a first step toward developing more information concerning queue lengths and travel times. This example uses a graphic technique to assess the performance of a segment of a 3-lane freeway carrying 5,500 vph during the peak period, where an incident blocks one of the three lanes for 15 min. The incident creates a condition whereby the capacity of the roadway is reduced to that of two lanes. This immediately creates queuing behind the site of the incident, and since the arrival rate of new vehicles is greater than the capacity of the constricted area, the queue continues to grow throughout the period in which the third lane is blocked. Once the blockage is removed, the capacity of the section is restored to three lanes. However, the maximum rate of flow for vehicles departing a queue is typically less than the capacity under stable high-speed flow. The queue, therefore, continues growing since the number of vehicles departing the cleared section is still less than the number of vehicles arriving at the rear of the queue. The queue will grow until the rate of arrival of new vehicles drops to a volume per hour that is less than the capacity of the roadway at the front of the queue. As the peak period wanes, the

queue is worked off until it is finally cleared, at which time throughput returns to normal.

The size and complexity of urban travel networks has always acted as a deterrent to more comprehensive analysis of the queuing process, including the development of time-dependent analyses. Most of these networks contain tens of thousands of links, with thousands of individual nodes. Increasing the complexity of these networks by introducing different periods of time and by including variables for queue length and volume-dependent capacity analysis has been unthinkable in the past.

The analytic methods underlying the capacity analysis framework do permit the treatment of such problems in the context of stochastic queuing networks. Moreover, if we can simplify the network to its fundamental components (which underscores part of the reasoning behind a multimodal corridor capacity analysis in the first place), then it is possible to develop tools of analysis that address the prediction problem. Although the development of an operational test of this concept is beyond the scope and resources used to prepare the first edition of the HCM, it is not impossible to lay out a scheme that could be refined and subjected to testing.

6.7 USING PERFORMANCE MEASURES IN EVALUATION

Although transportation performance measures are useful in their own right as indicators of the relative performance of segments in the corridor, the ultimate use of performance measures is in the evaluation process. If properly selected and developed, performance measures can be used in conjunction with an approximation of the travelers utility function to evaluate the performance of each alternative under consideration. This can be undertaken from the perspective of a single individual, or, when aggregated over all users and nonusers, the result approximates the point of view of the economy of the entire region. It is useful to develop the basic concepts here, and more technical discussion of these will be presented in Chapter 8.

One should think of travel as a disutility associated with acquiring a product for sale or for use in manufacturing or as a disutility associated with work. If one could snap his or her fingers and automatically be at work, or automatically have the product available, this would save the cost and time associated with travel. Utility measures attempt to measure utility (or disutility) from the disaggregated point of view of the traveler in the case of a passenger trip and from the point of view of the shipper or receiver of freight in the case of a freight shipment. Utility measures are thus directly related to those persons responsible for making travel decisions (i.e., whether to make the trip, its origin or destination, the choice of mode, and in the case of freight, the size of the shipment). When viewed in this manner, travel decisions are made in the broader context of the decision maker's overall pattern of economic behavior. In the case of a passenger trip, for example, the morning commute trip is a decision made in conjunction with the type of housing that travelers can afford, the location of good schools for their children, the availability of adequate shopping, automobile ownership, and a variety of other factors. The decision is affected by age, gender, income, size of family, ethnic background, and a host of other variables.

The factors influencing a shipper's choices can be incorporated into a utility function that reflects the total costs of the travel to the individual. This is expressed as the sum of performance multiplied by the value per unit of performance.

$$\text{utility} = \Sigma_i \text{ performance}_i * \text{value}_i$$

The appropriate unit of measurement for utility is the same as for other economic measure—dollars. If properly measured, the units are comparable with dollars of gross domestic product (GDP). The utility measures of freight transportation are, in fact, found in GDP although they are distributed over the various costs of production, transportation, warehousing, and capital. The disutility of passenger travel is not directly reflected in GDP in the same way that the value of home improvement or housework performed by a homeowner is not incorporated in GDP.

The utility function is also frequently known as a travel demand function because the equation is used in travel demand forecasting. Aggregate travel demand relationships express the number of trips by a particular mode as a function of the various costs by that mode. Disaggregate travel demand models compute the utility of a particular choice in order that the selection of the most favorable choice can be made in comparison with the other possible choices. Chapter 8 provides a more detailed discussion on these subjects.

The use of a travel demand function as the utility measure has a number of other beneficial outcomes. Since influencing travel demand is key to solving the multimodal capacity problem (or at least to improving it), having the travel demand relationships directly available for use in controlling the process is both necessary and convenient. Looking backward from utility measurement to performance measurement, and ultimately to capacity measurement, allows the entire process to be subject to intervention and control. At the same time, the most appropriate measure of the impact on society and the economy is reflected in the aggregate common utility measure. At this level, there is no longer a separate measure for freight and passengers but only a single utility measure for the system as a whole—avoided costs measured in dollars.

The relationship between utility assessment and cost-benefit analysis is also clarified by the use of a utility measure in the travel demand function. The difference between costs to the shipper before and after a change is reflected by the change in the shipper's utility function. The impact of

the change on society as a whole is given by the following equation:

$$\text{total cost saving} = \Sigma_{all\ travelers}\ \Delta\text{utility}_{all\ travelers}$$

Here the term "traveler" should apply to both passengers and freight. If the demand functions are correctly specified and estimated, the impacts on the economy as a whole are incorporated. Note that the distribution aspects of the change have not been taken into account. Also, the investment impacts and the multiplier effects are not yet accounted for. The result above should be viewed as the first-round (direct) impacts of the proposed change in the transportation system. This first-round impact will, however, take into account the impact on the economy of the reduced congestion that a proposed improvement in multimodal capacity will bring about.

6.8 CONCLUSIONS

This chapter has identified the role of performance measures in the corridor improvement evaluation process. It has pointed to a consistent set of performance measures that can be used for both passengers and freight. It then showed how these performance measures can be developed for use in the evaluation process. Although adequate techniques still do not exist whereby the full impact of peak spreading can be evaluated in a complex network, the process has been explained and the impact of queuing and peaking spreading on travel time has been elaborated. Ways in which v/c ratios, developed over different aggregations of time, can be used to approximate other performance measures have also been explained. Finally, a tentative procedure for developing a more detailed set of performance measures was suggested for the cases in which queuing dominates the transportation system.

CHAPTER 7

CAPACITY ENHANCEMENT OPTIONS

7.1 OBJECTIVE

The purpose of this chapter is to identify alternative actions for increasing capacity or for improving the performance of a corridor and its components by providing additional capacity, tapping unused or underutilized capacity, coordinating the movement of traffic, or influencing the demand for transportation services. Brief procedures for evaluating supply-side capacity enhancement actions are also included at the end of the chapter.

7.2 STEPS IN THE PROCESS

1. **Identify corridor components with low performance or LOS attributes.** Characterize each problem according to the primary causes, its manifestation, the location and extent of congestion, and the types and volume of traffic affected. Provide both qualitative and quantitative descriptions of the capacity problem (e.g., v/c ratio, VMT, types and number of accidents, etc.).
2. **Determine demand options** using the following steps:
   a. *Modal Occupancy/Freight/Handling Rate.* For each mode served by the component, determine if there is unused freight or person capacity by comparing the maximum person-occupancy/tonnage rate for the mode with the observed rates. Identify measures to utilize some or all of these unused capacities and estimate their impacts (in terms of new speed and LOS characteristics). Possible options include HOV lanes, ridesharing incentives, consolidation of freight terminals, LTL or less-than-barge load reduction, and frequency of trips reduction.
   b. *Modal Splits.* Determine if modal volume on a problematic link or node can be reduced and its performance enhanced by shifting traffic from this mode to an alternative mode that serves a similar function (e.g, car riders to bus or rail transit riders, truck to freight rail or waterway). The alternative mode should have available capacity and a high service level in order to warrant the demand shift.
   c. *Number and Distribution of Trips.* Classify traffic volumes on links and nodes according to purpose, destinations, and peaking patterns (time distribution). Identify the purpose, destinations, and time periods for and during which the travel demands are at their highest. Identify options that can minimize or eliminate specific trips for a particular purpose or destination (e.g., telecommuting to reduce work trips to the central business district (CBD), relocation of warehouses and distribution centers, zoning and land use) or distribute the trips to less-congested time periods (e.g., offer flexible work hours and ban trucks).
3. **Determine supply-side options** using the following steps:
   a. *Link and Node Impedances.* Compare the actual capacity of the corridor component with the capacity under ideal, uninterrupted conditions. Identify sources of delay (e.g., speed limits, intersections, toll booths, processing time at transfer facilities, poor alignment, substandard physical condition, and so on). Determine options to eliminate or reduce the sources of delay (e.g., signalization, access control, channelization, automatic toll collection, maintenance or repair, realignment, and so on).
   b. *Physical Capacity.* Identify expansion, widening, construction, and other actions to add physical capacity to links and nodes. These options are usually very costly in terms of capital, time, and labor resources as well as environmental impacts. Major construction projects such as building airports and highways, widening and dredging ports and waterways, implementing rapid and commuter rail, building railroad tunnel, and other infrastructure projects should be identified for capacity and performance problems that have been forecasted for the future (i.e., the long run). These options require many years to plan, evaluate, and implement.
4. **Summarize the problems (from Step 1) and list all measures,** both supply-side and demand-side, that have the potential to alleviate these problems for each problematic link or node and for the entire corridor. Describe each option in terms of extent, duration, requirements, constraints, and impacts.

7.3 INTRODUCTION

When enhancing a corridor, attempts are made to select the option that guarantees just the right amount of capacity

to meet the existing or projected demand. This is not always practical or desirable for a number of reasons, including agency budget constraints, discreteness of capacity enhancement options, different time frames or staging of actions, the influence of congestion effects, and the difference between design and actual (equilibrium) volumes. Due to congestion effects (even ignoring demand equilibration), the most attractive options may be different from the ones that just provide sufficient capacity to meet a specified demand level. Furthermore, when demand functions are explicitly considered, the choices may be even more significantly different, since actual volumes may be significantly different from design volumes or capacities (*1*).

This chapter not only identifies feasible options to increase the effective capacity of a corridor but also discusses which potential magnitudes of change or which short- and long-term impacts are anticipated if the options are implemented. The options are grouped according to the mode or corridor component, whether they are demand-side or supply-side actions, and whether they influence passenger or freight transport. For each option identified, the following are discussed where appropriate:

- How and why the option works,
- Impacts on the demand or supply,
- Costs and timing to undertake or implement,
- Barriers to implementation,
- Method to evaluate the effectiveness, and
- Examples of successful practice.

There are many different ways to enhance the capacity of a corridor or its components. Only those that are practical and most promising in light of recent technological and institutional changes are discussed here.

7.4 DEMAND-SIDE ACTIONS

The demand for transportation is a function of transportation system parameters and of socioeconomic characteristics of the individual (*disaggregate* level) or the groups of individuals in a study area (*aggregate/zonal* level). Chapter 8 provides a detailed discussion on travel demands and travel demand estimation. Demand-side actions are targeted at the users of transportation facilities and services to alter their preferences, behavior, and their perception of utilities and disutilities of alternative travel options. Demand-side actions are methods to influence the demand for transportation facilities and services by changing the options or relative attractiveness of options available to users, the environment in which travel decisions are made, and, sometimes, the behavior of the individuals themselves.

Ways to effect these types of changes in order to alleviate congestion in transportation facilities include the following:

- Limit or restrict the use of mode or facility,
- Increase the real cost of using the mode or facility,
- Provide incentives for a change of schedule or reduction in the frequency of trips,
- Discourage travel during peak periods,
- Decentralize movements and operations,
- Provide information to users that can help them make better choices and decisions, and
- Improve level of service attributes of less congested modes and facilities.

Many of these demand-side actions produce similar results in terms of influencing the demand for the corridor or facility. As stated earlier, most TDM strategies are demand-side actions, and a great number of TCM and TSM methods also fall under this category. Demand-side actions should be differentiated from supply-side actions, although in some cases the distinction is very vague because of the simultaneous effects of actions on both supply and demand.

7.5 SUPPLY-SIDE ACTIONS

Supply-side actions are those that increase the physical capacity of a facility in order to handle a specific transportation demand. To distinguish supply-side actions from demand-side actions, consider the v/c ratio. Demand-side actions result in changes in volume, whereas supply-side actions result in changes in capacity.

There are a large number of supply-side actions a transportation agency can effect to increase the capacity of a corridor. Actions can range from very minor and low-cost improvements such as pothole patching and shoulder paving for roads, to large capital outlays such as the purchase of rights-of-way and the construction of new airports, railroads, or marine ports. Supply-side capacity enhancement can result from improved management and processing of traffic such as that due to signalization, ramp metering, and channelization of roads, train scheduling, and containerization of freight. Technology also plays an important role in enhancing the supply of corridor capacity. Traffic flow and movement can be improved using advanced technologies such as high-speed trains [i.e., magnetic-levitation (Maglev) trains], vehicle guidance and navigation aids, adaptive traffic control devices, and automated toll collection.

7.6 HIGHWAY CAPACITY ENHANCEMENTS

Options to increase or enhance the capacity of roads and highways in a transportation corridor can be grouped as follows: (1) *supply*-side—highway improvements, traffic engineering improvements, traffic management and control, some transit service improvements, and ITS technologies and (2) *demand*-side—priority treatment for HOV, fringe and corridor parking facilities, transit service improvements,

transit fare changes, ridesharing programs, variable work hours, telecommuting, transit marketing/brokerage, and various forms of regulation/pricing/taxation. These options are described below.

7.6.1 Highway Improvements

- New construction,
- Reconstruction, and
- Widening.

Highway construction and reconstruction programs for increasing the capacity of roadways to carry traffic require major capital investments. The number of new constructions has decreased over the last few decades. Reconstruction has recently been the focus of highway programs. Highway reconstruction not only allows for the incorporation of improved design and provides needed additional capacity, but it also permits the use of new traffic management techniques (such as implementing restricted vehicle lanes for carpools, vanpools, and transit riders) for comprehensive congestion reduction. Transportation supply management techniques also involve low-cost techniques for optimizing the capacity of the freeways to carry traffic including freeway widening without reconstruction.

7.6.2 Traffic Engineering Improvements

- Traffic channelization,
- Reversible traffic lanes,
- Bus turnout bays,
- Pavement markings and improved signing,
- One-way streets, and
- Intersection geometry.

The following descriptions of traffic engineering improvements come mostly from the *Traffic Engineering Handbook* of the Institute of Transportation Engineers (*2*).

Channelization using traffic islands, raised medians, and corner radii can be used to restrict or prevent undesirable or wrong-way movements. It also promotes desirable vehicle speeds where possible, by providing open alignment to facilitate high-speed, heavy-volume traffic movements, or it may be used to limit vehicle speeds in order to mitigate serious high-speed conflicts. Other techniques such as the development of turning lanes, design of islands, and control of access points all serve to separate points of conflict.

A reversible lane system is potentially one of the most efficient methods of increasing the rush-hour capacity of existing streets under proper conditions. With relatively low capital cost, unused capacity may be assigned to the direction of heavier flow, with the result that all lanes are more fully utilized. The system is particularly useful on bridges and in tunnels, where the cost to provide additional capacity would be high or impossible. The disadvantages to reversible lanes include cost of installation (i.e., control devices) and/or operations (i.e., moving cones, variable message signs), increased accidents if the control methods are not clear and positive, concentrated enforcement efforts, changeover problems before and after peak periods, and provision of adequate capacity for minor direction may be difficult to solve. The reversible lane system is favored by the following conditions: lack of adjacent streets rule out consideration of one-way operations, wide streets (five or more moving lanes) with ratios of major to minor flow greater than 2:1, a high proportion of commuter-type traffic that tries to traverse the area without turns, and terminal conditions that permit the full utilization of the additional lanes.

Pavement markings include all lines, longitudinal or transverse, as well as symbols and words that are applied to the pavement. Object markers, delineators, cones, or other roadway guidance devices used to delineate the proper path of travel for motorists are also included even if they are not applied directly to pavement. They have a unique function in the proper control and regulation of both vehicular and pedestrian traffic. Mainly, markings channel or guide the traffic into the proper positions on the roadway.

One-way street regulations are generally used to reduce congestion and to increase the capacity of a street network. An intersection of two one-way streets has substantially fewer potential conflicts than does an intersection with two-way streets. The capacity of a street may be increased by as much as 50 percent by use of one-way regulations. Numerous studies have also shown that conversion of two-way streets to one-way reduces total accidents on an order of 10 to 50 percent. The disadvantages include extra travel distances, confusion, constrained transit operations, and elimination of turning movements.

7.6.3 Traffic Management and Control Systems

- Coordination of traffic signals,
- Continuous updating or optimization of signal plans,
- Computer-based traffic signal control,
- Bus priority signal systems,
- Freeway traffic management, and
- ITS technologies.

Traffic control systems are designed to reduce travel times, delays, and stops and to improve average travel speeds on arterial roads and freeways. Corridor control is an integration of urban street control with freeway control toward achieving the optimum utilization of corridor capacity (*3*). Implicit in the concept of corridor control is that it must be traffic responsive to be meaningful. The purpose of corridor control is to integrate the operation of various control and driver information systems in the corridor by the following: coordination of traffic signals on frontage roads

and parallel arterials; coordination of ramp control and frontage road operations to provide alternate routes on frontage roads during peak-period congestion on a freeway; coordination of ramp control queue override feature with the frontage road and cross street intersection control to prevent intersection queuing; and coordination of traffic signals at freeway interchanges with arterial cross streets. The Information for Motorists (INFORM) system on Long Island, New York, is one such effort that performs surveillance, control, and motorist information activities in a 5-mi by 35-mi corridor consisting of two parallel freeways, a parallel major arterial, and several crossing roadways (*4*). Many ITS technologies are also part of corridor control systems.

Typical experiences have shown that improved traffic signal systems result in at least a 10 percent decrease in travel times and vehicle delays on arterials. Use of ramp meter signals on freeways can smooth traffic flows and improve freeway speeds by approximately 20 percent (*3*).

7.6.4 Priority Treatment for HOV

- HOV lanes with or without separator,
- Carpools and vanpools,
- Ramp bypass lanes,
- Separate priority vehicle roadways,
- Contraflow freeway priority lanes,
- With-flow freeway priority lanes,
- Exclusive freeway ramps,
- Metered ramp bypass lanes,
- Tollway entry (ramps and plaza bypass), and
- Arterial priority lanes.

HOV facilities are intended to help maximize the person-carrying capacity of the roadway. This is done by altering the design and/or operation of the facility in order to provide priority treatment for HOVs including buses, vanpools, and carpools (*5*). Provision of priority facilities reserved for buses and/or carpools and vanpools is an element of transportation system management under the category "actions to ensure the efficient use of existing roadspace." Highway-based preferential treatments for HOVs include freeway HOV lanes, separate roadway, priority HOV entry, and arterial street priority applications. The following discussion of HOV effects comes mostly from *Traveler Response to Transportation System Changes* (*6*):

Priority treatment for HOVs can increase the people-carrying capacity of congested freeways and arterials, defer the need to construct additional roadway capacity, improve the efficiency and economy of public transit and ridesharing options, and provide a time and cost incentive for commuters to rideshare or to take public transit. The extent of travel time savings depends on the length of the HOV lane, level of use, and congestion in adjacent lanes; however, time savings of 2 to 12 min have been realized.

Both travel time and reliability are thought to be key factors in the decision to use transit or to carpool. Nevertheless, the travel time and reliability improvements afforded by most HOV facilities will induce HOV use only if other determinants of mode choice, such as frequency of transit service, are favorable. Although the mode shifts to transit (attributable to priority facilities) are often small, transit market share increases of more than 50 percent have been reported for entire metropolitan corridors with substantial prior transit service.

The opening of carpool and vanpool freeway priority facilities has led to total highway increases in high-occupancy carpooling of 50 to 500 percent. Associated increases in total highway automobile occupancy have typically ranged from 3 to 7 percent but have reached 19 percent. Bypass lanes at metered freeway ramps have, on the average, increased HOV volumes by 25 percent.

Highway person-volume increases of 8 to 15 percent have been typical when freeway and medium-distance arterial priority facilities have been introduced. Corresponding vehicle volume increases have been 5 percent or less, and in some cases vehicle volumes have diminished. Opening of under-capacity priority facilities to all HOV vehicles has provided the maximum flow rate because neither transit riders nor carpoolers are drawn disproportionately from competing high-occupancy modes. Approximately 40 to 60 percent, and more, of bus passengers and carpoolers on newly opened freeway and medium-distance arterial priority facilities previously drove.

7.6.5 Fringe and Corridor Parking Facilities

- Park-and-ride facilities,
- Parking lots,
- Rail service fringe parking,
- Bus service fringe parking,
- Carpool fringe parking, and
- Peripheral parking.

The primary purpose of these facilities is to shift parking supply from the downtown/activity center to the outlying area, thereby reducing travel demand and congestion through a corridor. Similarly, these facilities are intended to increase parking supply, shift demand to outlying low-density areas, and encourage commuters to use public transit or to rideshare. These parking facilities are usually owned by city, county, and/or state DOTs. However, they can also be leased by a public agency from a private organization. These parking spaces are often provided free, but when a fee is involved it is minimal (*3*).

The following discussion of the effects of parking facilities comes mostly from the 1981 FHWA Report *Traveler Response to Transportation System Changes* (*6*).

The typical park-and-ride lot served by rail rapid transit offers 400 parking spaces, is filled if parking is free, and is

three-quarters utilized if a fee is charged. Commuter and light-rail parking lots tend to be smaller but also obtain high utilization. Fringe parking lots served by express buses offer spaces for 150 to nearly 1,000 vehicles and obtain widely varying utilization rates, averaging 50 percent. The more successful bus service park-and-ride facilities are in cities with downtown parking charges of more than $2 per day (in 1982 dollars), are served by buses running at least every 15 min, and are less than a 30-min bus ride from the CBD.

Approximately 40 to 60 percent of park-and-ride transit users previously commuted as automobile drivers. In many instances, it is doubtful that high levels of transit service could be supported without fringe parking. The park-and-ride mode substitutes for expensive transit feeder services in low-density areas, especially those with high automobile ownership and above-average income. Nationally, 60 percent of the carpoolers at fringe lots drove alone prior to fringe parking availability. It appears that fringe lots for carpooling do induce carpool formation to some extent and may serve as an identifying factor for the carpool mode. Carpool fringe parking lots are normally free and are most successful where they are close to convenient routes of access, offer users advantages in safety or security, and alleviate parking shortages at strategic locations.

One recent study reported that peripheral parking lots close to the CBD and served by shuttle transit service provide parking for between 1,400 and 4,200 automobiles in four areas and more than 200 automobiles in others. High downtown parking cost is the primary reason for using peripheral lots. Peripheral lots that failed generally did so because they did not offer a sufficient total cost savings to the user. Charging a fee for peripheral lot use has been successful as long as the fee is significantly lower than commercial rates in the downtown. In instances where lots are within 1 mi of the CBD, a substantial portion of users eschew the available shuttle service and walk to their destinations.

7.6.6 Transit Service Improvements

- Express bus service,
- Bus transfer centers (coordinate intermodal transfer),
- Bus frequency changes,
- Train frequency changes,
- Schedule regularization,
- Schedule reliability,
- Frequency changes with fare changes, and
- Limited-stop bus routes (most effective with preferential lanes, signal priority, ramps for buses, and park-and-ride facilities).

Traveler Response to Transportation System Changes (*6*) is the primary source for the following description of transit service improvements.

Bus transfer centers provide a point where several routes in a corridor converge with coordinated time schedules to permit transfers to other line-haul or feeder routes (e.g., rail, taxicab, and automobile) with a minimum of waiting time. These centers can improve the frequency of transit service along corridors while providing a broader area of coverage, especially in less dense suburban areas (e.g., Portland, Oregon).

The traveler response to service frequency changes varies markedly, but there are underlying consistent patterns that relate to the widely varying circumstances attending individual transit route service modifications. Patronage increases exceeding 1 percent for each 1 percent in frequency improvement are apparently possible, as are circumstances where frequency increases fail to engender increased ridership. The average response to frequency improvements is roughly 0.5 percent patronage gain per 1 percent frequency increase.

Ridership is most sensitive to headway changes when the transit line involved serves middle and upper income areas and when the prior service was relatively infrequent. When transit headways are already short, and particularly when lower income areas are involved, ridership may be more sensitive to fare changes than frequency improvements. Otherwise, ridership is apparently more responsive to frequency changes, although the evidence is fully conclusive only in the case of commuter railroad operations.

The greatest concern expressed by transit riders is with dependability of service and with midday and evening service frequencies. Easy-to-remember departure times, readily available schedules, and service reliability may be major factors in achieving a favorable user perception of the wait for transit service. Off-peak ridership responds more to service frequency improvements, on a percentage basis, than peak-period ridership.

Frequency improvements affecting individual transit lines have the potential of diverting some riders away from other transit services. In business districts significant numbers of people who previously walked may be attracted. In general, however, 33 to 50 percent of new riders drawn to transit service by frequency improvements would otherwise have driven an automobile, as is the case with transit fare reductions.

7.6.7 Transit Fare Changes

- Fare increases/reductions,
- Free transit,
- Off-peak fares,
- Senior citizen fares,
- Paratransit fares, and
- Fare changes with service changes.

Transit fare changes are often implemented in connection with other transit service improvements or reductions and are frequently accompanied by marketing activities. Promotional fares and prepayment options are normally linked with marketing activities. The following discussions, taken from *Traveler Response to Transportation System Changes* (*6*), describe various ways of changing transit fares.

The effect of bus fare increases and decreases averages roughly a 0.4 percent ridership loss or gain per 1 percent change (equivalent to the rule of thumb that ridership shrinks one-third as much percentagewise as the typical percentage change increases). The response rarely exceeds 0.6 percent. Traveler response to free fare is similar or perhaps somewhat less than the proportionate response to lesser fare changes. Limited evidence concerning inflation effects supports the logic that fare change responses should be estimated with reference to constant dollar fares.

Ridership responds the least extent to fare changes on rapid transit in large cities and where transit service is exceptionally good or the cost of alternative modes is high. Patronage losses observed for rapid transit are 0.14 percent per 1 percent fare increase for the average case. Ridership is most sensitive to fares on small city and suburban bus operations and wherever transit service is light. Overall, transit ridership is one-third to two-thirds as responsive to fare changes as it is to an equivalent percentage change in service.

Fare changes targeted at specific markets such as express trips, intradowntown travel, or the elderly may evoke responses considerably different than the system norm. However, as a general rule, ridership is less sensitive to fare changes where transit is in a strong competitive position vis-à-vis the automobile than it is where transit usage and service are marginal. The impact of fare changes on off-peak and weekend transit patronage (when the proportion of journey-to-work travel is least) is typically about twice the corresponding percentage impact on peak-period transit volumes. Use of off-peak fares set lower than peak fares can significantly spread out transit demand.

Approximately one out of every two or three transit trips made as a result of fare reductions would otherwise have been made by an automobile driver; the remainder would have been made by an automobile passenger or via some other mode or else represent trips not taken previously. Urban travelers who start or stop transit use in response to fare changes tend toward choice rider characteristics in that they have higher incomes and automobile ownership rates than do consistent transit users.

Overall average surface transit ridership response to fare increases has historically been described by the Curtin Rule, a widely used rule of thumb in the transit industry. It states that an overall fare increase of 1 percent will shrink ridership by approximately one-third of 1 percent. This relationship is equivalent to a fare elasticity of −0.33. The American Public Transit Association recently conducted a time-series analysis of ridership impacts of transit fare changes and found that the fare elasticity for all transit systems averaged about −0.40 (*7*).

7.6.8 Ridesharing Programs

- Carpools/vanpools/buspools (matching services),
- Variable work hours/flextime,
- Employer-based efforts,
- Highway informational signs,
- Corridorwide promotions,
- Owner-operated vanpools,
- Short-haul industry operated buspools,
- Short-haul CBD-oriented buspools, and
- Long-haul commuter buspools.

The objective of ridesharing programs is to provide an attractive door-to-door or neighborhood paratransit alternative to the single-occupant private automobile for home-to-work travel. The main source of the following descriptions of these programs is *Traveler Response to Transportation System Changes* (*6*).

Vanpool/buspool service may be designed to provide an intensive form of ridesharing where conventional transit service does not exist and is unlikely to be cost-effective.

These programs have been most effective when implemented in cooperation with major employers or developers who wish to establish ridesharing programs at specific sites. These sites have high employment concentrations and are usually commercial, manufacturing, or retail activity centers in suburban and downtown areas.

Vanpools and buspools provide attractive and generally effective paratransit modes for home-to-work commuters not well served by conventional transit. Most vanpool programs do best where one-way trip lengths exceed 15 mi, where work schedules are fixed and regular, where employer size is sufficient to allow matching of 10 to 12 people from the same residential area, where public transit is inadequate, and where some congestion or parking problems exist. Buspools require higher densities of travel demand than vanpools, but the indicators of likely success are comparable. Buspool systems with average route lengths of less than 10 mi have failed except where the residential density of eligible employees approaches one employee per four households. Long-haul buspools, in the 10- to 60-mi range of route length, apparently have a very low failure rate.

Except for certain CBD-oriented programs, slightly over half of the new vanpool and buspool riders formerly drove an automobile to work. The majority of buspools and vanpools serve white collar workers on regular work schedules, but a number of significant operations oriented to blue collar workers exist. Van/buspool commuters appear more than willing to spend some extra time picking up and discharging passengers in order to gain the convenience of door-to-door or neighborhood pick-up in conjunction with travel cost savings and reduced stress. However, once extra time approaches and exceeds line-haul travel time, the vanpool or buspool service is not as attractive and normally fails to draw much of the potential market.

7.6.9 Variable Work Hours

- Staggered work hours,
- Flexible work hours, and
- Compressed work week.

According to *Traveler Response to Transportation System Changes* (*6*), the primary objective of variable work hour programs is to effect work scheduling changes that will reduce the degree of vehicular traffic and transit passenger peaking that occurs during the normal workday. The idea is to spread out travel demand by achieving work hour changes for a segment of all employees in the employment areas involved. The resultant reduction in peak transportation is intended to reduce rush hour highway congestion and transit overcrowding and to alleviate pressure for new transportation facilities or transit vehicle scheduling designed solely to serve heavy peak-period demands. The compressed work week has the additional and overriding objective of eliminating some commuter travel outright. The extent to which total travel is reduced also helps energy conservation and pollutant emission reduction goals.

The FHWA study also reported that one-quarter to one-half of all employees in a localized employment area can be expected to become involved in a variable work hours program if a dominant employer or an important employer or employee organization takes the initiative. The trip timing decisions employees make when given the option of flexible work hours are as effective as mandatory staggered work hours in spreading out work arrival and departure times. A large-scale program can smooth traffic peaks enough to reduce maximum 15-min passenger and vehicular loads by 15 to 35 percent at terminal facilities such as rapid transit stations and major parking lots.

Variable work-hour program effects dissipate, even by 50 percent or more, on radial transportation facilities serving the involved employment core. Even so, the impact may remain quite significant, particularly on transportation system elements such as radial bus routes. Maximum 15-min bus passenger load reductions, as great as 21 to 29 percent, have been reported. The transportation system elements offering the least potential for peak-period volume modification are those used heavily by traffic from diverse locations.

Employee attitudes toward staggered and flexible work hours are generally positive, with 80 to 90 percent of workers involved expressing a favorable overall reaction.

7.6.10 Telecommunications

- Telecommuting from home and
- Telecommuting from satellite centers.

The practice whereby telecommunications services are substituted, partially or completely, for transportation to a more traditional workplace is called telecommuting. Telecommuting does not necessarily imply working at home. Satellite "telework" centers near or in residential areas, fully equipped with appropriate telecommunications equipment and services, can serve employees of single or multiple firms, located together on the basis of geography rather than business functions. In 1993, telecommuting was being practiced by approximately 2 million workers (1.6 percent of the total workforce) and could reach 7.5 to 15 million (5 to 10 percent) in 10 years. Telecommuting is widely seen as a potentially valuable travel-demand management measure to reduce congestion and to meet existing national and air quality goals. Telecommuting can also expand opportunities for people with impaired mobility or who are tied to the home for any other reason (*8*).

A variety of obstacles to telecommuting are identified in the literature, including liability considerations, zoning and tax laws, labor union concerns, and occupational health and safety issues. Other concerns include the employee's feeling pressure to work excessive hours and trying to maintain a clear distinction between work and home life. Another concern is whether those who telecommute, particularly from a remote satellite center, will move still further into rural areas, thereby negating the energy and emissions benefits and accelerating urban sprawl. From the employer's perspective, concerns include the cost and effort necessary to implement a program and the challenge of remote supervision (*8*).

7.6.11 Transit Marketing/Brokerage

- Marketing of service changes,
- Information campaigns,
- Advertising campaigns,
- Fare promotions,
- Fare prepayment,
- Paratransit service marketing, and
- Transportation brokerage programs.

Transit marketing and brokerage are considered actions to improve transit service. In a broad sense, transit marketing covers not only informational and promotional activities but also other actions that make public transit service a more salable product. Brokerage is the process by which an outside party aids ridesharing development by helping to overcome obstacles to carpooling, vanpooling, and bus usage. Transportation brokerage acts as a link between those with a demand for service and those who do or supply service. Brokerage organizations may also be service providers (*6*).

Informational/promotional campaigns are an important ingredient in developing ridership on new or modified transit service. To be attracted and served, potential riders must be made aware of the increased travel opportunities afforded. Some attraction of additional ridership to existing services has been achieved through promotion with an emphasis on information dissemination. Market fare prepayment options such as passes and ticket books have led to increased use of these payment methods. The most successful programs have led to the use of prepayment by 20 to 30 percent of system riders and offer sales both to major employee groups through their employers and to the general public. Multimodal transportation brokerage programs are a recent innovation in helping to overcome the infor-

mation barriers and other impediments to forming various types of ridesharing arrangements. Brokerage programs aim to decrease single-occupant automobile travel but with reduced emphasis on costly expansion of peak transit service. As a general rule, employer-oriented programs are more successful than areawide efforts, and the degree of employer involvement and support is a primary determinant of the level of success. Previous outcomes varied widely, ranging from negligible mode shifts in a major multiemployer program to a decrease in single-occupant automobile mode share from 65 to 18 percent at a large downtown employer. A non-employer-oriented program run by the transit provider has helped achieve a 3 percent peak-period vanpool/buspool mode share and other shifts to ridesharing in the San Francisco/Golden Gate corridor (*6*).

7.6.12 ITS Technologies

- Advanced traffic management system (ATMS),
- Advanced traveler/driver information system (ATIS),
- Automated vehicle control system (AVCS),
- Commercial vehicle operation (CVO), and
- Advanced public transportation system (APTS).

ITS is an umbrella term that embraces a variety of proposed services and systems. ATMS includes enhanced equipment and telecommunications for real-time control of traffic, both private vehicles and public transportation. Examples of ATMSs are improved traffic surveillance and monitoring, signalization, ramp metering, variable message signs, electronic toll collection, and automated methods to help manage nonrecurrent congestion such as that resulting from accidents, hazardous spills, and lane closures.

ATIS embraces a combination of technologies and procedures including on-board navigation systems and home computers that can help drivers, public transit users, and commercial vehicle operators plan their trips and acquire real-time congestion information and optimal routing recommendations. ATIS can also permit business and recreational travelers to access various databases (e.g., electronic yellow pages, instant information on parking availability, and the location of gas stations, restaurants, hotels, tourist attractions, airline and bus terminals, and warehouse/consolidation facilities).

AVCS warns of hazards, helps drivers avoid collisions, and maintains spacing between vehicles and may even fully take over control of vehicles from their drivers. AVCS concepts range from in-vehicle collision avoidance systems to dedicated lanes and guideways that permit tightly packed platoons of vehicles to travel together, thus radically improving the capacity of highways.

CVO includes automatic vehicle location and data transfer technology for monitoring freight and commercial transport. Among the navigation technologies are Loran, satellite global positioning systems, and on-board navigation. Monitoring technology can be integrated with electronic data interchange to track shipments. CVO also includes automatic vehicle identification (AVI) methods used in electronic toll collection and electronic license plate applications, and it may include automated methods of classification and weighing of trucks. CVO is particularly useful to operators of vehicle fleets: those who handle trucks, buses, vans, rental cars, taxis, and emergency vehicles.

Finally, APTSs include the combination of functions described above, but are configured to serve public transportation. Examples of APTS elements are kiosks at bus stops that provide information on the arrival of buses, command and control systems including automatic vehicle location and monitoring, and preferential traffic control for buses such as for bus passage through intersections and access to HOV lanes.

The experience of the U.S. DOT with ITS has led to the definition of an intelligent transportation infrastructure (ITI), consisting of systems required to support a variety of ITS products and services described above in metropolitan and rural areas (*9*). The reported potential time savings of various ITI components are (1) 20 to 50 percent for freeway management; (2) 7 to 12 percent for traffic signal control; and (3) 5 to 20 percent for traveler information systems.

7.6.13 Corridor Preservation

- Right-of-way acquisition;
- Regulation; and
- Arrangement with owner.

As defined in Chapter 3, corridor preservation is a concept that employs the coordination and application of various measures to obtain control of, or otherwise protect, the right-of-way for a planned transportation facility. Corridor preservation techniques are applied after the transportation corridor is identified either along a new alignment or along an existing facility to prevent inconsistent development; minimize or avoid environmental, social, and economic impacts; reduce displacement; prevent the foreclosure of desirable location options; allow for the orderly assessment of impacts; permit orderly project development; and reduce costs (*10*).

Most states attempting early acquisition of right-of-way for corridor preservation have involved employing federal regulations that permit the use of federal aid for "hardship" and "protective" acquisitions in advance of location approval. Regulations, such as zoning and setback requirements, have often been used for right-of-way protection, whereas easements have been used primarily for the conservation and protection of parks and recreational facilities and to ensure the preservation of historic areas and open spaces. There have been only limited attempts to preserve open spaces for rights-of-way to accommodate the construction of

future transportation facilities. These have often been in the nature of zoning and setback regulations that have been vigorously and often successfully challenged in court as a "taking" requiring compensation (*10*).

Corridor preservation activities often have not been undertaken because of a perception that funds are not available to protect rights-of-way. State DOT budget levels are normally significantly less than the levels needed for construction of critically needed projects, and projects that may not be built for several years have not been able to compete with sorely needed construction projects for program dollars.

ISTEA made specific provisions for right-of-way acquisition and called on the secretary to report to the Congress on potential corridors identified for preservation. The Act provides state expenses for right-of-way purchases, before a project is approved for federal funding, if the state follows specific guidelines and adheres to federal laws regarding acquisition and relocation.

7.6.14 Truck Traffic Management

- Truck routes,
- Local area bans,
- Regional area bans,
- Truck lanes,
- Traffic signal settings/linked signals,
- Intersections geometry, and
- Parking/loading strategies.

The following discussion of truck traffic management strategies are taken mostly from the book *Urban Goods Movement: A Guide to Policy and Planning*, by K. Ogden (*11*).

Nomination of specific routes for use by trucks can be advisory or statutory. An advisory truck route system involves making particular routes attractive to trucks. Such a system usually includes all freeways and major arterial roads in an urban area and may encompass other roads that extend into industrial areas or truck terminal locations, as long as the roads are free of barriers to truck travel such as low overhead clearances. Enforcement and implementation costs are minimal, but the system's usefulness is determined by driver preferences. A statutory truck route system legally prohibits trucks from using routes other than designated routes. This approach tends to rely more on particular areas being protected by entry ban. There are also routes for designated vehicles such as overdimensional trucks (those exceeding statutory mass, height, width, or length limits), trucks carrying hazardous materials, and high-productivity vehicles (e.g., long combination vehicles that handle shipping containers and require access to ports).

Route ban involves a prohibition on the use of particular routes. Such a ban is applied only to trucks that exceed a certain mass or length limit, and it may be applicable only at certain hours of the day. Route bans need enforcement and may increase the cost of deliveries, and there may be negative reactions from people living on roads where truck traffic is diverted. Local and regional area bans involve prohibition of specific categories of trucks from entering a designated local area, town, or region. An areawide ban on large trucks, however, can also increase the number of smaller trucks, and any action that causes a single peak-period truck trip to be replaced by more than two light truck trips will worsen traffic congestion, all other things being equal.

Traffic lanes can also be allocated for the exclusive use of trucks. These lanes have the potential to reduce delay and to benefit truck traffic, especially on short sections of congested roads carrying heavy truck volumes. The application of exclusive truck lanes is likely to be extremely limited since the advantages are few. Another practice is restricting trucks to certain lanes on the roadway (usually the outer lanes). An examination of this practice found that headways were increased in the right lane (thus effectively reducing its capacity). It was also noted that a high proportion of trucks in the right lane creates a psychological, sometimes physical, barrier for drivers trying to merge and contributes to sideswipe and rear-end collisions. Traffic signal settings can also be improved to explicitly take into account of the needs of trucks in signal timing plans where truck flows are significant. Present signal design practices do not explicitly take into account the needs of heavy vehicles in terms of factors such as braking and acceleration capability and costs of stops. Moreover, current signal design practice concentrates on capacity maximization in the peak direction (usually radial), and this reduces the capacity in counterpeak and cross-town directions, which are the directions more likely to be used by trucks at peak hours. Linked traffic signals also provide progression along a route. However, trucks are disadvantaged by linked signal systems because they are offset by car times, which do not match truck acceleration and deceleration rates. Improved geometry of intersections and vertical curves (or provision of climbing lanes) can also enhance the movement of trucks to increase the throughput of the road. Other traffic management strategies described earlier also benefit truck traffic (e.g., speed limits, one-way streets, reversible lanes, and median barriers).

The lack of adequate loading facilities for trucks increases the cost of freight while having little effect on the number of trucks using the road system. Parking and loading strategies may involve curbside use, off-street facilities, and truck parking facilities. Arrangements for curbside use include the provision of loading zones at selected locations where only commercial vehicles involved in pickup and delivery operations are permitted, or the provision of loading zones for certain times of day only, either to encourage delivery operations at those times or because other demands take precedence at other times. An explicit and well-developed curbside management plan, developed in consultation with local officials, shippers and receivers of goods, and the road freight industry, should lead to more efficient use of limited curbside space,

reduced on-street congestion from double parking and development of off-street parking policies. Major new commercial, industrial, and retail developments should have adequate off-street loading and unloading facilities for trucks servicing the development. In some cases it is possible to coordinate the loading docks for several developments, with a common central facility. Truck drivers, however, show little willingness to use such facilities voluntarily unless they save time, meaning both the access and egress conditions and the layout of the off-street facility itself are well designed. In some cases, the use of an off-street facility is a costly imposition, both because it is nonleasable (and therefore an extra cost burden to the developer) and also because the use of the building may change over time. Truck parking is an important issue in urban freight because trucks spend a considerable proportion of their day at rest, and trucks used for long distance or exurban operations may sometimes have to wait for hours or even days to pick up a new load. Truck parking may be a public truck park providing parking or other facilities, a private facility, or a truck operator's depot or yard where the firm's trucks are kept when not in use.

7.7 RAIL CAPACITY ENHANCEMENTS

Many capacity enhancement options applicable to urban rail passenger transport systems (e.g., commuter, light, rapid, and people mover) were discussed above under transit enhancement options (i.e., fare changes, scheduling, fringe parking, service improvements, marketing, and brokerage). Some of them are discussed briefly below. Options for intercity rail passenger and freight capacity improvements are also described.

7.7.1 Urban Passenger Rail

- New construction,
- Rail fringe parking,
- Train frequency changes,
- Schedule regularization,
- Schedule reliability,
- Fare changes,
- Frequency changes with fare changes,
- APTSs,
- Automated guideway transit system (AGTS),
- Automated fare collection,
- Terminal improvements, and
- Free transit.

The Congressional Budget Office (CBO), in its 1985 report, found that given the patterns of land use and the density of urban development in U.S. cities, new construction of rail systems is rarely cost-effective in improving urban mobility or in reducing congestion (*12*). The CBO asserted that, in most cases, equivalent improvements in traffic circulation, noise, and pollution could be achieved by combinations of less costly investments in road and transit systems, as well as changes in traffic management and transit operations.

However, a widely distributed study by Pushkarev (*13*) identified a number of cities in the United States in which urban rail or light-rail systems might be warranted in accord with the criteria applied by the author.

Fringe parking facilities for existing commuter rail, rapid rail, and light-rail service are usually located in established lots at outlying residential stations. Fringe parking for modal transfers for rail has been well utilized in almost every application where a study of fringe parking has been conducted. Station distances from the CBD ranged from 3 to 30 mi and had no discernible effect on the level of usage. Severe shortages of parking still exist in many rail terminal stations. Financial limitations cause few to be constructed.

Aside from providing new facilities or lower fares, fixed rail systems are, for the most part, restricted to scheduling and frequency changes as a form of service improvement. Commuter rail lines typically serve middle- and upper-income areas. Although they have relatively long time intervals between trains, they also predominantly serve long trips.

Unlike bus service, the average wait time for commuter rail service cannot be adequately described for travel estimation purposes. The wait for commuter trains is perceived by the potential commuter as being shorter. Readily available schedules and long-term dependability of service, which allow users to minimize the wait at the station, may be major factors in the favorable perception of commuter rail scheduling.

Somewhat similar to schedule regularization, but more fundamental, is transit reliability. Studies of commuters have found "arrival at intended time" to be perceived as the second most important travel attribute for work trips. Periodic equipment failures during initial operation of the BART rapid rail system in San Francisco led to public perceptions of undependability and are thought to have inhibited ridership.

AGTS is the area in which rail research expenditures perhaps have been the greatest and in which the implementation results to date have been the most limited. AGTSs such as those funded by the Federal Transit Administration in Miami and Detroit are computer controlled and thereby eliminate the need for an on-board operator. AGTSs have been extensively researched because of the perceptions that they offer potentially major advances in speed, capacity, and cost compared with other urban travel modes (*14*).

The implementation of more automated fare collection systems, such as those in San Francisco, Washington, D.C., and Atlanta, can reduce the operating costs of rail transit and also increase the processing rate at terminals and train stations. This type of system can be adapted to other rail systems.

7.7.2 Intercity Passenger

- High-speed trains (e.g., Maglev),
- Train frequency and scheduling, and
- Track rehabilitation.

In many short, densely traveled corridors, air travel has become the preferred mode because of highway traffic congestion or the lack of rail or bus service affording an attractive combination of speed and convenience. In these markets, advanced surface transportation systems described earlier—high-speed rail, Maglev, and advanced superhighways—offer great promise. If surface transportation systems capable of speeds of 120 to 200 mph were developed, they could provide an alternative to air trips of up to 500 mi. In corridors such as Boston-New York-Washington, Milwaukee-Chicago-Detroit, San Francisco-Los Angeles-San Diego, Tampa-Miami, and Dallas-Houston, the shift of traffic from air to surface modes could substantially reduce the number of aircraft operations now required to serve these routes.

Trains operating at 150 mph or more may become an integral part of transportation in the United States. High-speed trains, already a part of everyday life in Europe and Japan, can make travel easier for a wide range of people. A growing number of corridors are in the planning stages in various regions of the United States. The following corridors have been identified as having high-speed potential:

- Northeast corridor between Washington, D.C., and Boston;
- Tampa-Orlando-Miami;
- San Diego-Los Angeles-Las Vegas;
- Los Angeles-San Diego;
- Pittsburgh-Harrisburg-Philadelphia;
- Detroit-Chicago-Milwaukee;
- New York City-Buffalo;
- Houston-Dallas; and
- Cincinnati-Columbus-Cleveland.

Despite the availability of the technology, many high-speed rail projects in the United States have not yet advanced beyond the conceptual stage (except for the Northeast corridor where "tilt" trains are in operation) because of the enormous initial capital costs. Foreign experience with high-speed rail projects suggests that a competitively designed high-speed rail line in a high-density corridor can generate revenues sufficient to cover maintenance and operating expenses, and no annual operating subsidy will be required. However, operating revenues are likely to make a minimal contribution to infrastructure capital costs and interest payments on debt for an extended period of time.

The principal source of support has been private businesses. For example, in Florida, the state government has offered real estate concessions (such as development rights on property adjoining lines or stations) to private interests who assume the cost and risk of initial construction of a high-speed rail line.

Factors such as track condition, curvature and grade, limited rights-of-way, grade separation, and cost of electrification can also hinder the implementation of high-speed rail systems. These factors are particularly restrictive in the most densely developed northeast corridor where, due to current and projected travel demand, high-speed rail service has great potential. Tilt vehicles have alleviated such restrictions, enabling rail cars to tilt with the track thereby permitting operation at higher speeds on existing tracks and rights-of-way.

Conventional rail passenger operations also require track conditions that are significantly better than those for freight operations. Although freight trains can be effectively and profitably operated at speeds of 30 to 50 mph, passenger trains must move considerably faster to keep a schedule competitive with airplanes, buses, or private automobiles. Most of the 700 mi of track Amtrak owns and maintains are in good condition and capable of handling relatively high-speed passenger trains. The remaining 23,300 mi of track used by Amtrak that are owned and maintained by the freight railroads do not always permit the speeds desirable for passenger trains.

7.7.3 Intercity Freight

- Rail/truck (intermodal) transfer facilities,
- Double-stack technology,
- Track rehabilitation,
- Track preservation/acquisition,
- New rail connections,
- Integrated transport companies (multimodal/intermodal operations),
- Hub centers
- Automated identification/tracking system,
- Expedited service,
- Dedicated trains, and
- Equipment pools.

The railroad industry's greatest advantage in competing for freight traffic with other modes of transportation is the efficiency of its line-haul (intercity) movement. The advantage is more pronounced for bulk commodities because freight cars can carry large quantities and large weights and tend to be moved directly from origin to destination. The railroad continues to handle a major percentage of many critical freight commodities. However, their top two commodities (coal and farm products) are not time-sensitive and have lower value per unit weight, and the rates paid to the railroads to move these commodities are generally lower than the rates for trucking. The railroad industry lags far behind the trucking industry in freight transportation revenues and struggles for profitability, partly because of the shortage of equipment during peak times. Recently there has been a lot of excess capacity in railroads, resulting in abandonment of many underutilized (unprofitable) rail lines whose operational costs are much higher than revenues. In order to utilize the line-haul efficiency of rail in the overall transportation of freight, intermodal transfer facilities (e.g., rail to truck, rail to marine terminal, etc.) must be enhanced.

Intermodal transfer facilities such as container, piggyback, and ro/ro terminals are specialized freight terminals that integrate rail, highway, and waterway transportation modes (*15*). They can be used as a means of transferring to rail the traffic that would otherwise travel on the highway system. In order to maintain access to markets, coordination between the highway system and transfer facilities is very important. It is imperative to locate transfer facilities in a way that directs truck traffic away from congested urban and suburban areas. Private investments can be used to finance these facilities.

Double-stack trains are examples of high productivity integral trains that have facilitated the growth of intermodal traffic in the rail freight industry. These trains are particularly efficient for long-haul and even cross-country shipment of marine containers from ocean ports. More than 100 dedicated double-stack container trains currently operate along mainline routes in the United States. The available height clearance on some rail lines limits the possibilities for double-stack operations. Numerous main lines east of the Mississippi River currently have bridge or tunnel clearances too low for certain types of double-stack container equipment. Such restrictions have to be eliminated.

From the point of view of the railroads, some rail lines should be abandoned or sold. However, the diversion of freight traffic from rail to truck results in increased congestion and accelerated deterioration of highway facilities. Preserving rail service can and must be viewed as a transportation and an economic alternative for areas experiencing high truck traffic and additional highway improvements. Not all lines can (or should) be saved. However, states can ensure that opportunities are available for maintaining rail service where it is the most cost-effective method for meeting transportation needs.

Freight control operations allow the tracking of freight cars through a rail network. These include AVI, automatic vehicle classification (AVC), and automatic vehicle location (AVL). AVI and AVC systems commonly use vehicle-based transponders that can be read by equipment at fixed points such as along the tracks, at terminals, and at yards. AVL technologies consist of equipment that locates freight cars based on dead reckoning, map matching, or satellite positioning systems.

7.8 AIR TRANSPORT CAPACITY ENHANCEMENTS

Air transportation is second only to private automobile as the primary mode of intercity passenger transportation in the United States. Many airports are currently experiencing severe congestion problems and the delays are expected to increase in the future as more than 1 billion passenger enplanements are forecasted for the year 2015. Actions have to be taken to add more capacity to the existing systems, spread the demand more evenly during the day and over the week, improve the air traffic control procedures, and upgrade the landside component (e.g., airport terminal and ground access). Methods to increase the capacity or to improve the performance of air transport to meet existing and long-term travel demand can be classified as (1) infrastructure options to increase the physical and processing capacity of airports and their components, (2) management actions that influence the demand for the airport and its components, and (3) advanced technology options. The descriptions of these options below are mostly taken from *TRB Special Report 226* (*16*).

7.8.1 Infrastructure Options

- Incremental capacity improvements at existing airports,
- New hubs at presently underused airports, and
- New airports in metropolitan areas with high traffic volume.

At some airports, capacity can be increased by some combination of new runways or taxiways and associated changes in air traffic control procedures. These measures, which are highly site-specific, would either add new operational capacity or allow more operations on existing runways, thus increasing the hourly aircraft service rate of individual airports. Estimates suggest that these measures, if applied throughout the system and fully successful, might allow a level of traffic up to perhaps 50 percent greater than in 1991, which is sufficient to accommodate 10 to 15 years of traffic growth at the projected annual increase rate. The chief advantage of this option is that it is relatively low in cost, it uses existing (or soon to be available) technology and it would provide immediate relief at congested airports. In some measures (i.e., independent and dependent converging approaches), no new construction is required. All that would be needed is a change in the procedures, aircraft separation rules, or visibility minima governing such operations on runways that already exist. Others require some amount of construction ranging from extending runways, to relocating or realigning runways, to building completely new runways.

Lack of capacity at hub airports (transfer points and connecting banks) is the main source of delay in the airport network. Creating new hubs at conveniently located points is a possible solution. Many airports have underutilized capacity that could relieve some of the congested airports now used as hubs by individual airlines. This option attacks the hub problem by creating more hubs. By drawing upon existing underutilized airport capacity within the network as a whole, this option avoids the difficulty and expense of building new airports. New secondary hubs would not reduce delay at all congested major airports. However, they would allow for growth that could not be accommodated at major hubs without severe delay. By making greater use of facilities available at medium-sized airports, this option takes advantage of overcapacity in the national airport system. New construction

would consist mainly of expanded aprons or taxiways and enlarged terminal buildings and landside facilities, which are rather low in cost compared with the cost of building new airports. Airlines would benefit from a greater availability of hubbing points, offset to some degree by inefficiencies that would result from more circuitous routes and decentralization of their present route structure.

Given the demonstrated linkage between economic growth and air travel, one option is to expand airport capacity in the metropolitan areas that will be the future centers of business, commerce, and tourism. The principal barriers to additional airports to serve major metropolitan areas are lack of a suitable site, conflict with other potential uses of land, introduction of noise into sensitive areas, and difficulty with providing adequate landside access, traffic pattern conflicts, and congestion in terminal-area airspace, opposition by incumbent airlines at the existing airports, and the large investment required to build a new facility in an already developed area. It is the past failure to achieve community acceptance and support for such projects that has contributed significantly to the lack of adequate airport capacity in our largest cities today. The key for emerging metropolises is far-sighted planning and immediate action to reserve land, and to protect it through zoning and development controls, until such time as it may be needed. For existing large cities such as Chicago, Los Angeles, and New York, the crux of the problem is to acquire sufficient land appropriately situated within the metropolitan area and served by an adequate (or expandable) surface transportation network. The next problem is gaining public acceptance of the need and desirability of new airport construction.

7.8.2 Demand Management Options

- Administrative and regulatory techniques, and
- Economic measures to redistribute demand.

Existing administrative and regulatory techniques involve some form of centralized system management applied to the use of airspace. These techniques can be expanded to manage demand. The options include managerial actions to assign functional roles for airports, to apply rules governing airport access, and to allocate the use of capacity, all in the interest of achieving a more efficient, safer, and less costly system. The actions that might be taken include assigning different classes of airspace and airport users to separate facilities and different portions of the airspace. Within each class, individual airports might be designated for specific users, or quotas might be set on operations at airports in high demand. The benefits would be both operational (demand smoothing and redistribution) and managerial (more efficient use of existing facilities and avoidance of costly investment to accommodate brief, severe, demand peaks). Since system management rules would apply to the use of both airspace and airports, coordination of these constituents of the air transport system would be essential. This option could be implemented in far less time than it would take to construct new facilities or to develop and install new technology. However, administrative demand management would clearly be controversial. Many airspace users would perceive airport and airspace system management as restrictive of their individual freedom and inhibitive of growth. For passengers, peak-period delay would be decreased and systemwide service reliability would be increased on average. However, there could be adverse effects locally on the schedule, frequency, or routing of flights on high-density routes and at the most heavily used airports.

Another option is to employ economic measures to influence demand. Through more economically efficient pricing, airports could provide market signals to influence choices of route and times of service based on the relative values that travelers place on air fare, delay, reliability of service, and convenience. If the price of airport access were adjusted to reflect the full cost of providing service or the marginal cost of providing service at peak periods, demand might be distributed in a more economically rational way. Depending on the level at which airport user fees are set, this approach could also provide a source of funds to pay for new capital investments to accommodate additional airport users. The techniques vary, but all entail pricing the use of airport facilities in a way that is consistent with either the cost of providing these facilities or the value that users place on them. This option would create a rational, market-based approach to pricing airport access, leading to greater efficiency in the allocation of scarce capacity and providing a source of capital for new capacity. The principal disadvantages would be increased air fares for peak-period travelers, reduced airport access for new entrants and financially weaker carriers unable to afford costly peak-period slots, and complication of airline scheduling. Some loss of regional air service might also result, with consequent negative effects for smaller cities in the region.

7.8.3 Advanced Vehicle and Control System Technology

- New aviation technology, and
- High-speed surface transportation technology.

The capacity or efficiency of air transportation is also influenced by the characteristics of the vehicles and the technology employed to control vehicle movement. New forms of aircraft and air traffic control technology would allow existing airport infrastructure to be used more efficiently and would ease certain kinds of restrictions on airport use. Two types of new aircraft offer promise: (1) those of substantially larger size, allowing greater seating capacity, and (2) those capable of operating on much shorter runways, resulting in more frequent takeoffs and landings. Some of the congestion and delay at airports is not due to a lack of runway capacity

but to limitations of the air traffic control (ATC) system. Programs to modernize the ATC system include installation of improved surveillance radar that provides greater position accuracy and faster scanning rates and use of more powerful computers to automate terminal and en-route traffic control functions. Promoting the development and encouraging the use of new types of aircraft could be an important part of a long-term airport strategy. In addition, new ATC technology could lead to more efficient and safer use of airspace, reduce delays, help ensure reliability of service in adverse weather, and permit more effective management of air traffic. There are technological risks, however, associated with all these advances, and the research and development and commercialization costs may be very high.

As urbanization increases and travel within and between nearby metropolises grows more difficult because of highway and air transportation system congestion, new modes of passenger and cargo transport will be needed. The development of advanced surface transportation technology will be prompted by the general urban and intercity travel demand and not by air travel alone. Still, the travel market for trips of 200 to 500 mi, now largely satisfied by air, would benefit from the introduction of new high-speed line-haul surface systems that could serve as substitutes for or supplements to air travel, chiefly because they would permit operating vehicles in train or on very short headways and provide much higher throughput than can be accomplished by aircraft. A second impetus for high-speed surface modes could be the situation of airports in relation to urban activity centers. New airports of the future probably will be farther from city centers and more difficult to reach by highway. Improved surface transportation links will be needed.

7.9 WATERWAY TRANSPORT CAPACITY ENHANCEMENTS

Navigation by water is usually constrained by the maximum draught of coasts, rivers, and waterways. In many situations, however, enhancing landside access to the ports poses a more serious problem. Trucks accessing seaports and marine terminals through urban corridors and routes have experienced delays due to congestion and mixing with passenger modes. Access by rail is also severely affected by at-grade crossings with roads and highway segments. Some of the options to improve access to marine terminals in order to enhance the movement of general and container cargo are described below. The discussion comes mostly from the U.S. DOT report *Landside Access to U.S. Ports* (*17*).

7.9.1 Infrastructure

- Dedicated freight corridors,
- On- or near-terminal rail access,
- Inland terminals, and
- Barge and intracoastal shipment of containers.

Infrastructure constraints to port landside access are characterized by deficient bridges, freeway access ramps, railway grade crossings, and rail tunnels and underpasses as well as congested or inadequate roadways serving marine terminals. Roadway access has been a major problem for marine transportation because of congestion in major truck routes serving marine terminals. Container ports are the most affected by congestion; 64 percent of container ports in 1992 reported that the major roads serving them are usually or always heavily used by passenger traffic, compared with 38 percent of noncontainer ports.

Developing dedicated rail-truck freight corridors between terminals and major rail and highway connections can divert truck traffic from local streets. Among the current dedicated freight corridors, the Alameda corridor in the Los Angeles plan is perhaps the farthest along and is the most ambitious. The corridor concept has much appeal. The traffic congestion caused by trucks and passenger vehicles sharing the same routes and intersections could be greatly reduced by building rail and highway facilities dedicated to freight movements. Dedicated freight corridors are expensive, however, as witnessed by the growing price tag of the Alameda corridor. They also require a great deal of coordination among the various units of government involved. Where the funding will come from, who should pay for the improvements, and whether the benefits are commensurate with the cost are all major issues.

Another infrastructure option is to have rail lines come nearer to, or even into, the marine terminals to reduce the amount of drayage between the ship and rail cars. Typical marine lines have a rail line adjacent to or within a mile of it. In theory, on- or near-terminal rail service can have different configurations. The rail lines can come onto the docks and thereby permit containers to be moved directly from ship to rail via gantry cranes, or the rail lines can be adjacent to container storage areas, which, in turn, are immediately adjacent to the cranes used to unload the ships. With on- or near-terminal rail service, handling costs are reduced compared with having marine and rail terminals separated by miles; drayage is greatly reduced and additional processing through gates is eliminated. It also reduces demand on highways and promises to reduce roadway congestion. These advantages are partly offset by other costs, most notably, from the port's perspective, the amount of land that is consumed, and from the railroad's perspective the cost of separating domestic from international containers and the increased switching complexity caused in double-stack operations.

Another way to improve port access is to shift the bulk of container sorting to an inland terminal instead of having the intermodal terminal at the port. Many container ports now have either on- or near-terminal rail facilities that allow containerized cargo to be moved off the container ship and onto a rail car with a minimum of drayage. Trains comprising these rail cars could take the containers to a separate inland rail terminal, perhaps many miles inland, where the contain-

ers would be sorted for local, regional, and national markets. These facilities would require an initial inland movement by rail, but transfers to trucks would still be required to transport containers destined for local and regional delivery because of the dispersed location of the firms receiving or generating them. If such inland terminals were located away from urban streets and highways, their truck traffic would contribute less to congestion. They would also reduce the trucking of domestic containers destined for the periphery of a metropolitan area. Although an inland terminal would increase the amount of handling, as congestion continues to grow in and around major urban centers, the benefits of reduced drayage through these congested areas could offset this cost. However, at-grade crossings of rail and highways should be reduced because long trains on these rail lines can tie up highway traffic.

Still another option is to rely more heavily on barge shipments to and from major container ports and other coastal cities. Rather than have containers drayed from a major port area to another major coastal city, it would be possible to move them by barge. Some barge movements on containers already occur on the East Coast between Boston and New York, New York and Baltimore, and Baltimore and Hampton Roads, Virginia. Increased barge shipments could also reduce some truck traffic and air pollution. The general demise of intracoastal shipping in recent years has weakened domestic shipping between major cities on the same coast that are too distant to rely on barges. For example, marine transportation of domestic trade between New York and Miami is made difficult by federal prohibitions on shipments of domestic goods in ships built outside of the United States, and by the high cost of acquiring and operating U.S.-built ships that would not be subject to these prohibitions. The loss of subsidies for ship construction has virtually ended the manufacture of commercial container ships in the United States.

7.9.2 Land Use Regulation

- Land banking and corridor preservation,
- Protective zoning,
- Congestion management, and
- Working with neighborhood groups.

Abandoned rail corridors are prime candidates to be purchased and reserved for future transportation use. It is important to preserve the corridor as well as rights-of-way along existing highways that may need widening in the future. Preserving the rights-of-way can be greatly aided if state highway agencies are given the right to acquire land and restrict its development. Land for corridors and rights-of-way can be preserved through official maps and subdivision regulations. Although ports that are already surrounded by an intensely developed urban environment may have little opportunity to preserve corridors, opportunities still exist to preserve land for future transportation needs at smaller ports and at possible sites for future inland terminals and the corridors to serve them.

Land uses can also be restricted through special zoning. In Massachusetts, for example, commonwealth law specifies waterfront land uses to be protected from industrial maritime uses and recreational uses, and it restricts uses of areas that are of specific environmental concern. The program ensures that areas of special physical and operational requirements that are dependent on access to navigable channels are not impaired by other development. To regulate the land uses, municipalities must enact complementary zoning ordinances.

Congestion management techniques can also be used to mitigate the increased traffic congestion that results when development occurs adjacent to port terminals or along access roads and corridors. Some of the traffic engineering and improvement changes that can be made on individual corridors have been discussed earlier (i.e., one-way streets, turn restrictions, street widening, and traffic signal coordination).

7.9.3 Terminal Operations

- Expanded operating hours,
- Information technology, and
- Mobile gates.

The large sizes of container ships and double-stack trains means that hundreds of containers are off-loaded onto the marine terminal. All of these containers need to be moved in a short period of time (usually within the 8-hr workday), creating a surge in demand that often causes congestion at terminal gates and on terminal access roads. The operation of gates for longer hours allows trucks and train movements to occur during the off-peak travel hours. Almost all container port terminals will operate round the clock when a large container ship arrives. For many container ports, expanded operating hours would reduce the delays encountered on landside routes. One of the major impediments to operating longer hours is the resistance of labor unions to changes in work rules and to extended work hours.

Improved technology can allow steamship companies, drayage firms, and double-stack rail operators to share data. It can also improve inventory control of containers, improve planning of terminal operations, and automate paperwork that continues to impede efficient throughput at marine terminals. Information-based technologies such as traffic management, cargo tracking, and computerized rail control will improve highway and rail access.

One approach to reducing queues at the gate would be to have multiple, mobile gates. If gates were operated at the berths as dictated by demand, the queues at the gate would be smaller and those that occur would be on terminal routes, not on public access routes.

7.10 EVALUATING SUPPLY-SIDE ACTIONS

Many supply-side and demand-side actions that can be taken to either increase the person and/or freight capacity or to reduce the existing demands of links and nodes in multimodal corridors were described in the previous sections. If implemented, these options can improve the LOS, or performance of the component in particular and the entire corridor in general. As stated above, supply-side actions for increasing the effective capacity of corridor components range from low-cost capital options, such as operational improvements and minor reconstruction, to capital-intensive options involving major reconstruction and the building of new facilities. The remainder of this chapter briefly describes the procedures for evaluating various supply-side capacity enhancement actions and strategies. Where demand-side options are more cost-effective or economically justified, they should be pursued first. Methods for evaluating demand-side options appear in Chapter 8.

Analysis of supply-side actions focuses on the cost and effectiveness of the options identified as having the potential to increase the physical capacity and/or improve the performance of a corridor and its components. The results of this analysis can be used to compare and contrast various capacity enhancement options. The following steps are recommended for evaluation:

Step 1. *Identify and characterize the actions that could possibly increase capacity or improve the LOS of the problematic links or nodes of the corridor.* Any type of action may have a number of options pertaining to different treatments or strategies. For example, the action to build and operate HOV lanes may consist of a number of options based on the number of lanes, types of vehicles that will be allowed, hours of operation, etc. Qualify and quantify the relationships between the options and the changes in physical capacity of the component. Similarly, define the relationship between link and node performance measures and the changes in capacity due to the action. Determine the benefits associated with each option.

Step 2. *Calculate all the quantifiable costs and specify the timing and staging of options identified in Step 1.* The costs should include initial capital outlays, routine and/or anticipated maintenance expenditures, and operational costs. The timing and staging of the options should also be defined in order to establish when the costs will be incurred and the benefits generated.

Step 3. *Use a checklist or matrix to assess the nonquantifiable impacts of supply-side options on various environmental, social, economic, and legal factors.* These factors may be weighted or ranked according to relative importance.

Step 4. *Perform an economic analysis to determine the attractiveness of each option and to compare and contrast various options.* Rank options based on cost-effectiveness, benefit-cost ratio, or other economic valuation measures.

7.10.1 Identification of Supply-Side Action and Change in Capacity and Performance

As stated above, supply-side actions are those that increase the physical capacity of a link or node in order to handle a specific transportation demand. A large number of these types of actions was identified and described earlier for various modes including highways, passenger and freight rail, waterways, and airports. The choice of action depends on the nature and extent of the capacity problem as well as the feasibility of the action.

Increasing the carrying capacity of multimodal corridors to reduce congestion and improve performance can usually be accomplished through physical changes. However, oftentimes these options are expensive and/or take time to implement, which means that they are most appropriate for meeting long-term transportation needs. Examples include the following:

- Buying and preserving corridor rights-of-way (highway, railroad, and water);
- Constructing new roads, interchanges, bridges, and so on;
- Building new airports, terminals, gates, and other airside and landside facilities;
- Developing advanced technologies for processing and moving passenger and freight traffic, including ITS and high-speed trains;
- Building new or upgrading existing railroad tracks to carry bigger and heavier trains;
- Building mass transit facilities, including transit lines, stations, and parking lots; and
- Building locks or making major river channel improvements (e.g., dredging and widening).

Substantial benefits resulting from increases in physical capacity and improved LOS can result from these supply-side actions, but the costs can be significant. Other ways to add effective capacity without expending as much time and resources include the following:

- Minor highway improvements such as signalization, channelization, lane markings, pavement resurfacing, shoulder widening, and providing truck climbing lanes;
- Highway-related operational changes such as reversible traffic lanes, coordination and optimization of traffic signals, and ramp metering;
- Rail track and station improvements such as changing of alignments and curvature, rehabilitation, yard expansion, signalization, and intermodal transfer facilities;
- Rail transit and freight operation improvements such as automated fare collection, optimal switching operations,

systematic classification procedures, and coordinated scheduling;
- Intercity and urban bus station operation improvements including advanced ticket purchasing, efficient transfers and connections to other modes, and coordinated scheduling;
- Lock capacity expansion and improved operations; and
- Airport terminal operation improvements such as better coordinated air traffic control systems, increased parking, improved baggage handling, faster screening, and larger waiting areas.

Another way to improve the performance of corridor links and nodes is by making regulatory, legal, organizational, or other institutional changes. For instance, changing the maximum allowable sizes or dimensions of vehicles, carriers, and containers (trucks, trains, aircraft, barges, and so on) may increase the maximum passenger and/or freight throughput on a given component (as long as the average speed remains the same). Raising the speed limits (or allowable processing rates) on roads, railroad tracks, waterways, runways, airspace, and others can raise the maximum possible throughput of these components. The safety and economic implications of these options have to be analyzed. Organizational and institutional changes can come in the form of increased cooperation/interaction among owners and operators of transportation facilities and services in order to provide a more efficient and coordinated network of links and nodes in the corridor. For example, transit properties in the city and outlying areas can coordinate their plans and operations to provide better transit services and connections. Similarly, freight and passenger movements in intercity rail corridors can be optimized by coordinating the operations of the service providers.

Changes in vehicular, passenger, and goods capacity due to each relevant supply-side option can be assessed using the various capacity determination formulae given in Chapter 5. Changes in LOS or performance can be assessed using the measures and procedures set out in Chapter 6, and the associated benefits can be calculated. A simple example is given below.

Example 1: For Example 4 in Section 5.4.1.4 of Chapter 5, determine the increase in capacity of the corridor if the two unsignalized intersections were signalized. Assume that the signal settings are identical to the existing signalized intersections and that the traffic is composed of 90 percent passenger cars and 10 percent light trucks. If the existing traffic volume is 1000 vph in both directions, what is the change in the v/c ratio as a result of this action? Calculate the benefits of this action in terms of number of persons moved per hour if the average occupancy of the passenger vehicles is 1.5.

Answer: The existing capacity of the corridor was calculated to be 1,368 vph in both directions, which is governed by the capacity of the unsignalized intersections. Signalizing these intersections will raise the corridor capacity to 2,158 vph in both directions, an increase of 790 vph. The existing v/c ratio is 1,000/1,368 = 0.73, and the new ratio with the proposed improvements is 1,000/2,158 = 0.46, a higher service level. The increase in person throughput due to the action is as follows:

= (90 passenger cars/100 vehicles) ∗ 790 vph
∗ 1.5 persons per passenger vehicle
= 1,066 persons per hour.

7.10.2 Cost and Timing of Supply-Side Action

The effect of an action to satisfy short- or long-term capacity requirements will depend, in part, on the timing of the action and, therefore, is important to identify. Each action that may be undertaken will have a cost associated with it. The cost of the action should be estimated and broken down by initial cost, maintenance, and operating costs. Information on both the timing and costs of the action (including the cost and timing of future maintenance and operational expenditures) is useful for life-cycle cost analysis.

7.10.3 Impacts and Cost-Benefit Assessment

The feasibility of undertaking a specific action will depend on many different factors including social, economic, environmental, legal, and institutional factors. A matrix or check list should be prepared to provide a preliminary assessment of the direct and indirect impacts of undertaking each potential supply-side action. The checklist or matrix should be designed to reveal when more detailed studies of the impacts of supply-side options need to be undertaken. In addition, a more detailed benefit-cost analysis should be conducted.

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CHAPTER 8

EVALUATING DEMAND MANAGEMENT OPTIONS

8.1 OBJECTIVE

This chapter describes the methods of assessing the cost and effectiveness of demand-side capacity enhancement actions (identified in Chapter 7) to permit both quantitative and qualitative evaluations of the impacts of demand strategies on the performance of individual components of the network and, where possible, the corridor or network as a whole. In order to perform such analysis it is necessary to determine the factors affecting demand and to describe the magnitudes of change in demand as a function of the changes in these factors for both the short- and the long-term future. It many situations, it is necessary to predict or to forecast future demands, especially when the options are to be implemented sometime in the future and the analysis calls for the use of future travel demand data. This chapter also explains how induced demand can be incorporated into the analysis.

8.2 STEPS IN THE PROCESS

1. **Identify where demand management strategies can be most effective** in influencing capacity utilization by identifying the traveled ways, links, segments, and nodes where capacity problems are the greatest. Distinguish between capacity problems for persons, goods, and vehicles.
2. **Identify the demand management options** described in Chapter 7 that have the greatest promise of mitigating capacity problems. Specify the timing of the options.
3. **Identify the type of travel-related choice** each demand management option most pertains to—residential location, job location, whether or not to make the trip, the time of departure, mode choice, or route choice.
4. **Determine the factors or attributes of choices** that most influence demand. For example, for passenger modal choice, the attributes of each mode and those of the traveler in different market segments need to be identified.
5. **Predict future demand(s)** for the travel modes or choices pertaining to the demand management option. The forecast year can be in either the short term or the long term, depending on when the options are going to be implemented in the future.
6. **Apply incremental analysis** (pivot-point methods including elasticity procedures) to estimate the effect of the demand management option on the travel-related choice of interest, and estimate the resultant change in the rate of flow for each demand mode and vehicle as well as for persons and goods.
7. **Assess the change in the performance** of each segment or node with capacity problems.
8. **Identify the type and estimate the magnitude of induced demand,** if any, resulting from the improvement in the corridor link or node, LOS, and performance.
9. **Assess the costs and benefits** of implementing the demand management option. Perform an economic analysis to determine the attractiveness of each demand management option and to compare and contrast various supply-side and demand-side actions. Use a check list or matrix to subjectively assess the environmental, social, economic, and legal feasibility of the option.

8.3 CANDIDATE SEGMENTS, LINKS, TRAVELED WAYS, AND NODES (STEP 1)

Demand management is one way to ensure that those people, goods, and vehicles that use a transportation facility do not confront severe delays due to congestion or other delay sources. The first step in analyzing the potential of demand management options is to list the traveled ways, segments, links, and nodes where traffic is heavy or near maximum capacity levels. An examination of key performance measures will reveal where capacity problems exist (see Chapter 6). It is important to distinguish between the capacity of a segment, link, and traveled way, node, path, and corridor. A segment or link within a traveled way may have reached its capacity, but the traveled way may not have. A path between an origin and destination may have a severe bottleneck problem, but other parallel paths in the corridor may not. It is also important to distinguish between capacity problems related to persons, goods, and vehicles. A segment may be reaching its vehicle capacity but not its person or goods capacity.

8.4 CANDIDATE DEMAND MANAGEMENT OPTIONS (STEP 2)

Chapter 7 provides a compendium of demand management options that have a potential role to play in addressing and mitigating capacity problems. Based on the list of segments, links, traveled ways, and nodes with capacity problems in a corridor or on a network, it is necessary to identify a corresponding list of potential demand management actions.

8.5 DETERMINE THE CHOICE CORRESPONDING TO A DEMAND MANAGEMENT OPTION (STEP 3)

It is useful to think of travel decisions as consisting of sequential or simultaneous choices regarding the following:

1. Where to originate travel,
2. Destination,
3. Whether or not to take a trip,
4. Time of travel,
5. Mode of travel, and
6. Route of travel.

For example, for home-based work trips, the choice of where to originate travel comes down to a choice about residential location. The choice of destination is a choice about where to work. The choice of whether or not to take a trip may involve decisions as to whether to telecommute or to work half-time. The choice of time of travel will involve determining on what days and during what hours (or even what 15-min intervals) to make a trip. The choice of mode of travel will involve the types of transportation available. And the choice of route will involve identifying which of the alternative paths between an origin and destination to take.

A shipper will make a similar set of choices, including business location, where goods will be shipped, and when they will be shipped. Sometimes the shipper will determine the form of transportation and the route of travel, although these decisions are often left to intermediaries such as a carrier or freight forwarder that handles more than one mode.

In assessing a demand management option, it is necessary to be clear regarding the choice that will be affected. In the case of multimodal transportation analysis, the only choice that may be of interest is modal choice. However, a comprehensive understanding of the potential role of demand management potentially concerns all of these different types of travel and shipper choices.

8.6 IDENTIFY THE FACTORS AFFECTING TRAVEL DEMANDS AND CHOICES (STEP 4)

Once the choice that corresponds to a demand management option has been identified, it is necessary to identify the attributes of the choice and the factors affecting the travel demands and choices. The literature on travel demand forecasting can provide a great deal of guidance in this regard. A number of travel demand parameters, including population, employment, income, household size, land use, and other social and economic characteristics pertaining to the individual decision makers or to the environment, which generally affect the trip-making behavior, have been classified as activity-system attributes. Another group of attributes pertaining to the transportation mode or system, called service attributes, also affects the choice of mode and other travel decisions made (*1*). Service attributes are either real or perceived characteristics associated with the travel alternatives (i.e., routes, modes, container sizes, departure times, etc.). The manner in which these two groups of variables are used in predicting travel demand depends on the type of facility (e.g., corridors, zones, routes, terminals, modes, vehicles, etc.), the dependent variable (e.g., number of work trips, probability that bus is chosen, tons of coal shipped, etc.), and the level of aggregation involved (i.e., person, household, citywide, industrywide). Many transportation demand models have been developed, calibrated, verified, and subsequently applied by agencies not only to forecast future needs but also to evaluate a variety of transportation policies and projects (see Section 8.7).

At the individual decision-making level, the factors that most influence the mode choice of travelers are normally classified into three sets:

1. Type or purpose of trip,
2. Modal attributes, and
3. Traveler attributes.

Tables 8.1 and 8.2 list typical attributes of choices for urban and intercity person travel.

The attributes that most influence the mode choice of shippers can be classified as

1. Commodity attributes,
2. Shipment attributes,
3. Modal attributes, and
4. Logistics cost.

Table 8.3 provides a list of typical attributes of the choice concerning selection of a mode for freight transportation.

8.7 FORECAST FUTURE DEMAND (STEP 5)

Forecasting is the process of estimating potential magnitudes of change over a specified period of time in the future. Forecasts can be made for either the short or the long run. The short run is defined as the period during which the behavior of transportation users and systems may change but the total demand for transportation remains constant. The long run is the period over which changes in land use, population, economic activity, and other factors cause the general demand for transportation to change.

TABLE 8.1 Attributes of choice of mode for urban person trips

TYPE AND PURPOSE OF TRIP
Purpose (work, shopping, recreation, personal)
Type (Home based vs. non-home based)
TYPICAL ATTRIBUTES OF MODES
Out-of-pocket costs (gasoline, parking, tolls)
Access time at both trip ends
Wait time
In-vehicle travel time
Transfer time
Walking distance
Privacy
Probability of obtaining a seat
Package carrying space
Flexibility for making connections
Protection (cover) from unpleasant weather
Availability of dedicated lanes (bike, pedestrian, bus)
Safety
Others
ATTRIBUTES OF TRAVELERS – SOCIO-ECONOMIC CHARACTERISTICS
Income
Household size
Size of party traveling
Vehicle ownership (auto, bike, motorcycle, van)
Gender
Age

8.7.1 General Approaches to Demand Forecasting

A wide variety of procedures are in use for forecasting future demand ranging from the exceedingly simple to the highly complex. Some of the most commonly used methods of developing forecasts or projections are briefly catalogued below:

Extrapolation. The most simple method is extrapolation of existing traffic volumes into the future based upon traf-

TABLE 8.2 Attributes of choice of mode for intercity person travel

TYPE AND PURPOSE OF TRIP
Purpose (work, shopping, recreation, personal)
Type (Home based vs. non-home based)
TYPICAL ATTRIBUTES OF MODES
Out-of-pocket costs (gasoline, parking, tolls)
Access time at both trip ends
Wait time
In-vehicle travel time
Transfer time
Walking distance
Privacy
Probability of obtaining a seat
Package carrying space
Flexibility for making connections
Protection (cover) from unpleasant weather
Availability of dedicated lanes (bike, pedestrian, bus)
Safety
Others
ATTRIBUTES OF TRAVELERS – SOCIO-ECONOMIC CHARACTERISTICS
Income
Household size
Size of party traveling
Vehicle ownership (auto, bike, motorcycle, van)
Gender
Age

TABLE 8.3 Attributes of choice of mode for freight transport

COMMODITY ATTRIBUTES
Commodity Class (Standard Industrial Code)
Weight
Volume
Value
Perishability (shelf-life)
Storage space requirements
Degree of Hazard
SHIPMENT ATTRIBUTES
Line haul miles
Miles per number of stops
MODAL ATTRIBUTES
Cube limit
Weight limit
Suitability for hazardous materials
Line-haul costs (per shipment or per mile)
Pickup costs (per shipment or per mile)
Delivery costs (per shipment or per mile)
Wait time
Travel time
Reliability
Probability of loss and damage claim
Load ratio
LOGISTICS COSTS PER UNIT
Order costs
Loading and unloading costs
In-transit capital carrying cost
In-storage capital carrying costs
Storage cost
Shelf loss in transit
Cost of filing loss and damage claims
Capital carrying cost on loss and damage
Carrying cost for safety stock
Emergency shipment cost

fic growth factors. Base level traffic volumes are established for each mode (vehicles, persons, and goods) and for the time periods of interest. Time periods of interest typically reflect daily and seasonal variations in traffic for each mode. Projected future annual growth rates are established and used to extrapolate the baseline traffic volumes into the future.

A commonly used growth factor is $(1 + r)^n$, where r is the decimal fraction representing the annual rate of growth and n is the number of years in the future. If one assumes that the growth rate is proportional to the initial number (i.e., exponential growth), another common expression used to make such extrapolations is

$$V = Ae^{rt}$$

where

V = the projected traffic volume for persons, goods, or vehicles for the mode and time period of interest;
A = the baseline traffic volume for persons, goods, or vehicles for the mode and time period (e.g., peak hour) of interest;
e = the base of the natural logarithm ($e = 2.71828\ldots$);
r = the growth rate per year; and
t = number of years into the future.

The principal advantage of extrapolation is its simplicity. Its main shortcoming is the failure to explicitly account for the important factors that influence future demand. Although extrapolation is frequently a successful technique, just as often it can result in very poor projections as a result of not accounting for structural change in the transportation sector and the economy at large.

Alternative Futures. A commonly applied approach to developing future projections of traffic is the development of alternative futures. This approach has the advantage of framing future traffic growth within a variety of reasonable future contexts and avoiding reliance upon a single projection. The normal procedure for identifying alternative futures is to establish a variety of dimensions that will be used to define each future scenario. These dimensions typically involve the following:

1. Demographics,
2. Economy,
3. Land use and growth management policies,
4. Environment,
5. Technology,
6. Social and cultural factors, and
7. Institutional setting.

Once alternative futures have been established, a variety of methods may be used to develop projections of future traffic. These include intuitive forecasting techniques (conjecture, brainstorming, heuristics, consensus building such as Delphi analysis), trend extrapolation, time series analysis, correlation, analogies, modeling with causal variables included, simulation, and optimization.

Although the development of alternative futures minimizes the risk of failing to account for the many factors that can shape future travel patterns, it can be time consuming, and it can be challenging to identify a future that is the most likely outcome.

End-State or Event-Stream Analysis. Many metropolitan areas and state transportation departments are developing vision plans for the future and defining the events that lead to the future vision. This is a highly normative approach to planning, and traffic projections must be developed that are consistent with the event-stream leading to the final vision. Many of the methods for developing traffic forecasts for alternative futures are also appropriate for end-state or event-stream analysis.

Pivot-Point Procedures. This method combines incremental procedures for making future projections with extrapolation or other forecasting methods such as alternative futures analysis. The idea is to pivot off a forecast to account for a specific change in one or more variables that influence either the aggregate behavior or individual choices. Commonly used methods for pivoting off trend lines or other future projections of traffic are elasticities (i.e., the percent change in travel volume due to a 1 percent change in a variable of interest) and the incremental form of the logistics (or logit) model, which predicts revised mode shares as a function of base mode shares and the change in the variable(s) of interest. Figure 8.1 illustrates the use of a pivot-point procedure applied in the context of the development of alternative futures performed for the Wisconsin DOT in the late 1970s (*2*).

In general, the prediction of traffic flows requires explicit consideration of both service and demand models. However, the analyst is often confronted with situations in which there is limited information available and estimates are needed quickly. Particularly common are situations in which there is inadequate time or resources to calibrate a model for a particular situation. In such cases, approxi-

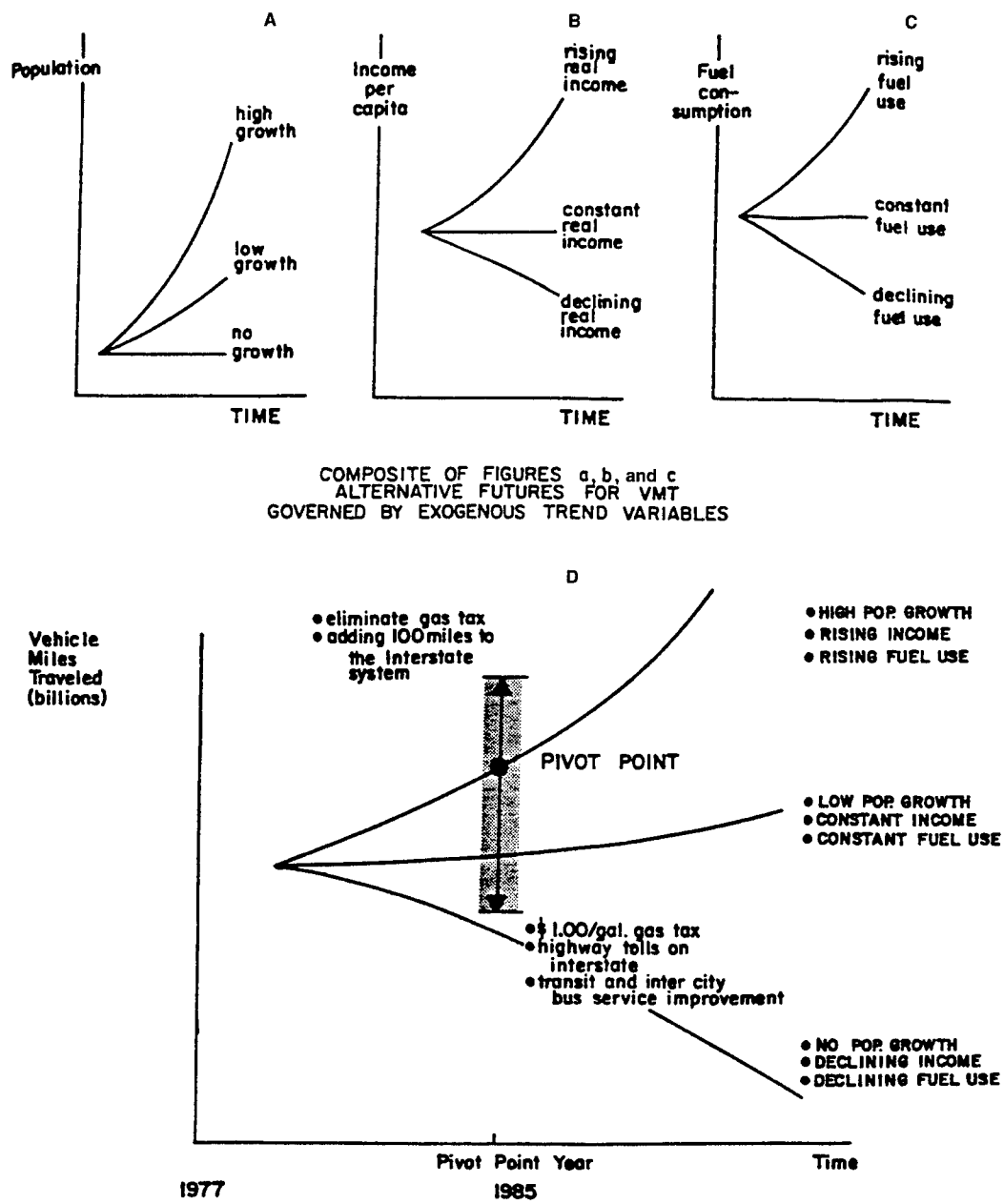

Figure 8.1. Illustration of pivot-point procedure with alternative futures (2).

mate prediction methods using knowledge gained elsewhere can be quite useful. Often the only data an analyst will find available are current traffic volumes and service levels. No other demand-related information can be collected. By adapting information developed elsewhere such as values of demand parameters or elasticities, perhaps modified by judgment, the incremental analysis or pivot-point procedure can still be applied.

Four-Step Procedure. This widely applied method of transportation forecasting and network flow analysis, more fully discussed below, involves the four steps of (1) trip generation or attraction; (2) trip distribution; (3) modal split; and (4) route or network assignment. The four-step procedure has been applied to many transportation planning problems ranging from state and metropolitan planning studies to special studies such as the examination of urban goods movement.

The problem of forecasting demand can also be approached from two different levels: (1) that of groups of individuals (aggregate) or (2) that of the individual decision maker (disaggregate). *Individuals* refers to any group that behaves as a single unit making transportation decisions. A single person or household makes decisions concerning personal travel. A company, a part of a company (e.g., transportation or logistics department), or a person (manager, consignee, or shipping clerk) makes decisions with regard to goods or commodity movements.

Aggregate Demand Models

Aggregate demand models predict the behavior of a group of consumers (several individuals, households, or firms) in response to any changes in future conditions affecting their choices. The most common aggregation criterion for travel demand estimation is geographic location. In almost all transportation studies the area is divided into geographic zones with all the consumers in each zone forming the main market segments. Such forecasting can be done satisfactorily with the databases and methods used by metropolitan planning organizations, which are intended to investigate policies having impacts on an entire metropolitan region or on large transportation corridors within a region.

The general form of aggregate demand models follows:

$$V = f(A,S)$$

where

V = volume and composition of traffic between two or more geographic units,
A = activity system variables (see Section 8.6), and
S = service attributes for a particular activity system (see Section 8.6).

Indirect Sequential Procedure (Four-Step Procedure)

The most common aggregate forecasting procedure that has been used by many transportation planning agencies in both rural and urban areas is the four-step procedure briefly described above. This technique breaks the demand model into four sequential submodels.

1. **Trip generation or attraction.** Total trips made by a particular market segment are estimated for each zone of the region or area being studied (a function of exogenous or activity system variables, no service attributes). Estimates are based on projected land use and economic activities. The number of trips generated and attracted are estimated.
2. **Trip distribution.** Total trips originating in each zone are distributed among possible destinations. The following methods are commonly employed:
   a. *Fratar Model* (growth factor method, iterative proportional fitting) assumes that the change in the number of trips in interchange between zones is directly proportional to the change in the number of trips in origin and destination.
   b. *Gravity Model* (O-D pair traffic volume is inversely proportional to distance) is based on the hypothesis that trips produced at an origin and attracted to a destination are directly proportional to the total trip production at the origin, the total trip attraction at destination, a calibration factor, and possibly a socioeconomic adjustment factor but are inversely proportional to the spatial separation measured in terms of distance or travel time.
   c. *Intervening Opportunity Model* assumes that trip interchange between the origin and destination zone is equal to the total number of trips emanating from the origin multiplied by the probability that each trip will find an acceptable terminus at the destination zone.
3. **Modal split.** The volumes of trips going from a particular zone to a particular destination are split among the possible modes; factors influencing modal split include socioeconomic characteristics of the area and the travelers as well as operating and comfort characteristics of competing forms of travel and systems.
4. **Route/network assignment.** Trips for each O-D mode combination are assigned to paths in the network.

The four-step aggregate demand models are relatively straightforward. However, it has been shown that aggregation of data prior to estimation of demand models will result in loss of precision of the estimated parameters if the aggre-

gate groups are not homogeneous with respect to the values of the explanatory (independent) variables.

Demand models have traditionally been developed at an aggregate level, with geographically defined zones used as a primary basis for aggregation. In general, there is more variation in behavior within zones than between zones. Thus if one wants to aggregate, one might prefer to aggregate across zones, keeping access conditions and/or market characteristics as bases for defining classes, rather than averaging out these important variables (*3*).

Although regional and metropolitan aggregate demand forecasting models can be used to reliably predict changes in the demand for a corridor as a result of changes in land use or socioeconomic characteristics of the zones or areas in which the corridor is located, they are mostly limited in their ability to evaluate corridor-level projects or actions. However, most models do not include feedback relationships between physical capacity improvements and changes in land use. The models usually have no built-in parameters that account for variations in market characteristics within the zones, which are required in order to evaluate the impacts of improvements in the corridor (or portions of it) on the different market segments. Disaggregation or segmentation of the geographic areas and markets into smaller groups is usually important.

The Urban Transportation Model System (UTMS), developed in the 1970s, is an example of an aggregate demand model consisting of these four sequential steps. It was the first large-scale transportation model, has been modified to a great extent over the years, and is still being widely used all over the world. Trips are classified according to purpose as follows:

- Home-based work trips,
- Home-based nonwork trips (shopping, social or recreational, school, and miscellaneous),
- Non-home-based trips, and
- Truck trips.

Aggregate person trips originating from or attracted to a zone are predicted using annual average income, average number of automobiles owned, average number of workers per household, percentage of households having income greater than a specified value, total population, acres of land in various land categories, and total employment. The trip ends for these zonal trips are determined using the trip productions, service variables, and attraction measures (the most common procedure is the gravity method). O-D trips are then assigned to specific modes by a variety of approaches including (1) curves and regression models in which the origin zones are classified by income level and automobile ownership, and (2) for each class of zones, relationships between fractions of trips by various modes and the time and cost ratios. The final step is prediction of modal trips by route, also called route assignment. Passenger demand is converted to vehicle demand using vehicle occupancy rates for various modes.

Although the UTMS procedure can reasonably predict flows in corridors and its components, it has been criticized because it does not correctly treat the dimension of consumer choice (e.g., sequential versus simultaneous choices of residential location, automobile ownership, frequency of trips, destination, and mode choice). It also hides the variability in passenger behavior. Moreover, it is not able to address many of the issues and policies pertaining to air quality and air pollution reduction, energy conservation, increased mobility for the elderly and handicapped, upgrade of transportation services, and better operational use of facilities.

The Urban Transportation Planning System (UTPS) software package, developed by the Urban Mass Transit Administration, now Federal Transit Administration, and the Federal Highway Administration, was the next-generation package of urban transportation planning software. It too includes the four-step aggregate forecasting technique in estimating trips between zones of urban transportation networks. It also contains a battery of other procedures including a disaggregate demand forecasting process for modal split and should be contrasted with the UTMS procedure.

Many commercial software packages exist that have used the UTMS and UTPS as their inspiration and therefore follow the four-step procedure but with different refinements depending on the vendor.

Direct or Simultaneous Models

Another type of aggregate demand forecasting model provides the means to directly forecast travel volumes by mode as a function of service attributes such as frequency of service, travel time, out-of-pocket costs, and, possibly, socioeconomic variables such as income. In other words, when this model is applied to a particular origin and destination, it simultaneously addresses trip generation and mode split of the four-step forecasting process described above. Typically, this type of model is estimated with aggregate traffic volumes by mode between origin and destination as the dependent variable and various service attributes and aggregate socioeconomic variables as independent variables.

In order to forecast with this type of model, it is necessary to project what the values of each of the dependent variables will be—usually a fairly straightforward task. Application of direct or simultaneous demand models has much appeal due to the simplicity and economy of the procedure relative to applying the full four-step forecasting procedure.

However, direct demand models are also potentially subject to loss of precision if aggregation of data occurs prior to estimation of the models. This type of model is also likely to have less transferability than models based on the travel choices of individuals.

Disaggregate Demand Models

A disaggregate demand model predicts the behavior of a single consumer (e.g., person, motorist, traveler, shipper, or firm) in response to changes in future conditions. Disaggre-

gate forecasting procedures can be easily applied to policies that affect only a small group or area. Disaggregate travel demand models are mostly based on the concept of utility maximization for individual consumers. A person-trip maker has to decide when, where, and how to travel. Similarly, a shipper or carrier needs to weigh options pertaining to which mode to use, what route to take, how many stops to make, and how much goods to carry. In both cases, the consumer makes discrete choices based on the actual and perceived utilities of available options. To estimate the probability that a decision maker will choose option k as opposed to option l, the relative utilities of both options and the characteristics of the individuals are factored as follows:

$$U_i(r) = S_r + E_{ir} + \mu_{ir}$$

$$U_i(l) = S_l + E_{il} + \mu_{il}$$

where

$U_i(r)$ = utility of option r for individual i,
$U_i(l)$ = utility of option l for individual i,
S = vector of service variables ($b_1 * S_1 + b_2 * S_2 + \ldots + b_j * S_j$),
E = vector of socioeconomic variables ($a_1 * E_1 + a_2 * E_2 + \ldots + a_k * E_k$), and
μ = disturbance term (with an assumed distribution).

$$\text{Prob}_i(r) = f[U_i(r) - U_i(l)]$$

The individual can have multiple options, and the model estimates the probability that each alternative is chosen. The parameters of the utility equations should be those that actually determine the choice; the coefficients of these parameters are calibrated based on a reliable dataset.

Utility measures are directly related to those persons responsible for making the travel decision (i.e., the decision to make the trip, its origin or destination, the choice of mode, and, in the case of freight, the size of the shipment). When viewed in this manner, travel decisions are made in the broader context of the decision maker's overall pattern of economic behavior.

The demand function for a disaggregate travel demand model is expressed in terms of choice probabilities. These choice probabilities are then aggregated for a group of individuals or market to determine the aggregate demand for a particular mode or route.

8.7.2 Intercity Freight Demand Models

The factors influencing the demand for freight transportation (i.e., volume of commodity and shipper's choice of mode) are more complex and interdependent than those influencing passenger demand because:

- The decision maker for freight transport consists of the shipper, carrier, and receiver (not just one person).
- There are many different types of commodities that make up the freight traffic, and these commodities have a wide range of prices or values associated with them (also some are perishable and others are not).
- Freight movements are measured in various units such as quantity, weight, volume, container, carload, truckload, etc.
- The demand for goods movement is derived from the commodity demand in the area or region and reflects existing social and economic needs, conditions, activities, priorities, and preferences of people within the area.
- The cost of moving freight is much harder to determine than the cost of moving passengers because more specialized services are required for freight (i.e., handling, loading, unloading, classifying, storing, packaging, warehousing, inventorying, etc.).

However, like passenger transportation, the demand for freight can be and has been modeled at the aggregate and disaggregate levels. Aggregate approaches to estimating freight transport demand include direct estimation of relationships between aggregate volumes of goods or shipments and shares transported by various modes (sometimes broken down by commodity groupings, regions, etc.) and the general characteristics of the area or region and the rates charged to shippers for transport by individual modes. Some aggregate freight demand models also employ the sequential four-step procedure consisting of commodity generation, commodity distribution, modal choice, and route assignment. Disaggregate models of freight demand pertain to individual goods or shipments and the firm's choice of mode based on minimization of costs by individual firms. Shippers' utilities are also often based on integrating mode choice and production decisions.

Transportation is a derived demand, especially in the case of freight transport. The magnitude of freight movement depends on the magnitude of demand for products and goods that need to be transported. In modeling the demand for freight transportation in a given location, it is necessary to determine what types and how much of each type of commodity is required or produced at the location. Some of these commodities are consumed; others are used as factors of production. It is almost impossible to itemize all of the commodities that are shipped to and from a large area (unlike person trips, which can be easily classified by purpose and type of traveler). Commodities, therefore, are usually grouped in very general categories. Furthermore, they are often expressed in common units (usually by size or by weight) so that transportation requirements (e.g., number and size of trucks, rail cars, or containers, etc.) can be easily estimated. Only by properly forecasting the quantity and quality of goods moved can the demand for freight transportation (e.g., modal choices) be accurately predicted.

Several key variables underlie the firm's choice of mode or carrier for freight transport. These may be classified into

three major groups: (1) the firm's (i.e., shipper, receiver) attributes, (2) commodity attributes, and (3) transport attributes. Characteristics that affect a firm's choice of mode include operating costs, location, number of customers or suppliers, and desired inventory levels.

Commodity attributes are important determinants of model choice. The product being shipped determines the loading and handling requirements as well as the maximum shipment size that can be accommodated in a given piece of equipment. Clearly, rail mode is capable of handling larger individual shipments than truck mode. Typical commodity attributes include density, value per pound, shelf life, and packaging.

Variables describing transport attributes of the modes under consideration have also proven to be important. These include equipment availability, transit time, reliability, and loss and damage experience.

Total logistics cost is what the shipper is attempting to minimize in choosing one mode of transportation over another or one shipment size over another. The components included in the shipper's total logistics cost function often include factors such as ordering cost, carrying cost, warehousing costs, cost of claims, and reloading or rehandling costs.

These variables detail the total logistics costs of acquiring, shipping, and storing the product as a function of these variables and other descriptive variables that affect the total. By describing the shipper's costs in a single utility function (such as a disaggregate model of mode choice) the "value" attached to the variables in the utility function can be estimated econometrically.

Most long-distance (i.e., intercity, regional) freight movements involve various modes of transportation such as trucks, barges, rail, air, and pipelines. Intermodal freight transfers such as rail to truck, or barge to rail, are also common especially when access to urban areas is not available through the primary (line-haul) mode. Intercity freight is often consolidated in central warehouses and terminals near urban areas so it can be distributed by trucks and other motor vehicles to the final destinations within and around the cities. The competition for corridor capacity between freight and passengers is most problematic in urban areas where freight movements by truck mix with person trips by car and other highway vehicles.

Further guidance on freight demand forecasting can be found in the report, *A Guidebook for Forecasting Freight Transportation Demand*, prepared under NCHRP Project 8-30. Among other things, the guidebook addresses demand forecasting for existing facilities. The following text is taken from the report:

> A relatively simple procedure for deriving forecasts of transport demand from economic forecasts is to assume that demand for transport of various commodity groups is directly related to variations in corresponding economic *indicator variables*. These indicator variables can be used either to derive *annual growth rates* or to derive growth factors representing the ratios of forecast-year to base-year values. The procedure requires data of estimates of transport activity or facility usage, by commodity group, for a reasonably, "normal" base year as well as forecasts of growth in the corresponding indicator variables. The basic version of this procedure is:
>
> 1. Divide base year transport activity or facility usage by commodity group.
> 2. Associate each commodity group with an economic indicator variable that is related to production or demand for that commodity group and for which forecasts are available from some exogenous source (e.g., transport of food products might be associated with production of food products).
> 3. For each indicator variable, obtain either a *growth factor* by dividing its forecast year value by its base year value, or obtain a forecast *annual growth rate* (e.g., by determining the average annual growth rate implied by the variable's base-year value and its value in any forecast year.
> 4. For each commodity group, estimate forecast-year demand either by multiplying base-year activity by the corresponding growth factor or by applying the indicator variable's annual growth rate to base-year activity.
> 5. Aggregate the forecasts across commodity groups to produce forecasts of total transport demand and forecasts of demand for any set of commodity groups of interest.
>
> The most desirable indicator variables are those that measure goods output or demand in physical units (tons, cubic feet, etc.). However, forecasts of such variables are frequently not available. More commonly available indicator variables are constant dollar measures of output or demand, employment, or, for certain commodity groups, population or real personal income.

8.7.3 Urban Freight Demand Forecasting

The primary means of goods movement in urban areas is by truck. Whether they are line-haul or delivery (feeder or distribution) movements, truck traffic is a major determinant of level of service in highway corridors serving urban areas. Unlike other modes such as waterway, rail, or air in which the freight movements do not interfere with person movements (exclusive rights-of-way or minimum points of conflict), trucks mix and compete directly with passenger vehicles for highway capacity. Long-haul freight movements may be feasible by modes other than truck, but for delivering the goods to their final destinations within a densely populated city trucks are still the most flexible and have the greatest coverage.

The multistep (sequential) procedure described earlier for predicting passenger trips in urban areas has also been

applied to movement of goods by trucks in these areas. The procedure consists of the following:

- Commodity generation,
- Commodity distribution,
- Commodity modal split,
- Vehicle loading, and
- Trip assignment.

8.8 APPLY INCREMENTAL ANALYSIS (STEP 6)

The most insightful, simplest, and least costly method of assessing how demand management actions affect capacity utilization is to apply some form of incremental analysis, frequently called pivot-point analysis.

Incremental Analysis. A method of evaluating demand by analyzing the *change* in demand that results from a *change* in one or more variables of interest given some base line information such as the total traffic and the initial modal shares.

Pivot-Point Analysis. A method of analyzing current or projected demand by "pivoting" off of the baseline-year or future-year conditions using incremental analysis.

Incremental analysis requires information only on the magnitude of the change in the variables of interest and information on the initial values of one or several key variables that define market conditions at the outset. The key attributes of the choice influenced by demand, such as most of those shown in Tables 8.1 through 8.3, are the types of variables that can be analyzed using incremental analysis.

Incremental analysis on the demand side is very inexpensive and easy to apply and can be performed with a scientific calculator or a simple spreadsheet program. This is an important virtue since many transportation agencies lack staff and resources to apply complex methods. This type of analysis can also be applied to either current or future demand. When applying incremental analysis to future demand it does not matter whether baseline travel information is generated by empirical observation or by aggregate or disaggregate forecasting methods as described in Section 8.7.

The methods of incremental analysis for determining the effect of demand management actions fall into two categories: (1) elasticity methods and (2) incremental form of the logit or chained-logit model.

8.8.1 Elasticity Methods

Elasticity methods are suitable for analyzing the sensitivity of demand with respect to a single variable of interest and can be used to "pivot" off either baseline demand or projected demand. Elasticities regarding different attributes of travel choice can be found in the literature on travel demand, can be inferred from aggregate or disaggregate demand forecasting models that have been estimated using rigorous statistical or econometric procedures, or can be inferred from case studies that provide information on traffic volumes before and after a variable of interest has changed. Methods of estimating changes of demand using each of these approaches are discussed below after a number of terms related to elasticity are defined.

Elasticity of Demand. The percentage change in demand due to a percentage change in a variable of interest that affects demand.

Point Elasticity of Demand. The change in demand due to an infinitesimally small change in a variable affecting demand. The point elasticity is applied to continuous (differentiable) functions and is calculated using the following formula:

$$\epsilon_S^V = \frac{S}{V} * \frac{dV}{dS}$$

where

V = traffic volume, and
S = LOS variable or other variable of interest.

Arc Elasticity of Demand. The change in demand due to a finite change in a variable affecting demand. The arc elasticity[1] is applied to a discrete change in a variable that affects demand and is calculated as follows:

$$\text{arc } \epsilon_S^V = \frac{S}{V} * \frac{\Delta V}{\Delta S}$$

Note that the use of elasticities for incremental analysis is applicable only to cases where the incremental change in the demand variable is small or if the demand elasticity with respect to the variable is constant.

Own Elasticity of Demand. The change in demand of a mode as a function of one of the variables that directly affects the demand for that mode. The own-point elasticity for mode i with respect to a change in an attribute of mode i is expressed as follows:

[1]We have chosen to define the arc elasticity as presented above. However, the measure that is the closest approximation to the point elasticity is the log arc elasticity, which in turn is closely approximated by a mid-point (linear) formulation:

Log arc elasticity:

$$\epsilon_i^i = \frac{\Delta \log V}{\Delta \log S} = \frac{\log V_2 - \log V_1}{\log S_2 - \log S_1}$$

Mid-point (linear) arc elasticity:

$$\epsilon_i^i = \frac{\Delta V}{(V_1 + V_2)/2} \div \frac{\Delta S}{(S_1 + S_2)/2} = \frac{\Delta V(S_1 + S_2)}{\Delta S(V_1 + V_2)} = \frac{(V_2 - V_1)(S_1 + S_2)}{(S_2 - S_1)(V_1 + V_2)}$$

$$\epsilon_i^i = \frac{S_i}{V_i} * \frac{dV_i}{dS_i}$$

The formula for the own arc elasticity is similar:

$$\text{arc } \epsilon_i^i = \frac{S_i}{V_i} * \frac{\Delta V_i}{\Delta S_i}$$

Cross Elasticity of Demand. The change in demand for a mode as a function of a change in an attribute affecting the demand for another mode. The cross point elasticity for mode i with respect to a change in an attribute of mode j is equal to the following:

$$\epsilon_j^i = \frac{S_j}{V_i} * \frac{dV_i}{dS_j}$$

The expression for the cross arc elasticity is similar:

$$\text{arc } \epsilon_j^i = \frac{S_j}{V_i} * \frac{\Delta V_i}{\Delta S_j}$$

Choice Probability Elasticity. The percentage change in the probability of choosing an option from a choice set due to a 1 percent change in a variable directly influencing the selection of the option. If the probability of an option has been estimated using a logit model the choice probability elasticity for an individual traveler or shipper with respect to the nth causal variable directly influencing the utility of the ith option, and in turn the probability of choosing option i is as follows:

$$\epsilon_{X_{in}}^{P_i} = a_{in}\overline{X_{in}}(1 - P_i)$$

where

a_{in} = the coefficient of the nth causal variable, X_{in}, in the utility function for option i,
$\overline{X_{in}}$ = the mean value of the causal variable X_{in}, and
P_i = the probability of choosing option i from the choice set.

Choice Probability Cross Elasticity. The percentage change in the probability of an option from a choice set due to a 1 percent change in a variable directly related to another option in the choice set. For a logit model the choice probability cross elasticity for an individual traveler or shipper with respect to a change in the nth causal variable directly influencing the utility of the jth option, and in turn the probability of choosing option i is:

$$\epsilon_{X_{in}}^{P_i} = -a_{jn}\overline{X_{jn}}P_j$$

where

a_{jn} = the coefficient of the nth causal variable X_{jn} in the utility function for option j,
$\overline{X_{jn}}$ = the mean value of the causal variable X_{jn}, and
P_j = the probability of choosing option j from the choice set.

Travel demand elasticities can be classified as aggregate (based on coarse data such as geographic unit) or disaggregate (based on more detailed data such as individual, household unit, or firm); empirical (obtained from field measurements before and after a notable incident such as a fare increase) or calibrated (derived from various types of demand models); and short-run (effects observed immediately after the changes are made) or long-run (when equilibrium conditions are reached). Empirical elasticities are often measured on a corridor- or areawide basis and are more aggregate than calibrated elasticities. Short-run elasticities reflect unstable responses, because adjustments that occur in response to long-run market trends may cancel out or amplify short-run effects.

The Literature As a Source of Elasticities

The transportation literature is a rich source of information regarding the elasticities of travel demands. There are a number of compilations of information regarding elasticities that can be very helpful to the analyst. An appendix to this chapter (Appendix 8A) draws from some of these compilations. In Chapter 7 of this manual, under various demand management options, additional information is provided on the sensitivity of demand with respect to service variables that these demand management options affect. In addition many articles in the literature frequently provide estimates of demand elasticities. Most elasticity information concerns urban person travel. Less information is available regarding intercity passenger travel. Furthermore, little information is available on freight demand elasticities.

Elasticities for Urban Travel

Direct demand (or simultaneous) models for specific modes and purposes have also been calibrated using aggregate data in a variety of urban areas. Some of these models predict the aggregate demand for automobile and transit trips (bus, rail, etc.) by trip purpose as a function of population characteristics (average automobile ownership, household income, household size) and price and service characteristics of the competing modes. Some of the general conclusions that have been drawn from empirical studies of aggregate demand and mode split elasticities for urban travel are as follows:

- Aggregate transit demand elasticities are quite inelastic.
- Individual transit ridership is more sensitive to service improvements than to price reductions.
- Transit ridership is more sensitive to improvements in access time than in line-haul time.
- Off-peak trip purposes such as shopping trips are more price sensitive than peak-period work trips.

Urban passenger demand elasticities that were estimated in the 1970s and early 1980s have been stratified by Chan and Ou (*4*) according to urban size (large versus medium) and urban structure (core concentrated versus multinucleated). These elasticities can be applied to a particular city (or setting) only if it shares common socioeconomic and travel characteristics with the representative cities for which the values have been estimated. (See Tables 8A.1 to 8A.4 in Appendix 8A for both empirical and calibrated transit demand elasticities and cross-elasticities for these city groups.) Specific models and elasticities estimated using aggregated data in many urban areas are generally not transferable to other areas because the aggregate characteristics are seldom identical.

Due to the limitations of aggregate procedures, disaggregate (individual) choice models are highly preferred for predicting urban passenger demands. The initial applications of disaggregate choice modeling techniques considered the choice of travel mode. Multiple dimensions of choice—destination (shopping and work), mode (automobile versus transit), and frequency—were first modeled by Charles River Associates using 1967 data in Pittsburgh. This model was used to evaluate the gas tax elasticities in Los Angeles and later the elasticities of aggregate choice and VMT with respect to proposed policy changes using the NPTS data (*5*). A summary of the work trip modal splits and VMTs, as well as the aggregate elasticities with respect to the policies, is shown in Table 8A.5.

Several other urban discrete choice models have been developed in the past, mostly for predicting mode choice for work and shopping trips (representing the largest proportion of peak-period travel) and using many level of service and socioeconomic variables. One of the most commonly used model systems was developed for the Metropolitan Transportation Commission in the San Francisco Bay Area. Also, multinomial logit models of work trips developed for several urban areas in Wisconsin in 1982 (*6*) using stated preference data produced direct and cross-elasticities of demand (see Table 8A.6).

More recent estimates of logit coefficients for travel time, transit fare, and parking costs for urban trips in major urban areas are shown in Table 8A.7. The coefficients were determined by various consultants who conducted the studies at different times and locations.

Elasticities for Intercity Passenger Travel

Aggregate passenger forecasting procedures have been applied extensively for intercity passenger travel. Most of these procedures have been estimated for single mode, with air travel demand being the most prominent mode studied because of the relatively high modal share for intercity air passenger trips. A 1975 study of Northeast Corridor Passenger Rail Service resulted in rail fare and block time elasticities as shown in Table 8A.8 and Table 8A.9.

Multimodal models for rail, bus, air, and car have also been developed; for example, the *Kraft-Sarc model* that was developed for the northeast corridor (*7*). This model is a simultaneous gravity model, which determines city-pair trips using population or employment, income, and a measure of zonal attractiveness, and a mode choice model based on modal price and time and service characteristics. Business and personal travel elasticities derived for these models are tabulated in Table 8A.10.

Variations of this gravity model and other gravity type procedures (e.g., abstract mode, composite analytic, share models, direct demand, etc.) have been developed to suit specific corridors or scenarios.

Disaggregate intercity passenger models include the quasi-individual choice models of travel behavior developed using the NPTS of 1972 (*8*). These are multinomial logit models explaining business and nonbusiness travel mode choices in terms of differences in time, cost, frequency, and distance. The coefficients of the parameters and the own- or cross-mode elasticities for the multinomial logit model are shown in Table 8A.11. The choice elasticity estimates are unreasonably high, uncertain, and sometimes counterintuitive. The averaging procedure for the independent variables produces complications which make interpretation of the model difficult.

Forecasts of intercity passenger travel are necessary in multimodal corridor analysis because some corridors or components of corridors handle local and intercity passenger transportation. Examples are interstate highway corridors radiating from the central business district. It is necessary to determine the composition of trips (e.g., intercity versus local) because the values of these trips are relatively different.

Freight Demand Elasticities

Compared to urban and intercity person travel, there is little comprehensive information available in the literature on freight transportation that addresses a broad cross-section of commodities. Many studies have been done for specific commodities or markets, and as a result, information is available on the elasticities of demand in some specific markets. The transferability of these elasticities to other circumstances is questionable. An introduction to the literature on freight demand forecasting can be found in the report prepared under NCHRP Project 8-30, *A Guidebook for Forecasting Freight Transportation Demand* (*9*).

Caveats Regarding the Use of Elasticities in the Literature

The analyst should exercise great care in applying an estimate of elasticity of demand developed in one market to another market. Transferability of elasticities should be carefully scrutinized. In general, elasticities derived from disaggregate models are most likely to be transferable because such elasticities are derived from the behavior of individuals. Individuals with the same socioeconomic characteristics in one setting are likely to behave similarly in other settings given the same set of choices and the same levels of attrib-

utes pertaining to each type of travel choice. Thus demand elasticities are transferable only if the available choices or options are identical and the model captures the socioeconomic and level of service variables that really influence the choice process. For example, bus demand elasticities in Wisconsin determined from discrete mode choices among shared ride, driver only, bus, bike, and walking cannot be used in New York City where the modal options include automobile, bus, rapid rail, commuter rail, ferry, bike, and walking. Even if the same modes are available for two locations but the model does not accurately account for modal attributes that influence the selection (e.g., ridesharing may be safer in one location compared with another), the model ceases to be applicable.

Elasticities that represent consensus estimates of a broad cross-section of case studies are usually transferable, but an elasticity developed from a single case study will be applicable only to the market for which the case study is developed or another market with nearly identical characteristics. Elasticities derived from aggregate demand models can also be transferred among similar settings but are less likely to be transferable than elasticities from disaggregate models.

Estimates of elasticities that appear in the literature may also be out of date. Elasticities based on disaggregate models are most likely to be stable over time, and aggregate elasticities are less so. Consensus elasticities derived from a broad cross section of case studies over many years are likely to remain valid for some time, but elasticities based on a single study conducted at a single point in time are not.

It is also important to be wary of applying disaggregate elasticities, which pertain to individuals (or individual firms), to groups of people. If disaggregate elasticities are applied to aggregate populations, the elasticities may under- or overpredict the responses. However, as a practical matter—especially in light of the staff time and costs of collecting data, estimating models, and deriving elasticities—there may be no alternative other than to apply elasticities found in the literature to a particular situation. The most robust elasticity measures in the literature frequently come from disaggregate models, and so sometimes one must live with the shortcomings of applying elasticities derived from individual behavior to larger population groups not necessarily segmented into markets. However, it is important to understand the implications of those shortcomings and to explain them to users of the travel demand estimates.

Some tabulations of elasticities from the literature appear in Appendix 8A. Future editions of this manual will provide comprehensive and systematic tables of elasticities that will be of direct use to the practitioner.

The following are examples of how to calculate the effect of various demand management options by drawing upon information in the literature:

Example 1: A city has a flat rate transit fare of $1.00 during rush hours. Total travel in a corridor between two zones is 12,000 people during rush hour. Transit ridership is 1,000, shared-ride automobile travel is 1,000, and driver-only automobile travel is 10,000. Determine the effect on each mode of reducing transit fare by 25 percent.

Answer: A key literature source describing the influence of fare reductions on bus ridership, based on case studies, indicates that the transit ridership elasticity with respect to fare reductions is in the range from −0.20 to −0.10 (hypothetical). Applying the formula for the own arc elasticity reveals the change in transit ridership is in the range from 25 to 50.

$$\text{arc } \in_S^V = \frac{S}{V} * \frac{\Delta V}{\Delta S}$$

The lower bound of ridership change is calculated as follows:

$$-0.10 = \frac{1.00}{1{,}000} * \frac{\Delta V}{-0.25}$$

$$\Delta V = -0.10 * \frac{1{,}000}{1.00} - 0.25 = 25$$

The upper bound of ridership change is calculated below:

$$-0.20 = \frac{1.00}{1{,}000} * \frac{\Delta V}{-0.25}$$

$$\Delta V = -0.20 * \frac{1{,}000}{1.00} - 0.25 = 50$$

The literature reveals little information on the effect of transit fare reductions on the demand for other modes based on case studies. However, estimates are available from demand models on own and cross elasticities with respect to changes in bus fares.

Example 2: A reference (hypothetical) indicates that the own fare elasticity of transit is approximately −0.26 and the cross elasticities of driver only and shared ride with respect to transit fare are 0.02 and 0.06, respectively. Determine the changes in the demand for each mode due to a 25 percent transit fare reduction.

Answer: The arc elasticity of mode i (i = transit) with respect to transit fare is from the previous equation:

$$\text{arc } \in_{\text{Fare}}^{Vi} = \frac{\text{Fare of } i}{V_i} * \frac{\Delta V_i}{\Delta(\text{Fare of } i)}$$

The change in transit ridership is determined as follows:

$$-0.26 = \frac{1.00}{1{,}000} * \frac{\Delta V_i}{-0.25}$$

$$\Delta V_i = -0.26 * \frac{1{,}000}{1.00} * -0.25 = 65$$

The arc cross elasticity of mode j (j = driver-only or shared-ride automobile travel) with respect to a change in the fare of mode i (again, i = transit) is as follows:

$$\text{arc } \in^{V_j}_{\text{Fare of } i} = \frac{\text{Fare of } i}{V_j} * \frac{\Delta V_j}{\Delta(\text{Fare of } i)}$$

The change in driver-only automobile travel is calculated as follows:

$$+0.02 = \frac{1.00}{1{,}000} * \frac{\Delta V_{auto}}{-0.25}$$

$$\Delta V_{auto} = +0.02 * \frac{1{,}000}{1.00} * -0.25 = -50$$

The calculation of the change in shared-ride travel follows:

$$+0.06 = \frac{1.00}{1{,}000} * \frac{\Delta V_{share}}{-0.25}$$

$$\Delta V_{share} = +0.06 * \frac{1{,}000}{1.00} * -0.25 = -15$$

Example 3: Estimate the effect on single-occupancy vehicle travel in a suburb-to-suburb corridor of increasing the daily rush-hour parking costs from an average of \$3.00 to \$20.00. One-way, driver-only vehicle trips by automobile and light trucks total 23,000 daily in the corridor.

Answer: An article in the literature (hypothetical) indicates a good estimate of the arc elasticity of driver-only vehicle travel with respect to parking cost pertinent to the situation under study is −0.017.

$$\text{arc } \in^{V_{sov}}_{\text{Parking}} = \frac{\text{Parking Costs}}{V_{sov}} * \frac{\Delta V_{sov}}{\Delta\text{Parking Costs}}$$

$$-0.017 = \frac{\$3.00}{23{,}000} * \frac{\Delta V_{sov}}{(\$20 - \$3)}$$

$$\Delta V_{sov} = -0.017 * \frac{2{,}300}{\$3.00} * \$17 = -2{,}216$$

Elasticities Derived from Models

If the literature does not contain transferable information on the elasticity of demand, the gap can be filled by developing travel demand models that are specific to the market under investigation. This approach requires data collection according to a statistically sound plan, statistical estimation of models, and validation. Ideally validation should occur on a dataset other than the one used to estimate the model. The various approaches to modeling were discussed in Chapter 5. Once a model has been developed for predicting traffic volume for a mode, the elasticity can be derived by calculus. The elasticities can then be used to estimate the effect of various demand management actions as in these examples:

Example 4: An aggregate demand function, y, for intercity bus travel, known as the *Cobb-Douglas model*, with the following functional form, was estimated:

$$y = a_0 x_1^{a_1} x_2^{a_2} x_3^{a_3}$$

where

x_1 = fare,
x_2 = travel time, and
x_3 = frequency of trips per day.

The demand function was estimated to have the following coefficients:

$a_0 = 3.214$,
$a_1 = -0.25$,
$a_2 = -0.103$, and
$a_3 = +0.107$.

The derivation of the own point elasticity of a Cobb-Douglas function shows that the elasticity of a variable is equal to its exponent:

$$\frac{dy}{dx_1} = a_1 a_0 x_1^{a_1 - 1} x_2^{a_2} x_3^{a_3}$$

$$\in^y_{x_1} = \frac{x_1}{y}\frac{dy}{dx_1} = \frac{x_1}{a_o x_1^{a_1} x_2^{a_2} x_3^{a_3}} * a_1 a_0 x_1^{a_1 - 1} x_2^{a_2} x_3^{a_3} = a_1$$

Similarly,

$$\in^y_{x_2} = a_2$$

$$\in^y_{x_3} = a_3$$

Therefore, the elasticities of the model above are as follows:

$$\in^y_{\text{Fare}} = -0.25$$

$$\in^y_{\text{Time}} = -0.103$$

$$\in^y_{\text{Freq}} = +0.107$$

Suppose the corridor daily intercity bus ridership is equal to 745. The above elasticities imply a change in intercity bus ridership due to various demand management strategies corresponding to each of the variables in the model.

The change in ridership due to a 15 percent reduction in fares from the current level of \$35.00 is as follows:

$$dy = \frac{y}{\text{Fare}} * d(\text{Fare}) * \in^y_{\text{Fare}} = \frac{745}{35.00}(-5.25)(-0.25)$$

$$= 28 \text{ riders per day}$$

The change in ridership due to a 10 percent reduction in travel time from the current 4 hr follows:

$$dy = \frac{y}{\text{Time}} * d(\text{Time}) * \in^{y}_{\text{Time}} = \frac{745}{4}(-0.4)(-0.103)$$
$$= 8 \text{ riders per day}$$

Following is the change in ridership due to a 100 percent increase in frequency from the current 2 times per day:

$$dy = \frac{y}{\text{frequency}} * d(\text{frequency}) * \in^{y}_{\text{Freq}} = \frac{745}{2}(+2)(+0.107)$$
$$= 80 \text{ riders per day}$$

Example 5: Transit's current share of a total of 321,000 transit and automobile work trips is 0.09. The average out-of-pocket costs of transit relative to automobile is −$0.80. The average in-vehicle travel time of transit relative to automobile is 10 min, and the average access and wait time of transit relative to automobile is 20 min. What is the effect on transit and automobile riderships of increasing transit out-of-pocket costs relative to automobile by 10 percent, reducing transit in-vehicle travel time relative to automobile by 10 percent, and reducing transit access and wait time relative to automobile by 25 percent?

Answer: A disaggregate demand model (binary logit model) for predicting the probability of choosing transit versus automobile for work trips was previously estimated for this market and has the following functional form:

$$P(\text{transit}) = \frac{1}{1 + e^{-U}}$$

where U is a linear function describing the disutility of transit relative to automobile.

$$U = a_0 + a_1x_1 + a_2x_2 + a_3x_3$$

where

x_1 = transit out-of-pocket costs relative to automobile,
x_2 = transit in-vehicle travel time relative to automobile, and
x_3 = transit access and wait time relative to automobile.

The demand function was estimated to have the following coefficients:

$a_0 = 2.83$,
$a_1 = -0.18$,
$a_2 = -0.24$, and
$a_3 = -0.13$.

The elasticity of the choice probability with respect to a change in a LOS variable x_i is as follows:

$$\in^{P(\text{Transit})}_{X_i} = a_i\overline{x_i}[(1 - P(\text{transit})]$$

where

a_i = coefficient of x_i in the utility function,
$\overline{x_i}$ = mean value of x_i, and
$P(\text{transit})$ = transit choice probability.

Therefore, the elasticities of the choice probability for the binary logit model with the coefficients shown above, the current mean values for each variable, and the current mode split are as follows:

$$\in^{P(\text{Transit})}_{X_1} = -0.18(-0.80)(0.91) = +0.131$$

$$\in^{P(\text{Transit})}_{X_2} = -0.24(10)(0.91) = -2.184$$

$$\in^{P(\text{Transit})}_{X_3} = -0.13(20)(0.91) = -2.366$$

These elasticities imply a change in transit and automobile riderships due to changes in the corresponding demand management strategies consisting of a reduction in transit fare, in vehicle travel time, and in access and wait time relative to automobile.

The change in transit ridership due to a change in variable, x_i, can be expressed as follows:

$$d(\text{Transit Ridership}) = d[P(\text{transit})] * (\text{Total Ridership})$$
$$= \left[\frac{P(\text{Transit})}{X_i} * dx_i * \in^{P(\text{Transit})}_{x_i}\right] * (\text{Total Ridership})$$

Therefore, using the point elasticity calculated above, the change in transit ridership due to a 10 percent increase in relative out-of-pocket cost (i.e., transit cost decreases relative to automobile, or automobile cost increases relative to transit) can be estimated as follows:

$$\left[\frac{0.09}{0.8} * (+0.08) * (+0.13)\right] * (321{,}000) = +3{,}756$$

This results in total transit ridership increasing to (0.09)(321,000) + 3,756 = 32,646 (from a base value of 28,890) and automobile ridership dropping to (0.91)(321,000)−3,756 = 288,354 (from a base value of 292,110). (Note: Actual revised transit probability is equal to 0.0911 or a total transit ridership of 29,243.)

The change in transit ridership due to a 10 percent reduction in relative in-vehicle time follows:

$$\left[\frac{0.09}{10} * (-1) * (-2.184)\right] * (321{,}000) = +6{,}309$$

This results in total transit ridership increasing to (0.09)(321,000) + 6,309 = 35,199 while automobile ridership drops to (0.91)(321,000) − 6,309 = 285,801.

(Note: Actual revised transit probability is equal to 0.1116 or a total transit ridership of 35,823.)

Following is the change in transit ridership due to a 25 percent reduction in relative access and wait time:

$$\left[\frac{0.09}{20} * (-5) * (-2.366)\right] * (321{,}000) = +17{,}088$$

This results in total transit ridership increasing to (0.09)(321,000) + 17,088 = 45,978 while automobile ridership drops to (0.91)(321,000) − 17,088 = 275,022. (Note: Actual revised transit probability is equal to 0.16 or a total transit ridership of 51,360.)

Example 6: A rail or truck mode share model has been estimated as a function of relative logistics cost based on the ratio of rail to truck costs. The coefficients of a simple two-parameter model were estimated by simple log-linear regression resulting in the following rail or truck competition model:

$$P(\text{rail}) = \frac{1}{1 + Ae^{b*lcr/lct}}$$

$$P(\text{truck}) = 1 - P(\text{rail})$$

where lcr/lct = the logistics cost ratio of rail to truck.

The demand elasticity of rail with respect to lcr is

$$\in_{lcr}^{P(\text{rail})} = \beta \frac{lcr}{lct}[1 - P(\text{rail})]$$

Similarly, the demand elasticity of rail with respect to lct is

$$\in_{lct}^{P(\text{rail})} = -\beta \frac{lcr}{lct}[1 - P(\text{rail})]$$

These elasticities can be applied to determine the impact of a change in the logistics cost ratio of rail. First, we develop the probability of rail for a base case, with

$$A = 0.03829,\ lcr = 2$$

$$B = 3.71455,\ lct = 1$$

$$P(\text{rail}) = \frac{1}{1 + 0.03829 * e^{3.71455*(2/1)}} = 0.015$$

$$P(\text{truck}) = 1 - 0.015 = 0.985$$

For the modal share model above the elasticity of rail with respect to lcr is

$$\in_{lcr}^{P(\text{rail})} = -0.03829 * (2/1) * (1 - 0.015) = -0.075$$

Now, if there is a change in the logistics cost for rail so that $\Delta lcr = -0.5$, we can use the point elasticity to estimate the corresponding change in the rail choice probability as follows:

$$\Delta P(\text{rail}) = P(\text{rail}) * \frac{\Delta lcr}{lcr} * \in_{lcr}^{P(\text{rail})}$$

$$\Delta P(\text{rail}) = 0.015 * \frac{-0.5}{2} * (-0.075) = 0.00028$$

$$P'(\text{Rail}) = 0.015 + 0.00028 = 0.01528$$

(Note: Actual probability if we change the value of lcr to 1.5 in the equation for P(rail), is equal to 0.09.)

If there is a change in the logistics cost for truck so that $\Delta lct = 2$ then, with the elasticity formula, the change in rail choice probability is as follows:

$$\Delta P(\text{rail}) = 0.015 * \frac{\Delta lct}{lct} * \in_{lct}^{P(\text{rail})}$$

$$\Delta P(\text{rail}) = 0.015 * (2/1) * (+0.08) = 0.0024$$

or the new P(rail) is 0.015 + 0.0024 = 0.0174. (Note: Substituting the value $lct = 3$ in the equation for P(rail) gives a new choice probability of 0.68.)

The example above demonstrates the limitations of applying elasticities in predicting changes in demand as a result of changes in variables. Generally, if the demand elasticity is not constant, incremental analysis with elasticities can be used only for small changes in the values of the parameters affecting demand.

Inferring Elasticities from a Case Study

Although it may not be possible to find transferable elasticities in the literature and it may be too costly to develop a new demand model, another option open to the analyst is to infer an elasticity from a case study. Doing this requires an assumption that no variables cause demand to change other than the variable of interest. Although this assumption never completely holds in practice, an elasticity derived from a case study nonetheless sometimes appears sufficiently valid for purposes of assessing a demand management option.

Example 7: What would be the effect of increasing average daily downtown parking costs by $0.50 from $3.10 per day on the 100,000 people driving alone in a corridor connecting a suburb with the CBD in City X. A case study regarding a suburban-commuter corridor in City Y similar to the one in City X revealed that a 20 percent increase in parking costs resulted in an 8 percent reduction in driver-only trips. In City Y the initial number of people driving alone to work was 245,000 and the initial average daily parking cost was $2.50.

Based on the case study, the elasticity of driving alone with respect to a change in parking cost is

$$\in_{\text{Parking}}^{\text{Driving}} = \frac{\frac{\Delta V}{V}}{\frac{\Delta S}{S}} = \frac{(-0.08)}{(+0.20)} = -0.4$$

Thus, driving alone would be expected to decline by 6,452 in City X based on the elasticity derived above from the case study in City Y, as follows:

$$\Delta V = \frac{V}{S} * \Delta S * \in_{\text{Parking}}^{\text{Driving}}$$

$$= \frac{(100,000)}{3.10}(+0.50)(-0.4) = -6.452$$

8.8.2 Incremental Analysis Using Logit Models

The incremental form of the logit model is a powerful, low-cost sketch planning tool for analysis when the objective is to simultaneously assess the relative changes among a set of mutually exclusive alternatives that result from changes in one or more variables.

This type of model requires information only on the magnitude of change of each variable of interest that is built into the model and the initial fraction of the population choosing each alternative in the choice set. Therefore, there is no need to project the values of each variable included in the logit model in order to provide estimates of changes in demand, which can be time consuming and costly. One has only to focus on changes in the variables of interest.

The formula for the incremental logit model as described earlier is as follows:

$$P'_i = \frac{P_i e \Delta^{U_i}}{\Sigma P_j e^{\Delta U_j}}$$

where

P'_i = the revised choice probability for mode i,
P_j = the base share for each modal option j, including mode i,
U_j = the change in the utility function for option j,
e = base of natural logarithm (2.71828 . . .), and
j = a modal option.

The utility is a function of the attributes of each possible choice and other explanatory variables such as socioeconomic factors influencing choice:

$$U_i = a_{i0} + a_{i1}x_{i1} + a_{i2}x_{i2} + \ldots a_{in}x_{in}$$

where $x_{i1}, \ldots, x_{in}$ are n variables in the utility function for the ith option and $a_{i1}, \ldots, a_{in}$ are their corresponding coefficients. If the utility function is linear, the effect of a change in one or more variables on U_i can be written as follows:

$$\Delta U_i = a_{i1}\Delta x_{i1} + a_{i2}\Delta x_{i2} + \ldots a_{in}\,\Delta x_{in}$$

where the Δ values may be positive, negative, or zero. If Δ is zero, there is no change in a variable. Therefore, if one knows the change in utility for each option one can easily calculate the revised share of each option out of the total number of individuals making a choice.

The incremental logit model is derived from a multinomial logit model estimated from disaggregate behavioral data (i.e., pertaining to individual travelers or shippers) that relates actual choices or stated choices (behavioral intentions) to variables that can explain the variation in the choices among individuals. With regard to person modal choice, these variables are attributes of the modes and socioeconomic characteristics of the travelers.

Indeed, the rationale presented for using the incremental form of the logit model for predicting changes in mode share is based on an exceedingly pragmatic approach to demand forecasting. It recognizes that transportation analysts in state, regional, and local agencies frequently do not have the staff or financial resources to do complex demand forecasting in a multimodal framework. Although the method proposed here does not involve rigorous statistical or economic modeling, it appears to have strong justification in supporting sketch planning for first-order approximations of changes in mode split due to various factors influencing demand. Experts in demand forecasting are often reluctant to use models where the constant coefficient of the utility functions are irrelevant. However, such a procedure is warranted on both the basis of the need for a low-cost method of demand forecasting and the derivation of the incremental form of the logit model from the logit model itself, which results in the constant coefficients of each utility function dropping out.

8.8.2.1 *Person Trips*

Application of the incremental form of the logit model to person trips requires only that the analyst have available a logit model that was previously estimated and relevant to the situation being examined. The logit model will usually be described in tabular and mathematical form. There is a need for a comprehensive set of models to address every type of choice individuals make with regard to travel (i.e., choice of origin, destination, whether to travel, time of travel, mode, and route). This applies to trip purposes for (1) urban and local trips for different classes of cities and (2) for intercity trips in different classes of corridors. It is anticipated that future research will result in such a comprehensive set of models, which can then be included in a future version of this manual.

To apply the incremental form of the logit model to assessing demand management options, one must perform the following steps:

1. Identify the demand management options.
2. Select a logit model that includes attributes (variables) corresponding to the demand management options.
3. Determine the magnitude of change in the variables of interest that reflects the intensity of each demand management option.

TABLE 8.4 Worksheet for estimating revised modal shares using incremental analysis

URBAN AREA: _____
MODEL SYSTEM: _____

	1	2	3	4	5	6	7	8	9	10
					1 x 2 + 3 x 4		e^S	6 x 7	8 / Σ	9 - 6
	VARIABLE 1 _____		VARIABLE 2 _____		Total Change in Utility	Base Mode Share	Approximate Factor by Which P Changes	Weighted Change in Factor by Which P Changes	Revised Mode Share	Change in P
MODE	Utility Coefficient	Change in Variable 1	Utility Coefficient	Change in Variable 2	ΔU	P	$e^{\Delta U}$	$P * e^{\Delta U}$	$\frac{P * e^{\Delta U}}{\%} = P^1$	$P^1 - P$
Mode 1										
Mode 2										
Mode 3										
Mode 4										
Mode 5										

Sum Col 8 = Σ = _____

4. Identify the initial percentage of users exercizing each alternative from the choice set and as a percentage of the total population.
5. If the model includes socioeconomic variables, separate the market into different categories by key socioeconomic factors.
6. Complete the worksheet shown in Table 8.4 for each market segment by doing the following:
   a. Enter the coefficient for each variable corresponding to the demand option under consideration (or for each term containing the variable) into the appropriate column.
   b. Enter the magnitude of the change for each variable into the appropriate column.
   c. Enter the initial proportion (before changes) of people selecting each alternative.
   d. Complete the worksheet by solving for the values of the expressions in the remaining columns of Table 8.4.

The assumption thus far is that a logit model relevant to a situation either has been estimated by an agency faced with the particular problem or a transferable model can be found in the literature. Frequently, however, neither will be available for the following reasons:

- A model will include some variables of interest but not others.
- A demand management option (e.g., congestion pricing or gas price increase) implies a change in the variable of interest (e.g., out-of-pocket travel costs) substantially outside the range of that variable in the dataset upon which the model was estimated (e.g., gas price in the dataset was in the range of 1.00 to 1.25, whereas the policy option under consideration was to double or triple gas price).
- A new technology is involved, implying a choice has attributes for which there is no historical precedent. Therefore, no data based on actual behavior or historical information can be used as a basis for predicting the change in demand.

The following subsections describe how to develop coefficients for use in an incremental logit model for predicting a change in person trips when existing disaggregate models are inadequate for the reasons stated above.

Borrowing Coefficients

If a model lacks a coefficient that directly relates to an attribute of choice pertinent to a demand management option, frequently it is possible to borrow a coefficient from another model. The condition for transferability is that the

donor model was estimated for a market with characteristics similar to the market for which the receiver model was estimated. This implies similarities in the following characteristics:

1. The choice set or alternatives,
2. The attributes of the choices,
3. The attributes of the decision makers, and
4. The transportation environment.

Example 8: City A uses a disaggregate multimodal demand forecasting model, which lacks sensitivity to biking distances. Policy makers in City A are interested in growth management policy options that encourage residential and commercial development conducive to biking. In particular, policy makers in City A have asked the question "What would be the effect on modal split and commuter travel if, through growth management, we could reduce the distance between home and work by 10 percent on average?" City B, which is similar in size and urban form to City A and has similar modal options, recently estimated a new, home-based work-trip modal-split model that includes a coefficient for the variable "bike distance to work" in the utility function for the bike mode. The utility equation for the bike mode has a component that identifies which age group the individual is in: (1) 25 or younger or (2) older than 25. The coefficients for the two age groups are −0.479 and −0.85, respectively. These coefficients can be borrowed from the modal-split model from City B and used for analysis of the growth management policy in City A. If City A's total home-based work trips number 179,000, the modal shares for the age group 25 or younger are 0.78 driver only, 0.07 shared ride, 0.07 mass transit, 0.05 biking, and 0.03 walking. For the age group younger than 25, the only difference is that the transit share is 0.08 and the bike share is 0.04. Furthermore, the breakdown of the tripmakers by age is 30 percent (25 or younger) and 70 percent (older than 25). The current average distance to work is 7 mi; the expected change in modal shares for the two age groups responding to a 10 percent reduction in average bike distance is shown in the worksheet presented as Table 8.5.

Inferring Coefficients from Elasticities

There is another way to use the incremental form of the logit model to analyze demand management options when there is no statistically estimated model or relevant coefficient. One may infer the coefficient from information regarding elasticity of demand. This is easily accomplished by using the following formulas for the own and cross elasticities of demand for the logit model. Solving for the coefficient in the equations above, the results are as follows:

TABLE 8.5 Worksheet for Example 8: Evaluating growth management strategy

URBAN AREA: City
MODEL SYSTEM: Intracity Work Trips Segmented by Age

	1	2	3	4	5	6	7	8	9	10
					1 x 2 + 3 x 4		e^5	6 x 7	8 / Σ	9 - 6
	VARIABLE 1 Bike Distance		VARIABLE 2 _____		Total Change in Utility	Base Mode Share	Approximate Factor by Which P Changes	Weighted Change in Factor by Which P Changes	Revised Mode Share	Change in P
MODE	Utility Coefficient	Change in Variable 1	Utility Coefficient	Change in Variable 2	ΔU	P	$e^{\Delta U}$	$P * e^{\Delta U}$	$\frac{P * e^{\Delta U}}{\%} = P^1$	$P^1 - P$
Drive Alone		0			0	0.78/0.78	1/1	0.78/0.78	0.76/0.76	-0.02/-0.02
Shared Ride		0			0	0.07/0.07	1/1	0.07/0.07	0.07/0.07	0/0
Transit		0			0	0.07/0.08	1/1	0.07/0.08	0.07/0.07	0/-0.01
Bike	-0.48/-0.85	-0.7			+0.336/+0.6	0.05/0.04	1.4/1.8	0.07/0.07	0.07/0.07	+0.02/+0.03
Walk		0			0	0.03/0.03	1/1	0.03/0.03	0.03/0.03	0/0

Sum Col 8 = Σ = 1.02/1.03

The coefficient given the own elasticity of demand follows:

$$a_{in} = \epsilon^{P_i}_{X_{in}} / (\overline{X_{in}}(1 - P_i))$$

Following is the coefficient given the cross elasticity of demand:

$$a_{jn} = - \epsilon^{P_j}_{X_{jn}} / (\overline{X_{jn}}(1 - P_j))$$

To infer the coefficient in a modal-split model, it is therefore necessary to have only three pieces of information:

1. The elasticity or cross elasticity of demand,
2. The modal share, and
3. The mean value of the variable of interest corresponding to the demand management option.

After obtaining the coefficient, it is then possible to analyze the demand management option that it corresponds to by using the incremental form of the logit model.

Example 9: City P is interested in improving accessibility to City Q 500 mi away, by improving intercity air, rail, and bus service. The current modal split in this corridor for intercity business trips is 74 percent air; 15 percent rail; 5 percent bus; and 6 percent automobile. The mean total travel time (in-vehicle plus access time) in minutes per mile is 0.2 air, 1.4 rail, 1.4 bus, and 1.0 automobile. City P does not have a multimodal demand model for predicting the effect of such accessibility improvements. However, a marketing study does exist that estimated the choice probability elasticity of demand with respect to changes in access and line-haul time for each of these four modes based on an analysis of other similar city pairs. The choice probability elasticities are −0.0175 air, −1.81 rail, −0.23 bus, and −0.08 automobile. The corresponding inferred coefficients are shown below:

Mode	Probability Elasticity		Mean Travel Time		$(1-P_i)$		Inferred Coefficient
Air	-0.0175	÷	(0.2	x	0.26)	=	-0.337
Rail	-1.81	÷	(1.4	x	0.85)	=	-1.521
Bus	-0.23	÷	(1.4	x	0.95)	=	-0.173
Auto	-0.08	÷	(1.0	x	0.94)	=	-0.085

The worksheet in Table 8.6 shows the result of sample calculations using the inferred coefficients and describes what would happen if line-haul travel time by rail was reduced by 15 percent from the current level of 7 hr and if air, rail, and bus access times were all improved by 5 per-

TABLE 8.6 Worksheet for Example 9: Evaluating intercity corridor enhancement option

URBAN AREA: Intercity
MODEL SYSTEM: Intercity Business Trips

	1	2	3	4	5	6	7	8	9	10
					1 x 2 + 3 x 4		e^5	6 x 7	8 / Σ	9 - 6
	VARIABLE 1 Total Travel Time		VARIABLE 2 _____		Total Change in Utility	Base Mode Share	Approximate Factor by Which P Changes	Weighted Change in Factor by Which P Changes	Revised Mode Share	Change in P
MODE	Utility Coefficient	Change in Variable 1	Utility Coefficient	Change in Variable 2	ΔU	P	$e^{\Delta U}$	$P * e^{\Delta U}$	$P * e^{\Delta U} = P^1$ %	$P^1 - P$
Air	-0.337	-0.025			+0.002	0.74	1.002	0.741	0.46	-0.28
Rail	-1.521	-1.07			+1.63	0.15	5.1	0.765	0.47	+0.32
Bus	-0.173	-0.029			+0.005	0.05	1.005	0.050	0.03	-0.02
Auto	-0.085	0			0	0.06	1	0.060	0.04	-0.02

Sum Col 8 = Σ = 1.616

cent from the current average levels of 30 min, 25 min, and 35 min, respectively.

Inferring Coefficients from Case Studies

A third possibility for analysts lacking a relevant model for analyzing a demand management option is to infer coefficients from case studies. Often it is possible to identify a before-and-after study that describes how demand will change in response to change in a variable of interest.

Example 10: An airport in Metropolitan Region M wants to significantly reduce the access time for the 18,000 business travelers who travel daily via public transportation between the airport and key downtown locations such as the convention center, major hotels, and government buildings. Currently, transit's mode share in Metropolitan Region M is 0.20, the mean travel time between the airport and downtown is 30 min, and the mean fare is $9.00 per trip. Planners do not have a model that can reliably predict how business travelers in the metropolitan region will trade off the improved accessibility and the potential increased costs from providing the improved accessibility. However, Metropolitan Region N recently completed a major initiative to reduce the travel time of taking mass transit between major downtown business locations and its airport. A case study documenting the accomplishments of the initiative revealed that a 13 percent reduction in travel time between the airport and downtown resulted from an increase in the frequency and timeliness of public transportation service. At first there was no fare change. The result was a 4 percent increase in the probability of business travelers using transit in the corridor that connects the airport and downtown in Metropolitan Region N. This change was from an initial level of 25,000 daily transit trips, with transit's mode share at 0.12 and current mean travel time 35 min. After a trial period, Metropolitan Region N increased the average cost of rides between the airport and downtown by $2.00 per trip from $10.00 in order to cover the costs of improved service. The result was that the probability of transit usage dropped by 2 percent, with a net increase of 2 percent in the probability of transit ridership.

Metropolitan Region M can infer travel time and fare elasticities from this case study regarding Metropolitan Region N and, in turn, deduce respective travel time and fare coefficients of a logit model that can be used in incremental analysis. The implied choice probability with respect to travel time for Metropolitan Region N is as follows:

$$\epsilon_{\text{time}}^{\text{transit}} = \frac{\text{percent change in probability of transit}}{\text{percent change in transit time}}$$

$$= \frac{+4}{-3} = -0.308$$

The corresponding coefficient for Metropolitan Region M follows:

$$a_{\text{transit,time}} = (-0.308)/(30 * (1 - 0.12)) = -0.01$$

The implied probability choice elasticity with respect to transit fare is as follows:

$$\epsilon_{\text{fare}}^{\text{transit}} = \frac{\text{percent change in probability of transit}}{\text{percent change in transit fare}}$$

$$= \frac{-2}{20} = -0.1$$

The corresponding coefficient for Metropolitan Region M follows:

$$a_{\text{transit,fare}} = (-0.1)/(10 * (1 - 0.16)) = -0.012.$$

The expected changes in the modal split and volumes in the corridor between the airport and downtown in Metropolitan Region M as a result of a 6 percent reduction in travel time and a $3.00 increase in fares, and given that current modal splits for business trips are 25 percent rental car, 50 percent taxi, 20 percent mass transit, and 5 percent other, are shown in Table 8.7.

Using Stated Preference Techniques

No data or case studies exist for an adequate assessment of the impact of demand management options that involve altogether new policy options or that exploit new or emerging technology. Examples are data on congestion pricing on the Interstate System, eliminating free parking at all suburban work sites, doubling the price of gasoline, mandating that employers provide computers and modems to workers for telecommuting, using advanced traveler information systems that involve in-vehicle routing and navigation aids, and using electronic fare media on mass transit and paratransit services throughout a city.

Traditional demand forecasting models are developed based on actual behavior. Such models are limited in the kinds of options that can be analyzed because they are rooted in historical behavior, whether it is very recent or in the more distant past.

An alternative approach is to develop models based on what people say they will do. Therefore, there are two classes of demand models.

Revealed preference models. Demand forecasting models that have been estimated based on data that describe what people actually do (and thus, based on past behavior) reveal their preferences among various alternatives.

Stated preference models. Demand forecasting models that have been estimated based on data that describe what people say they will do, thus revealing their inten-

TABLE 8.7 Worksheet for Example 10: Evaluating airport demand management options

URBAN AREA: Metropolitan Area
MODEL SYSTEM: Business Trips between Airport and Downtown

	1	2	3	4	5	6	7	8	9	10
					1 x 2 + 3 x 4		e^5	6 x 7	8 / Σ	9 - 6
	VARIABLE 1 Travel Time		VARIABLE 2 Fare		Total Change in Utility	Base Mode Share	Approximate Factor by Which P Changes	Weighted Change in Factor by Which P Changes	Revised Mode Share	Change in P
MODE	Utility Coefficient	Change in Variable 1	Utility Coefficient	Change in Variable 2	ΔU	P	$e^{\Delta U}$	$P * e^{\Delta U}$	$P * e^{\Delta U} = P^1$ %	$P^1 - P$
Transit	-0.01	-1.8	-0.012	+3	+0.018	0.20	1.018	0.204	0.20	0
Car Rent		0		0	0	0.25	1	0.25	0.25	0
Taxi		0		0	0	0.50	1	0.50	0.50	0
Others		0		0	0	0.05	1	0.05	0.05	0

Sum Col 8 = Σ = 1.004

tions about a future situation they may not have experienced.

Stated preference models are based on experiments conducted in a laboratory or by computer simulation or they are based on the use of a survey instrument where people are faced with various weighted factors believed to most likely influence their choice. Respondents describe what choice they will make in response to a hypothetical situation. The strength or levels of each factor believed to influence consumer choice reflect a rigorous experimental design that has a specific mathematical pattern. An example of such a survey instrument used in a study of urban work trips in Wisconsin appears in Table 8.8 (*6*). Here a respondent is asked how he or she would respond to a variety of situations, each of which is determined by the levels of each factor believed to be most important in making a choice between driving alone and bicycling to work. In typical survey instruments containing these experimental designs, the number of factors influencing choice is usually limited to seven or fewer because respondents have difficulty weighing more than seven in such an experiment. Catalogues of experimental designs are available for constructing survey instruments and for designing laboratory simulations.

Experiments such as these will produce a dataset for each respondent that relates a choice to the various factors that influence the choice. One can then estimate a model for predicting choice based on this data set. Implicit in the process is the estimation of one or more utility functions, depending on whether the choice is between two or more options. These utility functions capture the tradeoffs embedded in the experiment. There are various philosophies and approaches to estimating these models. The broader approaches are frequently referred to in the literature as one of the following: functional measurement, conjoint analysis, or direct utility assessment. Specific estimation procedures that are frequently used are linear regression and logit estimation.

The value of stated preference techniques is that they can be used to assess the impact on demand management options for which there is no historical precedent, either because the level of a variable of interest is outside the data range, there is no prior experience with the demand management option, or a new technology is involved.

For example, in the survey instrument above, which pertains to urban bicycle trips, situations are posed to the respondents that are completely outside their experience, such as

TABLE 8.8 Survey instrument for stated preference technique (Wisconsin) (*6*)

UNDER WHAT SITUATIONS WOULD YOU DRIVE ALONE OR RIDE YOUR BIKE?

Consider a trip short enough so that driving alone in an automobile or riding a bicycle are realistic choices. Assume the weather is nice.

Below are a number of factors describing eight different situations where you are faced with choosing whether to drive alone or ride a bike to make a one or three mile trip.

Look at each situation across the entire line and please answer in the last column to the right how likely you are to drive alone or ride a bike.

	AUTO FACTORS		BIKE FACTORS				PLEASE- ANSWER IN THIS COLUMN: HOW LIKELY ARE YOU TO DRIVE ALONE IN YOUR AUTO OR RIDE YOUR BIKE? (CIRCLE A NUMBER)				
	Gas Availability	Gas Price	Length of Trip	Whether There Is a Bike Lane	Street Surface	Level of Auto and Truck Traffic Along Route	Always Auto	Probably Auto	In-different	Probably Bike	Always Bike
SITUATION 1	Ample Supply	$2.60/gallon	3 miles	Marked bike lane in street	Smooth	Quiet	1	2	3	4	5
SITUATION 2	Ration of 10 gallons/week*	$2.60/gallon	1 mile	Marked bike lane in street	Smooth	Busy	1	2	3	4	5
SITUATION 3	Ration of 10 gallons/week*	$1.30/gallon	3 miles	None	Smooth	Busy	1	2	3	4	5
SITUATION 4	Ample Supply	$2.60/gallon	1 mile	None	Rough	Busy	1	2	3	4	5
SITUATION 5	Ration of 10 gallons/week*	$1.30/gallon	1 mile	Marked bike lane in street	Rough	Quiet	1	2	3	4	5
SITUATION 6	Ample Supply	$1.30/gallon	1 mile	None	Smooth	Quiet	1	2	3	4	5
SITUATION 7	Ample Supply	$1.30/gallon	3 miles	Marked bike lane in street	Rough	Busy	1	2	3	4	5
SITUATION 8	Ration of 10 gallons/week*	$2.60/gallon	3 miles	None	Rough	Quiet	1	2	3	4	5

*If your car gets 15 miles per gallon, you can travel 150 miles per week.

gas rationing, the doubling of gas prices, bicycle facilities separated from traffic, and smooth riding surfaces.

This experiment, presented in survey form, was part of a set of four instruments that were used to estimate urban work trip models for the state of Wisconsin in the aftermath of the energy crisis of the late 1970s. A total of 16,500 instruments were mailed with drivers license renewals, and the models were finally estimated based on the responses of 3,500 individuals.

Separate urban work trip models were developed for four classes of urban areas: one large city (Milwaukee), one medium city (Madison), three small cities (Eau Claire, Janesville, and Beloit), and a region experiencing the state's fastest growth and containing a number of small to medium cities (Fox River Valley, which covers Green Bay, Oshkosh, Appleton, Neenah, and Menasha).

Linear regression techniques were used to develop utility functions, which were then folded into a multinomial logit model. A validation procedure was used to determine whether the coefficients of the utility function based on stated preferences differed significantly from actual behavior, given data describing the choices people actually made and the strengths of the factors influencing their choices when the study was performed. Some minor adjustments of the coefficients in the models resulted from the validation procedure as shown in Table 8.9 (*6*).

TABLE 8.9 Wisconsin urban work trip mode choice model (*6*)

VARIABLE NAME AND DEFINITION	URBAN AREA			
	Madison	Milwaukee County	Fox River Valley Cities	Other Cities
AUTO UTILITY: (Ua)	COEFFICIENTS			
CA - Auto Constant	-5.271	-4.697	-4.448	-5.051
GA - Gas Availability: 1 if ample supply 0 if rationing	-0.320 (-6.30)	-0.377 (-6.57)	-0.318 (-7.93)	-0.315 (-8.99)
GP - Gas Price ($/month)	-0.234 (-5.48)	-0.320 (-6.62)	-0.284 (-8.41)	-0.284 (-9.59)
PK - Parking Cost ($/month)	-0.016 (-6.93)	-0.017 (-6.91)	-0.017 (-8.77)	-0.016 (-9.82)
WT - Wait Time to Buy Gas (minutes)	-0.008 (-0.89)	-0.004 (-0.38)	-0.013 (-2.30)	-0.007 (-1.29)
IN - Annual Household Income (Thousand of 1990$)	+0.012 (6.02)	+0.010 (3.73)	+0.001 (0.59)	+0.008 (5.09)
VP - Vehicles per person ≥ 16 years old in household.	+0.178 (3.12)	+0.078 (1.19)	+0.096 (2.48)	+0.004 (0.13)
TT - Travel Time (minutes)	-0.030 (-2.77)	-0.025 (-2.27)	-0.019 (-1.89)	-0.033 (-3.70)
SHARED-RIDE UTILITY: (Us)				
CS - Shared Ride Constant	+0.216 (3.08)	-0.090 (-1.21)	+0.360 (5.91)	+0.085 (1.61)
RD - Ridesharing Partner: 0 if general public matching 1 if co-worker/neighbor	+0.222 (2.58)	+0.216 (2.21)	+0.138 (2.00)	+0.081 (1.41)
WS - Work Schedule: 0 if flexitime 1 if fixed 8-hr. day	+0.401 (4.66)	+0.384 (3.94)	+0.581 (8.46)	+0.399 (6.93)
TT - Travel Time (minutes)	-0.030 (-2.77)	-0.025 (-2.27)	-0.019 (-1.89)	-0.033 (-3.70)

TABLE 8.9 *(continued)*

VARIABLE NAME AND DEFINITION	URBAN AREA			
	Madison	Milwaukee County	Fox River Valley Cities	Other Cities
	COEFFICIENTS			
WALK UTILITY: (Uw)				
CW - Walk Constant	+0.386 (4.46)	+0.268 (2.82)	+0.151 (2.30)	+0.119 (2.01)
WD - Walk Distance to Work (miles)	-0.089 (-3.36)	-0.936 (-3.08)	-0.925 (-5.48)	-0.784 (-5.03)
SW - Sidewalks: 0 if all the way 1 if partway	0 (coeff. set to zero)	0 (coeff. set to zero)	0 (coeff. set to zero)	-0.053 (-0.68)
SN - Season: 0 if summer 1 if winter	-0.756 (-5.66)	-0.750 (-4.93)	-0.868 (-10.29)	-0.848 (-10.83)
BIKE UTILITY: (Ub)				
CB - Bike Constant	-0.275 (-3.81)	-0.130 (-1.61)	-0.225 (-3.56)	-0.418 (-7.49)
BD - Bike Distance to work (miles)	-0.245 (-5.24)	-0.213 (-3.67)	-0.259 (-6.69)	-0.276 (-8.19)
BL - Bike Lane: 0 if marked lane in street 1 if no lane	-0.356 (-3.81)	-0.216 (-1.87)	-0.330 (-4.27)	-0.296 (-4.401
SS - Street Surface: 0 if smooth, 1 if rough	-0.383 (-4.11)	-0.470 (-4.05)	-0.431 (-5.57)	-0.400 (-5.93)
TR - Traffic: 0 if quiet, 1 if busy	-0.517 (-5.53)	-0.500 (-4.31)	-0.417 (-5.39)	-0.378 (-5.61)
BUS UTILITY: (Ut)				
BT - Bus Transfer Time (minutes)	-0.044 (-2.00)	-0.035 (-1.58)	-0.019 (-0.96)	0 (coeff. set to zero)
BF - Bus Fare (dollars)	-0.221 (-0.81)	-0.443 (-1.58)	-0.240 (-0.96)	-0.195 (-0.88)
HW - Bus Headway (minutes)	0 (coeff. set to zero)	0 (coeff. set to zero)	-0.848 (-10.83)	-0.007 (-1.14)
TT - Travel Time (minutes)	-0.030 (-2.77)	-0.025 (-2.27)	-0.019 (-1.89)	-0.033 (-3.70)
R^2 =	0.151	0.116	0.139	0.131
F =	21.44	14.24	32.56	38.73
No of Respondents =	305	273	534	679
Data Points =	2440	2184	4272	5432

These models were used to perform an extensive series of policy analyses with the aid of the incremental form of the logit model. Several examples follow:

Example 11: What is the effect on mode split of gas rationing in a city such as Milwaukee when the base mode shares are 50 percent automobile, 15 percent rideshare, 22 percent bus, 8 percent walk, and 5 percent bike? Table 8.10 shows the worksheet calculations.

Example 12: Using the base mode shares in Example 11, what is the effect of shifting from a general public ridesharing program that matches up strangers to a program that is focused entirely on ridesharing with coworkers and neighbors where people know one another? Table 8.11 shows the worksheet calculations.

Methods for applying stated preference techniques have been refined in the last decade and the reader should refer to the literature for guidance.

8.8.2.2 *Freight Demand*

The field of freight demand forecasting is not nearly as well developed as the field of person travel. Few disaggregate multimodal freight models are found in the literature,

TABLE 8.10 Worksheet for Example 11: Evaluating impacts of gas rationing on city trips

URBAN AREA: City
MODEL SYSTEM: Urban Work Trip

	1	2	3	4	5	6	7	8	9	10
					1 x 2 + 3 x 4		e^5	6 x 7	8 / Σ	9 - 6
	VARIABLE 1 Gas Availability		VARIABLE 2 _____		Total Change in Utility	Base Mode Share	Approximate Factor by Which P Changes	Weighted Change in Factor by Which P Changes	Revised Mode Share	Change in P
MODE	Utility Coefficient	Change in Variable 1	Utility Coefficient	Change in Variable 2	ΔU	P	$e^{\Delta U}$	$P * e^{\Delta U}$	$\frac{P * e^{\Delta U}}{\%} = P^1$	$P^1 - P$
Auto	-0.377	+1			-0.377	0.50	0.685	0.34	0.40	-0.10
Ride Share					0	0.15	1	0.15	0.18	+0.03
Bus					0	0.22	1	0.22	0.26	+0.04
Walk					0	0.08	1	0.08	0.10	+0.02
Bike					0	0.05	1	0.05	0.06	+0.01

Sum Col 8 = Σ = 0.84

TABLE 8.11 Worksheet for Example 12: Evaluating impacts of ride-sharing option

URBAN AREA: City
MODEL SYSTEM: Urban Work Trips

	1	2	3	4	5	6	7	8	9	10
					1 x 2 + 3 x 4		e^5	6 x 7	8 / Σ	9 - 6
	VARIABLE 1 Ride Sharing Partner		VARIABLE 2 _____		Total Change in Utility	Base Mode Share	Approximate Factor by Which P Changes	Weighted Change in Factor by Which P Changes	Revised Mode Share	Change in P
MODE	Utility Coefficient	Change in Variable 1	Utility Coefficient	Change in Variable 2	ΔU	P	$e^{\Delta U}$	$P * e^{\Delta U}$	$\frac{P * e^{\Delta U}}{\%} = P^1$	$P^1 - P$
Auto					0	0.50	1	0.50	0.48	-0.02
Ride Share	+0.216	+1			+0.216	0.15	1.24	0.19	0.18	+0.03
Bus					0	0.22	1	0.22	0.21	-0.01
Walk					0	0.08	1	0.08	0.08	0
Bike					0	0.05	1	0.05	0.05	0

Sum Col 8 = Σ = 1.04

and even these are not well suited for directly predicting future travel by substituting values of each variable. However, a strong argument can be made that highly reasonable results can be obtained by applying the incremental form of the logit model to assess changes in the demand for freight transportation at the commodity level by (1) taking into account changes in relative logistics costs among freight-modes and (2) construing relative logistics costs as relative utilities among modes. If one assumes that prices in the marketplace reflect the relative utilities of goods or services purchased, then those prices (or costs) can also be treated as the relative utility (or disutility) a shipper receives from selecting a specific mode of transportation over another to ship a commodity.

The consequence of construing the logistics costs of each mode as being the same as the utility of each mode is that a very simple and powerful analytical tool for predicting changes in modal split due to changes in relative logistics costs results. If for each mode one substitutes logistics costs for utility in the formula for the incremental logit model, one obtains the following:

$$P_i' = \frac{P_i e^{\Delta U_i}}{\sum P_j e^{\Delta U_j}} = \frac{P_i e^{\Delta lc_i}}{\sum P_j e^{\Delta lc_j}}$$

where

P_i' = revised mode share for mode i for commodity shipments for a certain industry and size,
P_i = initial mode share for mode i,
P_j = initial mode share for mode j (mode i is included among possible mode j's) for commodity shipments for a certain industry and size,
U_i = utility of mode i,
U_j = utility of mode j,
e = base of the natural logarithm (2.7182 ...),
Δlc_i = change in logistics cost of mode i, and
Δlc_j = change in logistics cost of mode j.

The following example, describes how to use this model to assess the change in demand due to a change in the logistics costs of rail transport relative to other modes.

Example 13: Suppose that for the movement of frozen carcasses from Norfolk, Virginia, to Columbus, Ohio, the total transportation and logistics costs per hundredweight for rail declines from $9.35 per hundredweight to $8.67 per hundredweight. This drop in rail transportation and logistics costs occurs because rail transit time has improved by almost 50 percent, reliability has improved to an average of 2.0 days in transit from 7.0 days in transit, and the probability of loss and damage has dropped to 0.050 and the cost per claim is now $77.73. The result is new rail movement costs of only $700 per shipment rather than the current $888.64 per shipment. Suppose the base mode shares for transport of frozen carcasses between Norfolk and Columbus are as follows:

Mode	Mode Share (%)
Rail	2.4
Intermodal	15.0
Double Stack	9.0
Road Railer	2.0
Truckload	67.1
LTL Truck	3.0
Private Truck	1.5
Total	100.0

In order to predict the change in freight modal shares the analyst needs to know only the base mode shares and the change in total rail transportation and logistics costs from $9.35 to $8.67 per hundredweight and substitute these into the formula for incremental logit model, where the change in utility for each mode is equated with the change in total transportation and logistics costs for each mode. Table 8.12 shows the calculations.

Although this example pertains to frozen carcasses, the procedure will work with any type of commodity provided the change in transportation and logistics costs are calculated reasonably accurately. In other words, the change in logistics costs will depend on commodity-specific attributes such as annual use of the commodity by receivers, value per pound, shipment size, density, and reliability. For example, if firms are using very small amounts of a commodity throughout the year, by ordering in truckload quantities (in large amounts), the firms would incur very high storage costs. Choice of mode will have a direct relationship to logistics cost, in this case through the effect on inventory costs.

The rationale for treating relative transportation and logistics costs as relative utilities is fully developed in the previous sections on demand forecasting.

Using Incremental Analysis in the Freight (SUA) Model

A pivot-point methodology using the incremental form of the logit model can also be applied where subjective utility assessment (SUA) has been used to develop the utility functions for each of the modes. Since the change in utility for each of the modes is multiplied by the current mode share, the model may produce better final estimates of mode share than direct use of the model, especially where the current mode shares are known. Note, however, that the mode share at issue is the mode share for that particular disaggregate observation or for that market segment. There are typically many more market segments for freight than for passengers.

It is useful to provide an illustration of the use of the pivot-point methodology applied to the subjective version of the model. Note that for the subjective model the coefficients in the utility function are all 1. The utilities for each mode i, therefore, are precisely the change in the receiver's total logistics cost:

TABLE 8.12 Worksheet for Example 13: Pivot-point analysis for evaluating freight options

URBAN AREA: Intercity
MODEL SYSTEM: Freight Trips

	1	2	3	4	5	6	7	8	9	10
					1 x 2 + 3 x 4		e^5	6 x 7	8 / Σ	9 - 6
	VARIABLE 1 Logistics Cost		VARIABLE 2		Total Change in Utility	Base Mode Share	Approximate Factor by Which P Changes	Weighted Change in Factor by Which P Changes	Revised Mode Share	Change in P
MODE	Utility Coefficient	Change in Variable 1	Utility Coefficient	Change in Variable 2	ΔU	P	$e^{\Delta U}$	$P * e^{\Delta U}$	$P * e^{\Delta U} = P^1$ %	$P^1 - P$
Rail	-1	-0.68			+0.68	0.024	1.97	0.047	0.046	+0.022
Inter Modal		0			0	0.15	1	0.15	0.147	-0.003
Double Stack		0			0	0.09	1	0.09	0.088	-0.012
Road Railer		0			0	0.02	1	0.02	0.019	-0.001
Truck Load		0			0	0.671	1	0.671	0.656	-0.015
LTL		0			0	0.03	1	0.03	0.029	-0.001
Private Truck		0			0	0.015	1	0.015	0.015	0

Sum Col 8 = Σ = 1.023

$U_i = \text{term}_{i1} + \text{term}_{i2} + \ldots \text{term}_{in}$

These can be developed with the shipper logistics cost model. If we apply this model to the example presented earlier involving the movement of frozen carcasses from Norfolk to Columbus, the result is a modest change in the total transportation and logistics cost for rail relative to the other modes (see Table 8.13). The total cost per hundredweight is now $8.67 compared with $9.35 before. The cost would be smaller if the capital carrying cost in transit and in storage were lower, but the large shipment size by rail causes these costs to be incurred regardless of what happens to rail LOS and cost.

The resulting change in utility is multiplied by the current mode share. Suppose that the mode shares are known and are used in the pivot-point formula to compute the modal shift. This was developed in Table 8.12 earlier.

8.8.3 Incremental Chained Logit

Transportation decisions are now frequently modeled as a series of chained or nested decisions that concern, for example, trip generation, trip frequency, mode choice, and route choice. The modeling framework is beyond the scope of this manual but the reader can refer to the large literature on the subject. A series of interrelated choices can be assessed by using the incremental form of the chained logit model. This procedure might best be explained by using an example of intercity passenger and trip generation models that were developed by stated preference techniques for the Wisconsin DOT in the early 1980s to assess alternative transportation policies in the face of potentially acute energy shortages.

However, one can observe that if there is a set of choices for a certain level of a hierarchical decision-making process, some change in the utility a person derives from each set of options in the choice hierarchy is a measure of accessibility. More specifically, this measure of accessibility is expressed as

$$M = \frac{1}{\mu} \ln \Sigma_i \, e^{U_i}$$

where

μ = a scaling parameter for the model, and
U_i = the utility the person derives from option i in the choice set.

It can be shown, for example, that for a nested set of choices, where the first level of decision making is whether

TABLE 8.13 Shipper logistics cost model

	Observation No. = 47		Origin = Norfolk, VA		Destination = Columbus, OH		
Commodity Description	20125 : Carcasses Fresh Frozen				Destination is mixing warehouse (Y=1, N=0)		
Shipper/Commodity Characteristics							
units presented in Carcasses							
units/year	1,923		lbs/year =	250,003			
pounds/unit	130		lbs/cuft =	13.00			
cube/unit	10		$/lb =	1.56			
$/unit	202.54		to mixing warehouse =	0			
shelf life (days)	150						
warehouse sq. ft./unit	2.00						
warehouse $/sqft	5.00						
cost per order	25.00						
internal cost of capital %	15.00%						
LTL discount	35.00%						
Shipment Characteristics	Rail	Intermodal	Dblstack	RoadRailer	Truckload	LTL Truck	Pvt. Truck
line-haul miles	583	583	583	648	507	507	507
pickup mi/no. stops	0	0	0	0	0	20	1
delivery mi.dlvrys per yr.	0	10	5	106	0	30	50
no. units in target order	1,524	362	362	370	369	76	38
Modal Characteristics	Rail	Intermodal	Dblstack	RoadRailer	Truckload	LTL Truck	Pvt. Truck
cube limit	7,200	3,634	4,130	4,130	4,130	2,142	4,130
weight limit	198,200	47,100	47,100	47,100	48,00	10,000	48,000
cost/ship	$200.00	$100.00	$100.00	$100.00	$119.01	$200.00	$347.31
cost/mile	$0.80	$0.62	$0.65	$0.65	$1.05	$1.12	$0.43
load ratio	0.75	1.00	0.85	0.85	1.00	1.00	0.50
load/unload	$62.50	$18.75	$18.75	$18.75	$18.75	$0.00	$18.75
pickup $/ship	$0.00	$97.00	$97.00	$97.00	$234.00	$100.00	$0.00
pickup $/mile	$0.00	$1.44	$1.44	$1.44	$0.00	$1.00	$0.00
delivery $/ship	$0.00	$97.00	$97.00	$97.0	($323.00)	$100.00	$0.00
delivery $/mile	$0.00	$1.44	$1.44	$1.44	$0.00	$1.00	$0.00
Modal Performance	Rail	Intermodal	Dblstack	RoadRailer	Truckload	LTL Truck	Pvt. Truck
wait time	1.0	0.5	0.5	0.5	0.5	0.5	5.0
transit time	2.4	2.5	0.7	0.9	1.0	2.3	0.5
reliability	2.0	2.0	0.3	0.4	0.5	2.0	0.1
probability of L&D claim	0.050	0.050	0.010	0.005	0.010	0.020	0.005
$/claim	$77.73	$66.98	$61.30	$59.62	$39.40	$130.43	$67.84
claim payment days	90	90	90	60	60	30	30
Shipment Output	Rail	Intermodal	Dblstack	RoadRailer	Truckload	LTL Truck	Pvt. Truck
cube-limited ship	720	363	413	413	413	214	413
weight-limited ship	1,525	362	370	369	369	77	369
target order	1,524	362	370	369	369	76	38
final units/ship	720	362	370	369	369	76	38
transport charges/ship	$700.00	$669.83	$851.77	$562.91	$562.91	$1,630.39	$1,130.68
no. shipments/yr	3	5	5	5	5	25	50
transport charges/yr	$1,870	$3,558	$4,427	$2,934	$2,934	$41,255	$56,534
Logistics Cost per Unit	Rail	Intermodal	Dblstack	RoadRailer	Truckload	LTL Truck	Pvt. Truck
order cost	$0.035	$0.069	$0.069	$0.068	$0.068	$0.329	$0.650
load/unload	$0.174	$0.014	$0.104	$0.101	$0.102	$0.000	$0.975
capital carry in transit	$0.200	$0.205	$0.055	$0.071	$0.080	$0.189	$0.042
capital carry in storage	$5.687	$2.859	$2.859	$2.923	$2.915	$0.600	$0.304
storage cost	$3.744	$1.882	$1.882	$1.924	$1.919	$0.395	$0.200
shelf loss in transit	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000
filing L&D claims	$0.005	$0.009	$0.002	$0.001	$0.001	$0.034	$0.009
capital carry on L&D	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000
safety stock carrying cost	$0.166	$0.164	$0.027	$0.036	$0.040	$0.170	$0.004
emergency shipment cost	$0.286	$0.286	$0.286	$0.286	$0.266	$0.286	$0.286
Total Logistics Costs per Unit	$10.998	$5.579	$5.285	$5.409	$5.410	$2.004	$2.470
Transport Charges	$0.972	$1.850	$2.117	$2.302	$1.526	$21.453	$29.397
Transp. & Logistics Cost per Unit	$11.270	$7.429	$7.401	$7.711	$6.935	$23.457	$31.867
Purchase Cost	$202.540	$202.540	$202.540	$202.540	$202.540	$202.540	$202.540
Total Costs per Unit	$213.810	$209.969	$209.941	$210.251	$209.475	$225.997	$234.407
Transp. & Logistics Cost per Cwt	$9.35	$5.71	$5.69	$5.93	$5.33	$18.04	$24.51
Total Costs per Cwt	$165.15	$161.51	$161.49	$161.73	$161.13	$173.84	$180.31

or not to take a trip and the second level is the choice of mode to use, the first decision is a function of the accessibility across the modes in the choice set and thus dependent upon the utilities of these modes as follows:

$$P_1 = \frac{e^{\theta_1 * \ln \sum_i e^{U_i}}}{e^{U_0} + e^{\theta_1 * \ln \sum_i e^{U_i}}}$$

$$P_0 + P_1 = 1$$

where

P_1 = probability of making a trip,
P_0 = probability of not making a trip,
θ_1 = logsum coefficient ($=1/m_1$),
ln = natural logarithm,
i = a mode in the choice set, and
U_0 = utility of not making a trip (= constant).

Therefore, the utility of making a trip is the logsum coefficient θ_1 multiplied by the logarithm of the sum of the exponentiated utilities of the available modes.

It can be shown that when using the logsum coefficient, the chained pivot-point logit equation is analogous to the simple pivot-point equation:

$$P_j' = \frac{P_j * e^{\theta_j * \ln \sum_i P_i e^{\Delta U_i}}}{\sum_k P_k * e^{\theta_k * \ln \sum_i P_i e^{\Delta U_i}}}$$

or

$$P_1' = \frac{P_1 * e^{\theta_1 * \ln \sum_i P_i e^{\Delta U_i}}}{P_0 + P_1 * e^{\theta_1 * \ln \sum_i P_i e^{\Delta U_i}}}$$

where j and k are second-level decisions (e.g., whether or not to make a trip) based on the utilities of the mode(s) i in the choice set. θj and θ_k are logsum coefficients for the second-level decision (note that j is included in k).

Example 14: A Wisconsin DOT study performed in the aftermath of the energy shortages of the 1970s showed that, for recreational trips, 90 percent of all travelers use automobile, 5 percent use air travel, 2.5 percent go by bus, and 2.5 percent go by rail. At the time, there was concern about disruptive energy shortages and there was a need to explore questions such as what would be the effect of a gas shortage on trip frequency and mode choice that caused a 2 cent per mile rise in gasoline price and forced gas sta-

TABLE 8.14 Intercity trip frequency model coefficients (Wisconsin) (*6*)

$$P_1 = \frac{e^{U_1}}{e^{U_1} + e^{U_0}}$$

Recreation:

$$U_1 = \underset{(*)}{0.754} * ln(e^{U_b} + e^{U_r} + e^{U_a} + e^{U_k})$$

Personal:

$$U_1 = \underset{(*)}{0.717} * ln(e^{U_b} + e^{U_r} + e^{U_a} + e^{U_k})$$

Business:

$$U_1 = \underset{(*)}{0.760} * ln(e^{U_b} + e^{U_r} + e^{U_a}) + \underset{(*)}{0.427} ** U_k$$

P_i	=	probability of choosing mode i, conditional on making a trip
P_1	=	probability of making an intercity trip
U_i	=	utility of mode i
U_0	=	utility of not making an intercity trip
U_1	=	utility of making an intercity trip
(...)	=	t-statistic; "*" indicates computed coefficient for which no t-statistic is available
ln	=	natural logarithm (base e)

TABLE 8.15 Intercity mode choice model coefficients (Wisconsin) (*6*)

Recreation:

Bus: $U_b = -1.27 - .170\, c_b/d - .85\, t_b/d - .58/f_b - .14RC$

Rail: $U_r = -0.10 - .170\, c_r/d - .85\, t_r/d - .58/f_r - .14RC$

Air: $U_a = -0.66 - .158\, c_a/d - .094\, t_a/d - .010/f_a - .14RC$

Auto: $U_h = -0.40AD - 0.71CW - 0.89RA - 0.041g$

Personal:

Bus: $U_b = -.73 - .170\, c_b/d - .93\, t_b/d - .93/f_b - .40RC$

Rail: $U_r = -.18 - .170\, c_r/d - .93\, t_r/d - .93/f_r - .40RC$

Air: $U_a = -.86 - .057\, c_a/d - .16\, t_a/d - .064/f_a - .40RC$

Auto: $U_h = -.27AD - .46CW - .86RA - .059g$

Business:

Bus: $U_b = -2.11 - .110\, c_b/d - 1.25\, t_b/d - 1.86/f_b - .41RC$

Rail: $U_r = 0.30 - .110\, c_r/d - 1.25\, t_r/d - 1.86/f_r - .41RC$

Air: $U_a = -0.57 - .027\, c_a/d - .72\, t_a/d - .26/f_a - .41RC$

Auto: $U_h = -.37AD - 0.0CW - .73RA - .037g$

where

c_i	=	one-way cost of mode *i* (cents)
d	=	one-way auto distance (miles)
t_i	=	time difference between mode *i* and auto, including terminal time (min.)
f_i	=	daily frequency or number of scheduled trips on mode *i*
AD	=	1 if gasoline is available alternate days; 0 otherwise
CW	=	1 if gasoline stations are closed weekends; 0 otherwise
RA	=	1 if gasoline is rationed at 12 gallons per auto per week; 0 otherwise
g	=	gasoline price (cents/mile)
RC	=	1 if rental car is the only public access mode available at the destination; 0 otherwise
U_i	=	utility of mode i

tions to close on weekends. The revised mode shares can be estimated by the simple pivot-point logit procedure based on stated preference models that Wisconsin DOT developed at the time (see Tables 8.14 and 8.15).

In such a fuel shortage, we would not expect each person who decides not to use an automobile to switch to another mode. Many would decide not to make the trip at all. Assume that previous survey results reveal that 23 percent of the population makes a trip over a certain time period. Then, the probability of making a trip, P_1, is equal to 0.23 and the probability of not making a trip, P_0, is equal to 0.77.

The recreation trip logsum coefficient, θ_1, is 0.754 (see Table 8.14). Because the utility of not making a trip remains constant, $\Delta U_0 = 0$, the only modal utility that changes is the one for automobile, $\Delta U_h = -0.792$, found in Table 8.15 and calculated as follows:

$$\begin{aligned}\Delta U_h &= -0.71\ \Delta CW - 0.41g \\ &= -0.71 * (+1) - 0.041 * (-2 \text{ cents/mi}) \\ &= -0.792\end{aligned}$$

The revised probability of making a trip is therefore

$$\begin{aligned}P_1' &= \frac{0.23 * e^{0.754*\ln(0.90*e^{-0.792}+0.05*e^{0}+[2*0.025*e^{0}])}}{0.77 + 0.23 * e^{0.754*\ln(0.90*e^{-0.792}+0.05*e^{0}+[2*0.025*e^{0}])}} \\ &= \frac{0.117}{0.77 + 0.117} = 0.13\end{aligned}$$

The fuel shortage and price increase decreases the total number of trips by almost half. If 1,000 households were the group of interest, their recreation tripmaking would fall from 230 trips ($P_1 = 0.23$) to 130 trips ($P_1' = 0.13$). The

mode shares for these 130 trips are given by the standard pivot-point model.

In many cases, trip generation, destination, and mode choice DUA model systems will be estimated without the use of logsum variables. In these cases, each model is written as a standard logit model. For example, trip frequency is given by the following:

$$P_1 = \frac{e^{U_1}}{e^{U_0} + e^{U_1}}$$

and

$$P_1' = \frac{P_1 e^{\Delta U_1}}{P_0 e^{\Delta U_0} + P_1 e^{\Delta U_1}}$$

No explicit relationship to the mode choice model is used (see Table 8.15). This approach is simpler than the chained approach, but it lacks the consistency conditions of the logsum variables. When forecasting with unlinked models, therefore, the analyst must constantly check for consistency. For example, take a base case where 20 transit trips and 80 automobile trips are made. Assume that the mode choice model predicts a 10 percent increase in transit market share (from 0.20 to 0.30) and a 20 percent increase in total travel due to an improvement in transit service. This implies there are 36 transit trips and 84 automobile trips after the change. This is impossible, however, because an improvement in transit cannot increase automobile trips (from 80 to 84). Logsum variables inherently prevent this situation from occurring, but care is required in non-logsum models to avoid illogical results. In this case, automobile trips should be reduced to their "before" value of 80.

8.9 CALCULATE INDUCED DEMAND AND SECOND-ORDER EFFECTS OF HIGHWAY SPEED (STEP 7)

If various supply-side enhancement or demand management actions are taken, there will be induced travel demand. For example, actions such as improving transit service, offering carpool incentives, and creating disincentives to automobile use will divert automobile users to other forms of transportation. This, in turn, will reduce the number of vehicles using highway facilities. However, because of reduced automobile congestion, speed is greater and the cost of travel in terms of time is lower, which has the second-order effect of encouraging additional people to use the highways.

Similarly, suppose capacity is added to a highway. Because of the increase in travel speed, the first-order effect is to attract new users to the highway. But as the number of new users increases, the speed of travel begins to decrease again, and a certain fraction of those who were originally induced to use the improved highway now do not use it.

The following expression, taken from the FHWA transportation impacts estimation course manual (*10*), can be used to assess the extent to which an initial change in VMT (the first-order effect) is offset by a change in traffic associated with changes in highway speeds (the second-order effect):

$$F = (1 + (E_d * E_s)^{-1})^{-1}$$

where

F = the fraction of the initial change in VMT offset by the change in traffic due to a change in speed (e.g., $F = 0$ implies that none of the initial change is offset). For very high values of both E_d and E_s, F approaches 1.0.

E_d = the percent change in VMT due to a 1 percent change in the cost of highway travel (e.g., travel time per VMT). This can also be referred to as the elasticity of demand expressed in VMT with respect to a change in travel time per vehicle mile.

E_s = the percent change in the cost of highway travel per vehicle mile due to a 1 percent increase in VMT (also called elasticity of supply).

8.10 REFERENCES

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APPENDIX **8A**

ELASTICITIES AND LOGIT COEFFICIENTS

This appendix provides elasticity estimates and logit coefficients for various types and modes of transportation. The material used in this chapter is illustrative of numbers found in the literature. Many of the elasticities were derived from models estimated more than two decades ago and therefore should be used with extreme caution. However, more current logit coefficient estimates are presented in Table 8A.7. Future editions of this manual should contain more current and comprehensive tables of elasticities. The reader is referred to Chapter 8 for commentary on this material.

TABLE 8A.1 Range of empirical transit demand elasticities for overall trips for medium cities

	Medium Multinucleated Cities Transit[1]			Medium Core-Concentrated Cities Transit[2]		
Item	**Total**	**Bus**	**Rail**	**Total**	**Bus**	**Rail**
Total						
Line-Haul Time	NA	NA	NA	NA	NA	NA
Excess Time	NA	NA	NA	NA	NA	NA
Cost	NA	NA	NA	NA	NA	NA
Bus						
Line-Haul Time	NA	NA	NA	NA	NA	NA
Excess Time	NA	NA	NA	NA	-0.83	NA
Cost	NA	-0.12 to -0.34	NA	NA	-0.25 to -0.65	NA
Rail						
Line-Haul Time	NA	NA	NA	NA	NA	NA
Excess Time	NA	NA	NA	NA	NA	NA
Cost	NA	NA	NA	NA	NA	NA

Source: Chan, Y. and F. L. Ou. A Tabulation of Demand Elasticities for Urban Demand Forecasting. Transportation Research Record 673. pp 40-46. Transportation Research Board. Washington D.C. 1978.
[1] Salt Lake City and Springfield, Massachusetts
[2] Chesapeake, Virginia; Portland , Maine; Tulsa; and York, Pennsylvania

TABLE 8A.2 Range of empirical transit demand elasticities for overall trips large cities

	Large Multinucleated Cities Transit[1]			Large Core-Concentrated Cities Transit[2]		
Item	**Total**	**Bus**	**Rail**	**Total**	**Bus**	**Rail**
Total						
Line-Haul Time	NA	NA	NA	NA	NA	NA
Excess Time	NA	NA	NA	NA	NA	NA
Cost	NA	NA	NA	NA	NA	NA
Bus						
Line-Haul Time	NA	-0.55	NA	NA	NA	NA
Excess Time	NA	-0.20 to -0.60	NA	NA	-0.63 to -3.8	NA
Cost	NA	-0.11 to -0.64	NA	NA	-0.08 to -0.6	NA
Rail						
Line-Haul Time	NA	NA	NA	NA	NA	NA
Excess Time	NA	NA	NA	NA	NA	-0.24
Cost	NA	NA	NA	NA	NA	-0.07 to -0.19

Source: Chan, Y. and F. L. Ou. A Tabulation of Demand Elasticities for Urban Demand Forecasting. Transportation Research Record 673. pp 40-46. Transportation Research Board. Washington D.C. 1978.
[1] Atlanta, Boston, Detroit, Philadelphia, San Diego and San Francisco
[2] Baltimore, Cincinnati, Milwaukee, New York and St. Louis

TABLE 8A.3 Range of calibrated work-trip demand elasticities for overall trips for medium cities

Transportation System Variable	Medium Multinucleated Cities[1]					Medium Core-Concentrated Cities[2]				
		Transit					Transit			
	Para Transit	Total	Bus	Rail	Auto	Para Transit	Total	Bus	Rail	Auto
Paratransit										
Line-Haul Time			NA		NA	-0.315		0.194		0.194
Excess Time			NA		NA	-0.189		0.117		0.117
Cost			NA		NA	-0.057		0.035		0.035
Total										
Line-Haul Time			NA		NA	NA		NA		NA
Excess Time			NA		NA	NA		NA		NA
Cost			NA		NA	NA		NA		NA
Bus										
Line-Haul Time			-2.8 (Total Time)		1.11	0.022		-0.19 to -0.373		0.022
Excess Time			NA		NA	0.092		-0.38 to -1.55		0.092
Cost			-0.31		0.06	0.05		-0.40 to -0.852		0.05 to 0.15
Rail										
Line-Haul Time			NA		NA	NA		NA		NA
Excess Time			NA		NA	NA		NA		NA
Cost			NA		NA	NA		NA		NA
Auto										
Line-Haul Time			2.81 (Total Time)		-1.11	0.173		0.173		-0.138 to -0.39
Excess Time			NA		NA	0.173		0.173		-0.138
Cost			1.39		-0.55	0.115		0.115		-0.092 to -0.12

Source: Chan, Y. and F. L. Ou. A Tabulation of Demand Elasticities for Urban Demand Forecasting. Transportation Research Record 673. pp 40-46. Transportation Research Board. Washington D.C. 1978.

[1] Richmond, Virginia

[2] Louisville, Kentucky

TABLE 8A.4 Range of calibrated work-trip demand elasticities for overall trips for large cities

Transportation System Variable	Large Multinucleated Cities[1]					Large Core-Concentrated Cities[2]				
		Transit					Transit			
	Para Transit	Total	Bus	Rail	Auto	Para Transit	Total	Bus	Rail	Auto
Paratransit										
Line-Haul Time	-0.02 to -0.664	NA	-0.27	NA	NA	-0.59		0.22	NA	NA
Excess Time	-0.122	NA	NA	NA	NA	-0.28		0.10		NA
Cost	-0.01 to -0.092	NA	-0.06	NA	NA	-0.10		0.04		NA
Total										
Line-Haul Time	NA	-0.20 to -0.39	NA		NA	NA		NA		NA
Excess Time	NA	-0.09 to -0.709	NA		NA	NA		NA		NA
Cost	NA	-0.09 to -0.58	NA		NA	NA		NA		NA
Bus										
Line-Haul Time		NA	-0.46 to -1.10	0.23	0.04 to 0.14	NA		-0.30 to -0.78		0.25
Excess Time		NA	-0.17 to -2.28	0 to 0.06	0.05 to 0.373	NA		-0.94		0.30
Cost		NA	-0.1 to -0.58	0 to 0.28	0.02 to 0.138	NA		-0.12 to -0.20		0.06
Rail										
Line-Haul Time	NA	NA	0.13 to 1.02	-0.60 to -0.80	0.10	NA		NA		NA
Excess Time	NA	NA	0.03 to 1.15	-0.12 to -2.06	0.02	NA		NA		NA
Cost	NA	NA	0 to 0.25	-0.86 to -1.80	0.13	NA		NA		NA
Auto										
Line-Haul Time	NA	0 to 0.37	0.36 to 0.39	0.27 to 0.41	-0.02 to -0.82	NA		0.17	NA	-0.18
Excess Time	NA	0	NA	NA	-0.027 to -1.437	NA		0.33	NA	-0.35
Cost	NA	0 to 0.80	0.06 to 0.97	0.06 to 0.97	-0.01 to -0.494	NA		0.15	NA	-0.16

Source: Chan, Y. and F. L. Ou. A Tabulation of Demand Elasticities for Urban Demand Forecasting. Transportation Research Record 673. pp 40-46. Transportation Research Board. Washington D.C. 1978.

[1] Boston, Chicago, San Francisco, Los Angeles, San Diego, Minneapolis-St. Paul

[2] Washington D.C.

TABLE 8A.5 National personal transportation study mode splits and VMT elasticities under various policies

	Base Case	100% Gas Tax	10% Transit Speed Increase	10% Transit Access Decrease	Low Transit Access Improvement	Low & Middle Transit Access Improvement	Low Performance Dial-a-Ride	High Performance Dial-a-Ride
Mode Split:								
- Auto Drive Alone	0.635	0.564	0.619	0.631	0.600	0.583	0.631	0.622
- Transit	0.159	0.212	0.179	0.163	0.202	0.223	0.156	0.148
- Carpool	0.206	0.224	0.209	0.205	0.198	0.193	0.205	0.201
- Dial-a-Ride								
VMT	19,913	17,365	19,273	19,780	18,518	17,859	19,857	19,718
VMT Elasticities with respect to:								
- Auto Operating Cost		-0.256						
- Pump Price of Gas		-0.184						
- PreTax Cost of Gas		-0.128						
- Transit Speed			-0.322					
- Transit Access Time				0.067	0.111	0.147		
Transit Ridership Elasticity with Respect to:								
- Transit Speed			1.26					
- Transit Access Time				-0.252	-0.429	-.593		

Source: Charles River Associates. Disaggregate Travel Demand Models. National Cooperative Highway Research Program Project 8-13. February 1976.

TABLE 8A.6 Wisconsin urban mode choice models

	Direct Elasticities				Cross Elasticities*		Marginal Value of Time ($/Hr)**
URBAN AREA	Gasoline Price	Parking Cost	Bus Fare	Bus Travel Time	Gasoline Price	Parking Cost	
- Milwaukee County	-0.166	-0.059	-0.247	-0.349	+0.448	+0.186	$4.64
- Madison	-0.196	-0.106	-0.117	-0.396	+0.249	+0.134	$7.69
- Madison Outer	-0.245	-0.058	-0.006	-0.103	+0.448	+0.107	$1.15
- Fox River Valley	-0.152	-0.071	-0.141	-0.279	+0.387	+0.183	$4.01
- Other Cities	-0.183	-0.082	-0.189	-0.480	+0.356	+0.158	$7.15

Note: All elasticities are point elasticities and were calculated at the mean value of the independent variables in the experiment data sets: Gas Price = $1.90 per gallon, Parking = $15/mo, Bus Fare = $0.60; $1.50, Travel Time = 15 minutes.

* Logit models have constant cross-elasticities, i.e., for a 1% change in gas price, for example, all other modes have the same change in demand.

** Marginal values of time calculated using the travel time coefficient and the gasoline price coefficient.

[1] Source: Wisconsin Department of Transportation. Development of Wisconsin Work Trip Models For Forecasting Modal Choice. Technical Report. March 1982.

TABLE 8A.7 Logit coefficients for major urban areas

Urban Area	Source	Year	IVT	OVT	Transit Fare	Parking Cost
Southeast Florida	WGA/BAA	1982	0.0200	0.0450	0.0080	0.0080
Seattle	GWS/BAA	1978	0.0200	0.0480	0.0140	0.0140
Minn.-St Paul	GWS/RHPA	1975	0.0310	0.0370	0.0140	0.0140
Houston	GWA/BAA	1978	0.0310	0.0370	0.0240	0.0240
New Orleans	GWS/BAA	1980	0.0145	0.0551	0.0078	0.0215
St. Louis	GWS/BAA	1982	0.0228	0.0570	0.0084	0.0084
Los Angeles	?	1982	0.0111	0.0329	0.0190	0.0190
Honolulu	?	1982	0.0290	0.1320	–	0.0210
San Juan	?	1982	0.0130	0.0445	0.0040	0.0040
Washington, D.C.	GWS/BAA	1985	0.0173	0.0583	0.0044	0.0094
Somerset Co., NJ	WGA/Garmen	1989	0.0085	0.0100	0.0080	–
Seattle	GWS/PBQD	1991	0.0250	0.0500	0.0050	0.0120
Seattle TDM	JMR/COMSIS	1991	0.0170	0.0340	0.0021	0.0043
Cobb Co., GA	GWS/COMSIS	1990	0.0145	0.0488	0.0037	0.0079
Minneapolis TDM	RHP/COMSIS	1991	0.0200	0.0450	0.0032	0.0080
Phoenix	WAD/BAA	1990	0.0145	0.0769	0.0078	0.0078
I-80 corridor (N.J.)	WGA/Garmen	1990	0.0200	0.0450	0.0080	0.0200
Unweighted Mean			0.0194	0.0504	0.0082	0.0127
Median			0.0200	0.0450	0.0078	0.0107
Team Recommendation			0.0200	0.0500	0.0040	0.0100

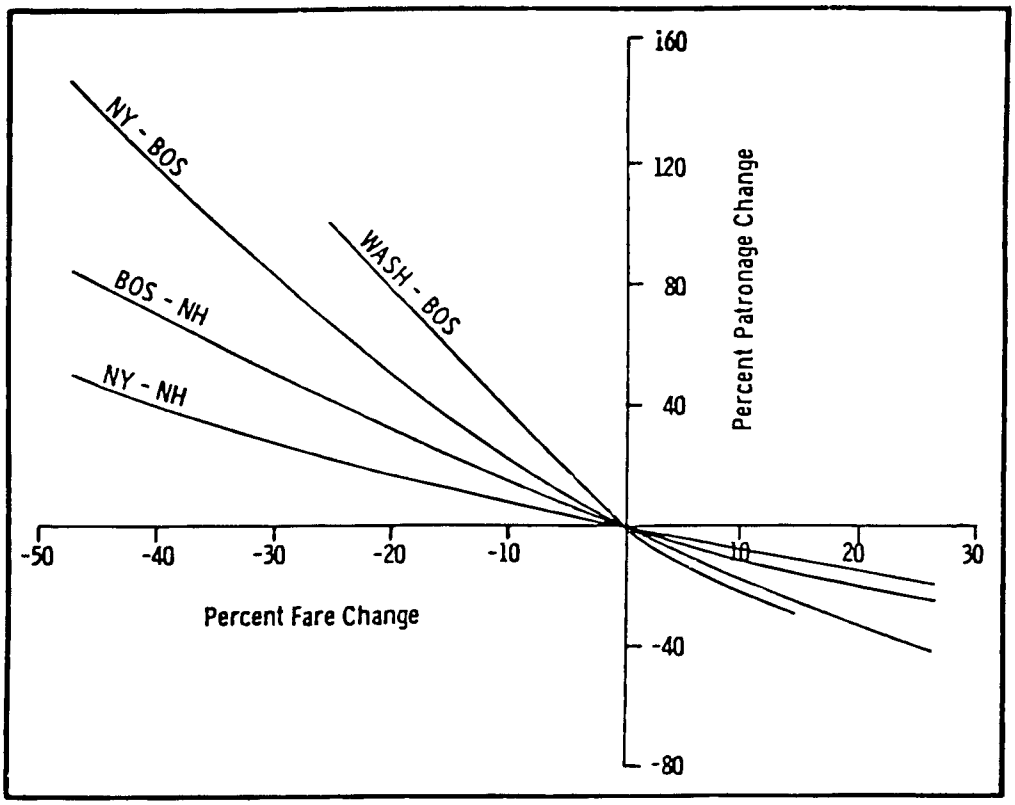
Source: Travel Demand Evaluation Model: User's Guide. Comsis Corporation. June 1993.

* Divided by Income

Source:

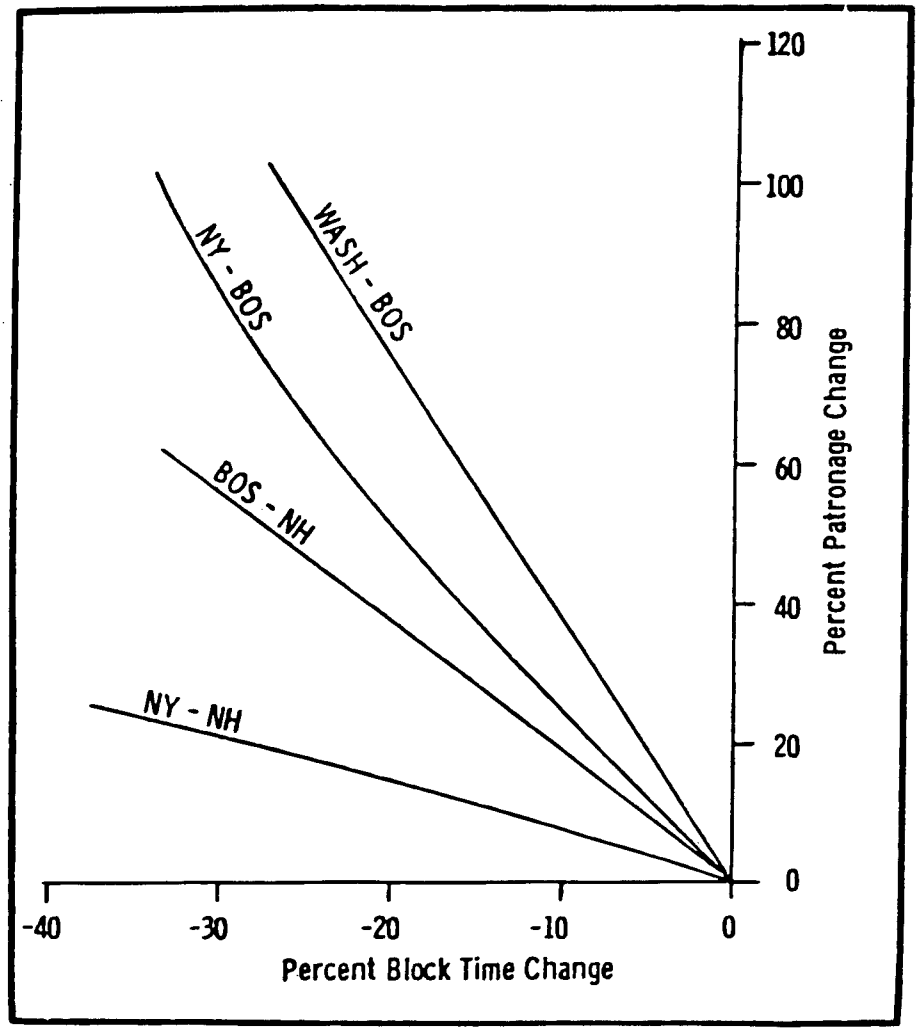
WGA: W. Allen, Consultant
GWS: Gordon Schultz
BAA: Barton Aschman Associates
RHP: Richard H. Pratt, Consultant

TABLE 8A.8 Northeast corridor rail passenger service fare elasticities



Source: Systems Analysis and Research Corporation. Demand for Intercity Passenger Travel in the Washington-Boston Corridor. Prepared for the Office of the Undersecretary of Commerce for Transportation. U.S. Department of Commerce. 1963.

TABLE 8A.9 Northeast corridor rail passenger service block time elasticities



Source: Systems Analysis and Research Corporation. Demand for Intercity Passenger Travel in the Washington-Boston Corridor. Prepared for the Office of the Undersecretary of Commerce for Transportation. U.S. Department of Commerce. 1963.

TABLE 8A.10 Kraft-Sarc multimodal demand elasticities for northeast corridor

(a) Results of Constrained Regression Estimation for Business Trip Demand Models

Mode	Elasticities of Business Trip Demand with Respect to:											
	Employ -ment Product	Rail Cost	Bus Cost	Air Cost	Auto Cost	Rail Time	Bus Time	Air Time	Auto Time	Income	Attrac-tiveness	R^2
Rail	0.893	-0.354	2,283	0	0	-4.376	0	0.361	0	not in model	not in model	0.91
Bus	0.802	0	-0.740	not in model	0	0	-1.700	not in model	0	not in model	not in model	0.73
Air	0.929	0	not in model	-0.891	0	0.973	not in model	-2.103	1.078	1.418	0.836	0.92
Auto	1.067	1.127	0	0	0	0.844	0	0	-3.410	not in model	0.333	0.71

(b) Results of Constrained Regression Estimation for Personal Trip Demand Models

Mode	Elasticities of Personal Trip Demand with Respect to:											
	Popula-tion Product	Rail Cost	Bus Cost	Air Cost	Auto Cost	Rail Time	Bus Time	Air Time	Auto Time	Income	Attrac-tiveness	R^2
Rail	0.854	-3.003	3,150	0	0	-2.636	0	0.052	0.056	0.465	1.601	0.89
Bus	0.673	0	-0.689	not in model	0	0	-1.589	not in model	0	2,542	1.869	0.78
Air	0.911	0	not in model	-0.914	0.095	0.857	not in model	-2.213	1.120	1.905	1.020	0.91
Auto	0.794	0.185	0	0.489	-0.929	0.458	0.074	0	-1.364	1.523	1.574	0.90

Source: Systems Analysis and Research Corporation. Demand for Intercity Passenger Travel in the Washington-Boston Corridor. Prepared for the Office of the Undersecretary of Commerce for Transportation. U.S. Department of Commerce. 1963.

TABLE 8A.11 Disaggregate intercity passenger demand elasticities

(a) Selected "Best" Models of Intercity Mode Choice from NTS 1972 Data.

Trip Purpose	Coefficients (t-Statistic)									
	Relative Distance	Relative Time	Relative Cost	Relative Access/ Egress Time	Freq.	Bus Const.	Rail Const.	Air Const.	χ^2 (d.f.)	% Correct Predicted
Business	-10.64	-0.632	-3.957	-0.517	0.00987	-1.646	-0.399	3.128	1016	83.1
	(5.78)	(2.10)	(9.79)	(3.31)	(3.44)	(4.31)	(0.93)	(5.10)	(8)	
Non-	0.523	-1.689	-4.252	-0.156	0.0120	-1.410	-0.365	2.476	1561	77.8
Business	(0.29)	(5.65)	(7.95)	(1.59)	(4.48)	(4.42)	(0.96)	(4.08)	(8)	

(b) Elasticities and Cross Elasticities for Business Travel

Demand Attribute	Auto Demand	Rail Demand	Bus Demand	Air Demand
Auto Time	-0.700	0.001	0.022	0.677
Auto Cost	-2.914	0.004	0.093	2.821
Auto Distance	-9.440	0.012	0.302	9.126
Auto A/E	-0.900	0.001	0.029	0.870
Auto Frequency	1.288	-0.002	-0.041	-1.245
Rail Time	0.088	-0.677	0.019	0.569
Rail Cost	0.950	-7.273	0.202	6.121
Rail Distance	1.411	-10.802	0.301	9.090
Rail A/E	0.042	-0.320	0.009	0.269
Rail Frequency	-0.025	0.189	-0.005	-0.159
Bus Time	0.101	0.001	-0.751	0.650
Bus Cost	0.405	0.003	-3.016	2.605
Bus Distance	1.393	0.012	-10.379	8.974
Bus A/E	0.050	0	-0.370	0.320
Bus Frequency	-0.056	0	0.417	-0.360
Air Time	0.017	0	0.004	-0.021
Air Cost	0.858	0.007	0.183	-1.048
Air Distance	1.220	0.010	0.260	-1.490
Air A/E	0.064	0.001	0.014	-0.079
Air Frequency	-0.092	-0.001	-0.020	0.113

(c) Elasticities and Cross Elasticities for Non-Business Travel

Demand Attribute	Auto Demand	Rail Demand	Bus Demand	Air Demand
Auto Time	-1.638	0.092	0.009	1.537
Auto Cost	-2.133	0.120	0.011	2.002
Auto Distance	0.643	-0.036	-0.003	-0.603
Auto A/E	-0.317	0.018	0.002	0.298
Auto Frequency	1.263	-0.071	-0.007	-1.185
Rail Time	0.584	-1.887	0.007	1.296
Rail Cost	1.018	-3.288	0.012	2.257
Rail Distance	-0.162	0.523	-0.002	-0.359
Rail A/E	0.039	-0.127	0.001	0.087
Rail Frequency	-0.064	0.208	0.001	-0.143
Bus Time	1.199	0.159	-4.018	2.659
Bus Cost	0.895	0.119	-2.999	1.985
Bus Distance	-0.155	-0.021	0.521	-0.345
Bus A/E	0.045	0.006	-0.150	0.099
Bus Frequency	-0.170	-0.023	0.571	-0.378
Air Time	0.098	0.013	0.001	-0.112
Air Cost	1.715	0.228	0.021	-1.964
Air Distance	-0.136	-0.018	-0.002	0.178
Air A/E	0.048	0.006	0.001	-0.055
Air Frequency	-0.301	-0.040	-0.004	0.345

Source: Stopher, P. and J. Prashken. Intercity Passenger Forecasting: The Use of Current Forecasting Procedures. Transportation Research Forum. Vol. 17. 1976. pp. 67-75.

CHAPTER 9

EVALUATING ECONOMIC CAPACITY

Economic criteria, rather than physical constraints, often determine capacity. The literature on capacity analysis recognizes that economic capacity is as valid a criterion for establishing capacity as are measures of physical capacity (*1–3*). Although the principles of economic capacity analysis are not unknown to public agencies, only recently (because of budgetary pressures and capacity problems) have agencies found that economics increasingly is driving project selection. This has been reflected in ISTEA and related planning, air quality, and management system procedures concerning life-cycle cost analysis and economic optimization as well as in certain design, planning, and programming activities. ISTEA also requires that state and metropolitan plans and programs be financially constrained, thus forcing decision makers to make explicit economic tradeoffs.

9.1 OBJECTIVE

This chapter describes a method for determining the economic capacity of segments, nodes, and other elements of multimodal corridors. The chapter identifies the important factors that determine economic capacity and how they can be incorporated in evaluating the marginal costs and benefits of operating transportation facilities.

9.2 STEPS IN THE PROCESS

1. **Determine total costs.** Examine and develop the functional relationships among physical capacity, demand, and the total cost to society of operating a transportation segment or a node. Total costs include agency costs (e.g., equipment, maintenance, and fixed and variable costs of infrastructure), user costs (e.g., fare, vehicle operation, accidents, fuel, and depreciation), and societal costs (e.g., air quality and noise).
2. **Determine total benefits.** Identify the relationships among physical capacity, travel demand, and the total benefits to society of accommodating persons, freight or vehicles on each transportation link, segment of link, or node. Benefits include the economic value to individuals and society of specific person trips (business or personal) and freight trips (goods).
3. **Maximize net benefits.** Using derivatives, differentiate the expressions for economic costs and economic benefits with respect to the travel demand to obtain marginal costs and marginal benefits. Equate the two expressions and solve for the physical capacity of the link, segment of link, or node. This is the capacity that would maximize the net benefits derived from it (also called economic capacity).
4. **Compare economic capacity with physical capacity.** Identify deficient links, segments of links, and nodes. Identify options and associated agency costs to attain the economic capacity.
5. **Repeat step 3 for all links, segments of links, and nodes.** Each time determine the capacity that maximizes the net benefits given the travel demands and traffic volumes.
6. **Determine economic capacities under budget constraints.** If an agency has limited resources to undertake measures or projects aimed at attaining economic capacities of links, segments of links, and nodes, determine the mix/combination of these actions that maximizes the total net benefits subject to budget constraints.

9.3 DETERMINE ECONOMIC CAPACITY (STEPS 1, 2, AND 3)

The physical capacity of the corridor expressed in terms of the maximum throughput of vehicle passengers or freight (multimodal throughput) that one or more segments or nodes can handle does not imply that it is economically justified to operate the facility with traffic volumes that are close to or approach these levels. Although a high level of throughput (or production rate in economics) is desirable, the marginal value of an incremental increase in traffic volume may not offset the marginal cost associated with this increase. Figure 9-1 shows the theoretical relationships between throughput volume (or LOS in terms of v/c ratio) and the total costs and benefits for various throughput levels. There are fixed costs associated with operating a corridor (e.g., there will still be traffic lights on the highway, even if there is no traffic) and variable costs that constitute the sum total of the user costs and agency costs associated with a traffic level.

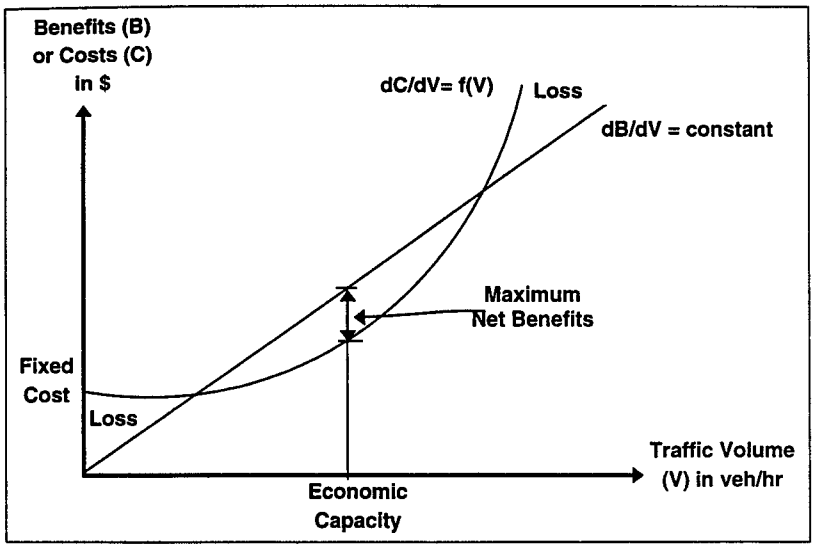


Figure 9-1. The relationships between traffic volume and total costs and benefits of transportation.

benefit of travel = price $*$ volume
price = value of the good or value of travel to a person
volume = ton of goods, number of passengers, or number of vehicles
cost of travel = transport cost $*$ volume + CC (volume)
transport cost = fuel, handling, vehicle operation, and so forth
CC (volume) = congestion cost (e.g., accident, delay, and discomfort)

Total benefits of travel is a linear function of traffic volume. However, the costs increase in a nonlinear manner with traffic volume because congestion impacts are greater at higher traffic volumes. The maximum net benefits (benefits minus cost) gained from the corridor are achieved when the slopes of the benefit curve and the cost curve are equal. This is true at traffic volume levels in which the marginal cost of travel is equal to the marginal benefit. This is referred to as the economic capacity of the corridor.

The economic cost is usually computed on the basis of traffic level (number of vehicles or units) for the facility. Economic benefits, on the other hand, depend on how much traffic in terms of passengers or freight can be transported. Therefore, the economic capacity of a corridor in terms of traffic volume might have been reached but the economic capacity expressed as the maximum number of passengers or tons of freight might not yet be attained. There is considerable excess capacity if the average car occupancy is 1.2 or if many trucks carry LTL freight.

More accurate expressions for the costs and benefits of transportation in a multimodal corridor (or a component of it) that differentiate between passengers and freight are as follows:

$$\text{total benefits} = \Sigma_m(P_p * O_{mp} * N_{mp} + P_f * O_{mf} * N_{mf})$$

where

P_p, P_f = values of one person-trip and ton-trip, respectively,
O_{mp}, O_{mf} = occupancy or handling rates for person and freight of mode m, and
N_{mp}, N_{mf} = number of passengers and freight vehicles in the traffic stream.

$$\text{total costs} = \Sigma_m[C_{imp} * O_{mp} * N_{mp} + C_{vmp} * N_{mp} + C_{imf} * O_{mf} * N_{mf} + C_{vmf} * N_{mf} + CC\,(N_{mp}, N_{mf})]$$

where

C_{imp}, C_{imf} = costs of one person-trip and ton-trip, respectively, using mode m (cost varies with number of persons or tons carried),
C_{vmp}, C_{vmf} = costs of one vehicle-trip for person and freight, respectively, using mode m (cost only relates to the vehicle, regardless of how many persons or tons are carried),
O_{mp}, O_{mf} = occupancy or handling rates for person and freight of mode m,
N_{mp}, N_{mf} = number of passenger and freight vehicles in the traffic stream, and
$CC\,(N_{mp}, N_{mf})$ = congestion cost.

If freight and passenger vehicle movements are expressed in equivalent transport units, such as pce,

using derivatives, one can differentiate the expressions for total benefits and total costs to obtain marginal benefits and marginal costs, equate them, and solve for the number of equivalent transport units. This will give the economic capacity of the facility in terms of traffic volume per unit time.

The results depend on the time horizon used. Benefits and costs are a function of traffic volumes, which may grow over time. If costs are relatively constant in real terms while benefits grow, then economic capacity will be larger the further into the future the planning horizon is.

9.4 BUDGET-CONSTRAINED ECONOMIC CAPACITY

Economic capacity can also be defined as the physical capacity of a facility, corridor, or network consistent with the supply- and demand-side capacity actions that maximize net benefits (or profit) subject to any budget constraints.

On the one hand, various supply-side actions can increase physical capacity of a facility, corridor, or network. On the other hand, various demand-side actions can improve capacity utilization. Some combination of supply-side and demand-side actions will maximize net benefits. The physical capacity consistent with the actions that maximize net benefits is the economic capacity. The maximization of net benefits can be performed subject to budget constraints if such constraints exist.

Various operations research and economic analysis procedures exist for determining budget-constrained economic capacity as defined in this section. The most common method is incremental cost-benefit analysis. Incremental cost-benefit analysis identifies the set of actions that maximizes net benefits on the basis of the incremental cost-benefit ratio of each option. The method produces a priority ranking on the basis of descending cost-benefit ratios up to the point where the funds are exhausted. By making the budget arbitrarily large (e.g., a trillion dollars), incremental cost-benefit analysis becomes a procedure with no budget constraints and can be used for needs analysis unconstrained by funding.

9.5 REFERENCES

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2. Peat, Marwick and Partners, *Passenger Service Costing: The Impact of Freight/Passenger Interference on Capacity and/or Cost.* Prepared for Transport Canada, Montreal (July 1977).
3. Khan, Ata M., *Railway Capacity Analysis and Related Methodology.* Research Branch, Canadian Transport Commission, Ottawa, Ontario (March 1979).

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 MULTIMODAL CORRIDOR CAPACITY ANALYSIS

Existing and projected bottlenecks in the transportation system continue to be a major concern. As the population and economy grow, traffic will increase too. As a result, increasing congestion and delay at many locations on corridors throughout the nation's transportation system will occur. Some of these bottlenecks are found on line-haul facilities and others occur at intermodal connections. ISTEA has been an impetus for conducting improved multimodal and intermodal analysis. States and MPOs have made considerable progress in developing performance measures of mobility and accessibility for various modes; however, measures of capacity and capacity utilization of various facilities that would be useful for statewide and metropolitan planning are rudimentary, except for modes with capacity analysis techniques that are well known and widely used by practitioners in public agencies.

The HCM has been the most widely used reference work with regard to various types of transportation capacity, but its focus is limited to highway, transit, bicycle, and pedestrian movements. It does not consider rail freight, air, waterborne, and pipeline transportation. Moreover, the HCM concentrates only on the supply side—the facilities and vehicles used to provide transportation. In other words, the manual gives primary attention to the denominator capacity in the v/c ratio. The manual does not give enough attention to the complementary and important role of managing demand, the numerator. In sum, there has long been a need for more readily accessible material and guidance on capacity analysis that address supply-side and demand-side actions, involving all modes of passenger and freight transportation. Another shortcoming of the HCM has been its focus on vehicle movement instead of person and freight movement, which vehicles serve. Transportation is a derived demand, stemming mainly from economic activity. Demand for vehicle transportation is a derived demand stemming from the need to move persons and goods integral to economic activity.

This research has sought to provide knowledge and techniques on how to address capacity problems of transportation corridors, particularly where multimodal and intermodal solutions can play an important role.

The original problem statement for this research called for a thorough review and compilation of literature related to addressing the capacity problems of corridors and development of a method for addressing corridor capacity problems. The challenge put to the research team was to determine what combinations of capacity expansion, corridor preservation, demand management, and technological solutions would be most appropriate for a specific set of circumstances. The research called for the development of a typology of transportation corridors and recommended actions appropriate to each type of corridor.

A major conclusion of the research is that the types of corridors and the range of potential solutions are so broad that simple answers are insufficient. Practitioners need a toolkit that can be used to evaluate a wide range of capacity problems involving all the principal person and freight transport modes. The toolkit also needs to address supply-side and demand-side solutions. This *Multimodal Corridor and Capacity Analysis Manual* is a significant effort to compile multimodal capacity analysis methods into a single reference document. The manual provides guidance on the following:

- Definitions and terms central to multimodal corridor and capacity analysis;
- A typology of corridors that helps illuminate the underlying reasons for capacity problems;
- Sample corridor case studies that illustrate how to define the scope of a multimodal corridor study and how to sharpen the definition of the problem as well as identify a preliminary set of alternatives;
- Capacity analysis methods pertinent to most major forms of transportation, including examples of how to perform capacity calculations (these address not only vehicle movement but also person and freight transportation);
- Performance measures for multimodal corridor analysis;
- A compendium of supply-side and demand-side strategies for addressing capacity problems and involving all the principal modes of person and freight transportation;
- Procedures for assessing the impacts of supply-side actions;
- Methods for assessing long-run demand and demand management options (these methods are suitable for sketch planning and involve various pivot-point procedures); and

- A sketch of a method for performing economic capacity analysis, which can complement methods of physical capacity analysis.

Economic capacity analysis needs to complement methods of physical capacity analysis. Some literature defines capacity in economic terms as the throughput such that the marginal benefits equal the marginal costs. Although physical characteristics of facilities may constrain throughput, practical decisions concerning transportation improvements often concern economic considerations to a great extent. It is important to evaluate the incremental benefits and costs of various actions, to account for budget constraints, and not to treat the supply side independent of the demand side.

This research included a major investigation of the feasibility of an overarching and generic approach to multimodal capacity analysis. An important conclusion of the study is that mode- and facility-specific capacity analysis techniques exist for a good reason. A unified and integrated framework that is simple to apply at the corridor level or more refined level of detail does not appear feasible. There are some sound general principles of capacity analysis, but their application goes only so far in obtaining meaningful answers to specific capacity problems. Capacity analysis, for the most part, requires methods tailored to specific modes and types of facilities, such as a particular type of intermodal terminal.

10.2 CASE STUDY CORRIDORS

The procedures in the *Multimodal Corridor and Capacity Analysis Manual* were developed during the first phase of the research. For the second phase, the NCHRP panel asked the research team to develop a series of case studies that would illustrate how to define the scope of a corridor study, establish the key parameters, identify the nature of the corridor problem, and develop a preliminary set of options for addressing the problem. The purpose of carrying out these corridor studies was twofold. First, the case studies, when included in the manual, would provide guidance to practitioners on how to begin a corridor study. Second, the panel hoped that carrying out the case studies would provide information and feedback on whether the manual required refinements.

After completing the case studies, the researchers concluded that the steps in Chapter 4, Corridor Identification and Problem Definition, are sound and worthwhile for a practitioner to perform. Moreover, nothing in the case studies suggests a need to modify other chapters of the manual. This is not to suggest the manual does not require considerable refinement.

10.3 RECOMMENDED FUTURE RESEARCH

This edition of the *Multimodal Corridor and Capacity Analysis Manual* should be the first of many editions. Just as the HCM has been updated regularly over the years, this new manual will need similar regular enhancements. A valuable and recommended action would be for a task force or other established institution to oversee this effort; appropriate funds should be provided and considerable breadth and depth of expertise covering all the modes should be brought to bear. The manual should be updated regularly, and computer software should be developed to assist the analyst who wants to apply the methods in the manual to multimodal capacity problems.

APPENDIX A

FEASIBILITY OF AN OVERARCHING APPROACH TO CAPACITY ANALYSIS

From the early stages of the study, the research team was very enthusiastic about the NCHRP Project, Long-Term Availability of Multimodal Corridor Capacity, because it offered an opportunity to identify and propose solutions for severe capacity problems throughout the country and because the project included development of the *Multimodal Corridor and Capacity Analysis Manual*. It was believed that there has long been a need to develop such a manual to complement the HCM and other capacity analysis procedures specific to certain modes. As stated in Chapter 2, Introduction and Research Approach, the development and dissemination of multimodal capacity analysis procedures has become an important issue in the ISTEA era with the emphasis on moving people and goods as opposed to merely vehicles.

From the outset, the research team explored two parallel paths, the first being the traditional one involving mode-dependent capacity analysis procedures as described in Chapter 5, and the second seeking an innovative, overarching approach applicable to most modes of transportation. One particular overarching approach was explored in great detail and involved the following formula for vehicular capacity:

$$\lambda_V^* = \left[\frac{L}{\left((h_d + l)\left(\frac{L}{V} + \sum_{i=2}^{N} n_i D_i\right)\right)}\right] * y$$

where

λ_v^* = capacity of a segment expressed as throughput of vehicles per unit time,
L = length of the segment,
h_d = minimum distance headway,
l = average length of vehicles,
V = desired speed,
$i = 1, \ldots, N$ index for source of noncongestion delay,
D_i = mean delay time for delay source of type i,
n_i = number of times delay source of type i found along the segment, and
y = number of lanes within the segment.

The innovative method of capacity analysis proposed was motivated by the idea that buffer capacity, and thus the length of the segment, has a bearing on capacity. The literature on stochastic processes seems to support the idea of accounting for buffer capacity. The method explored in detail breaks down because, in addition to accounting for buffer capacity, it indicates that capacity can be a function of the additive effect of delay, which is generally wrong. It seemed at first that accounting for buffer capacity has merit because it can address phenomena such as gridlock. That, however, proved to not be workable in the context of simple corridor analysis of the type the *Multimodal Corridor and Capacity Analysis Manual* intends to facilitate.

It was concluded that the formula above is correct and capacity can be a function of the cumulative noncongestion delay found along the segment only when the noncongestion delay is perfectly nonlocalized (i.e., uniform) over a segment. The presence of stop signs, stop lights, changes in roadway widths, and so on along a segment violates this condition. If there are no disruptions to traffic flow and the characteristics of the environment, roadway, driver behavior, and vehicle performance are perfectly uniform along the segment, then capacity can be a function of the sum of noncongestion delay sources. In practice, there are few circumstances in which these conditions apply. Thus, specific techniques tailored to various circumstances are required to account for buffer capacity and noncongestion delay in practical problems, and a simple generic and overarching approach of the type explored does not appear feasible.

APPENDIX B

SUMMARY OF CORRIDOR STUDIES

The following are summaries of multimodal corridor studies.

■ NORTHWEST CORRIDOR FEASIBILITY STUDY

San Antonio-Bexar County MPO
San Antonio, Texas
August 1993

The northwest sector of the city of San Antonio is adversely affected by traffic congestion, and projections show that congestion problems are expected to worsen substantially as traffic volumes increase beyond the capacity of improved roadways. The presence of some of the largest and fastest growing activity centers in the suburban areas of this sector creates a unique traffic flow pattern. The corridor experiences a reverse traffic flow pattern toward the suburban activity center as well as traffic flow toward downtown. As traffic congestion has worsened, significant improvements have been made to the existing roads. Construction, widening, and other roadway improvements have been completed or are under way. However, even after widening, existing north-south roadways will have a capacity that is well below expected traffic volumes by the year 2005 (projected average v/c ratio for any segment on the corridor for year 2005 is 1.1).

Solutions to the problems that were explored in this study are

- Further expand existing roadways,
- Develop HOV facilities,
- Increase vehicle occupancy through carpool and vanpool programs, and
- Use railroad rights-of-way (Southern Pacific Railroad).

The addition of more capacity on existing roadways is unlikely due to cost, right-of-way, and environmental considerations.

Major street grade crossings of the railroad right-of-way could exacerbate projected congestion levels. Grade-separated structures and realignment of local streets are therefore a potential capital expenditure especially if frequent transit headways are implemented along the railroad right-of-way. There are no environmental constraints on the use of the Southern Pacific Railroad corridor for public transportation purposes.

Evaluation of capacity enhancement transit options considered resulted in the following:

HOV Facilities. A single, reversible HOV lane on I-10 was proposed by the Texas Transportation Institute.

Passenger Shuttle Train. It appeared feasible to run a passenger train on an hourly frequency schedule without a signal system, but protection for the numerous crossings is strongly recommended due to the high concentrations of unprotected crossings in the first few miles. This concept was not pursued.

TSM. Low-cost TSM options investigated include bus-only lanes, signal preemption, bus stop spacing, and ridesharing.

Busway. Exclusive facility separated from mixed traffic by barriers. Entrance and exit ramps provide bus-only access to the facility. Flexibility is its main advantage in that buses on feeder routes can operate at high speeds within the busway. However, a more extensive feeder bus network is needed.

Busway + HOV. The addition of HOV to the busway alternatives will not increase operating costs based on assumptions. However, additional expenses may be incurred for an effective enforcement program.

Monorail. The technology evaluated was a fully automated, electric, straddle beam monorail similar to the one at Disney World in Orlando, Florida.

Light Rail. Light-rail transit may be constructed at-grade (mixed traffic) or elevated (exclusive right-of-way).

■ THE I-80 CORRIDOR STUDY: TRANSPORTATION OVERVIEW REPORT

Metropolitan Transportation Commission
Oakland, California
February 1987

A comprehensive study of the San Pablo corridor portion of I-80 from the San Francisco-Oakland Bay Bridge through Solano County was conducted in 1986. This corridor

includes portions of 4 counties, 15 cities, 10 public transit providers, and portions of 2 Caltrans districts. During the study, the I-80 corridor experiences severe congestion during commute periods, with peak-hour travel time in one segment increasing from 31 to 44 min. Despite the magnitude of highway improvements, the corridor is projected to experience severe peak-hour congestion in the year 2000. Construction of HOV lanes and other improvements will take 7 years, and only $90 million of $220 million total expenditures were committed.

Other capacity enhancement options studied are as follows:

Rail Transit Frequency Change. BART is to increase frequency from 9 to 12 trains per hour.

Bus Transit Route System Change. This is done to maximize efficiency.

Commuter Ferry Service. Ferry service between Vallejo and San Francisco is competitive with automobiles in terms of cost and travel time during peak periods.

Casual Carpooling. An informal system of drivers who pick up passengers in order to use carpool lanes results in lower transit usage in the morning than in the evening. Permanent and casual carpooling are expected to increase.

TSM. None of the communities along the corridor requires employers to implement alternative commuter programs in an effort to reduce the number of people who drive alone to work. However, free ridematching services are available to commuters throughout the corridor.

■ BINARY LOGIT COMPETITION MODELS OF NEW YORK CITY-BUFFALO INTERCITY RAIL PATRONAGE: DEVELOPMENT AND APPLICATION

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New York State Department of Transportation
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Using a 1975 aggregate database of 31 pairs of cities, forecasts are made of 1975 to 1980 rail patronage in the New York City-Buffalo corridor. A two-stage modeling process is used to estimate total city-pair volume by purpose, using gravity formulations relating annual volume to city size, government employment, and hotel and motel sales receipts. Binary logit models are then developed in which rail competes differentially with air, automobile, and bus in order to avoid independent irrelevant alternatives assumptions. Rail service and terminal quality variables are included with time, cost, and frequency. The total rail share is then determined algebraically from the binary models. Pivot-point analysis is used to increase the accuracy of the forecasts.

Results show that rail competes differently with each mode. Against air, the key variables are frequency and time ratios; against automobile, the frequency, cost, and time ratios and terminal quality are important; against bus, train service quality, frequency ratio, and time difference are important. Elasticities of demand vary considerably by mode and distance. Forecasts show that if train, track, service, and terminal improvements are implemented as planned in the corridor over the next 5 years, 1980 link volumes will increase from 58 to 105 percent over 1975 levels, with most diversion coming from short-distance automobile trips. The net effect of this diversion will be to reduce 1980 corridor energy requirements by 9 percent from 1975 levels. Without such improvements, however, the general expansion of total corridor traffic will not substantially increase rail traffic.

■ NORTHEAST CORRIDOR HIGH-SPEED RAIL SYSTEM PATRONAGE ANALYSIS

Sokolsky, S.
Aerospace Corp.
Energy and Resources Division
El Segundo, California
Sponsor: Transportation Systems Center, Cambridge, Massachusetts
Contract No. DOT-TSC-936
April 1975

A high-speed passenger rail service between Washington, D.C., and Boston was called for in the Regional Rail Reorganization Act of 1973. Planning for the service has been conducted by the Office of Northeast Corridor Development in the Federal Railroad Administration. Engineering studies were undertaken to develop detailed plans and costs for the required facilities improvements. This report provides a program overview, an arena description, a high-speed rail system patronage, Northeast Corridor improvement options, high-speed rail system improvement options, patronage elasticities, and projections for 1982 and 1990.

The results for the baseline system mode split analysis indicate significantly lower patronage in the north corridor (New York-Boston) relative to that in the south corridor (New York-Washington, D.C.). There are a variety of reasons for this, beginning with the historical fact of much lower patronage in the north than in the south. With respect to the simulation, north corridor system patronage is impacted by the fact that block times are significantly longer than those in the south, automobile costs are lower in the north because of lower tolls, and air fares in the north are slightly less than those in the south. Furthermore, air system block times are slightly better in the north corridor despite the fact that block distance is slightly longer, because delays are experienced only in the New York area, whereas south corridor traffic experiences delays both in New York and in Washington, D.C. Block time and fare reduction strategies are seen to generally induce higher patronage. The results indicate large percentage improvements in patronage in most city-pairs. The two city-

pairs emanating from New Haven, Connecticut, exhibit the lowest percentage increases, because the most split is already reasonably good for the baseline system. The New York to Boston mode split still remains lower than that for New York to Washington, D.C., but it may be observed that a factor-of-two increase is possible through the improvement program.

■ IMPROVING FREIGHT MOVEMENT IN DOWNSTATE NEW YORK

Regional Plan Association
1211 Avenue of the Americas
New York, New York
November 1992

Economic competitiveness and quality of life in downstate New York (includes counties in New York, northern New Jersey, and southwestern Connecticut) are being undermined by an aging and overloaded ground-freight transportation system that is not well-balanced between rail and trucking. These factors increase costs and pollution and reduce efficiency and shippers' choices.

The problems are as follows:

- Close to 40,000 trucks cross the Hudson River from New Jersey each day, and approximately one-third of these travel during the 6:00 to 10:00 a.m. period when the automobile commuter traffic is heaviest.
- One out of every three persons has a car, up from one out of every five in 1950.
- Key trucking corridors such as the George Washington Bridge/Cross-Bronx Expressway/New England Thruway and I-278/Gowanus Expressway/Brooklyn-Queens Expressway/Long Island Expressway have traffic volumes exceeding capacities.
- Excessive single-occupant vehicle use in key corridors gets tangled up with truck traffic, causing freight movement delays.
- In downstate New York, freight movement by rail is only 2 percent of total, whereas nationally it is 40 percent. The reasons are as follows: (1) only one long-haul carrier (Conrail) exists; (2) there is a lack of direct rail access to important customers; (3) there are physical restrictions on the use of most modern and efficient rail equipment (e.g., rail clearance and antiquated infrastructure); and (4) there is lower quality and higher cost service in New York relative to rail transfer facilities in New Jersey.
- New Jersey and, more recently, Pennsylvania have become the distribution hubs for the downstate New York area as a result of their access to modern rail and terminal facilities, cheaper land, and less congested major highways. Two-thirds of the region's population lives east of the Hudson River but it is supplied by freight terminals, warehouses, and distribution centers to the west.
- Poor curbside management and limited off-street loading facilities force many to double park or to cruise the area in search of an open parking space, thus adding to traffic and pollution.

The Regional Plan Association proposed several short-term and long-term actions to solve these problems including (1) improve rail competitiveness, (2) create truck priorities, (3) improve truck efficiencies, (4) employ "smart highway" technology, and (5) minimize truck-induced air pollution.

■ MACRO ANALYSIS OF THE IMPLICATIONS OF MAJOR MODAL SHIFTS IN INTEGRATED REGIONAL TRANSPORTATION NETWORKS

Billheimer, J.W.; Bullemer, R.; Holoszyc, M.
Systan, Inc.
Los Altos, California
Report No. SYSTAN-D147; DOT/TST-76-65
April 1976

The report describes a macroanalytic approach to the problem of analyzing changing travel patterns in an integrated regionwide transportation network. Separate models of residential areas, transportation corridors, and central business districts are combined in a modular representation of urban structure suitable for use in policy analysis and transportation planning. This analytic approach treats demand parametrically, has minimal data requirements, and provides rapid insights into the impacts of alternative patterns of transit and automobile usage. Such impacts as travel time, user costs, congestion, and energy consumption are examined explicitly. Application examples discuss the potential economies of scale available from major shifts in current transit usage patterns, tradeoffs between flexible-route and fixed-route systems, and the potential benefits from policies to reduce the effects of demand peaking.

■ FORECASTING INTERMODAL COMPETITION IN A MULTIMODAL ENVIRONMENT

Neels, K.; Mather, J.
***Transportation Research Record 1139*, pp. 15–19, 1987**

In this paper, the problem of accurately describing patterns of intermodal competition in a situation in which there are a large number of alternative modes available is discussed. This research was motivated by efforts to increase the capacity and usage of the existing Hudson River crossings connecting Manhattan and northern New Jersey. This corridor is characterized by the presence of an unusually large number of distinct transportation options and a high level of transit use. In such a setting, it is important to know not just how many commuters might use a new service but also from which existing services they would be drawn. The mathematical structure of an innovative model developed for NJ Transit and the Port Authority of New York and New Jersey to allocate demand across seven primary modes is presented. The representation of intermodal competition that this model provides is considered, and its properties are contrasted with those of some commonly used variants of the familiar logit model. Empirical estimates of the own- and cross-elasticities

of demand implied by the model coefficients are broken down by mode, service attribute, and geographic area.

■ WEST COAST CORRIDOR STUDY, WASHINGTON SUBCORRIDOR

Cowan, G.R.; Horn, A.L.; Guillot, E.D.; Heller, T.A.
Washington State Department of Transportation
Olympia, Washington
Sponsor: Federal Railroad Administration, Washington, D.C.
Contract No. DOT-FR-6041
September 1978

Intercity travel demand in the Washington subcorridor of the west coast corridor has been rising and will continue to do so in the future, based on the projected rising population and increasing per capita income. The extent of the growth in travel demand will depend to a large degree on the price of fuel and the achievement of federally mandated automobile fuel efficiencies. A price elasticity of −0.28 percent was found for gasoline within the state of Washington. Population growth is projected to be greatest in suburban areas not currently well-served by public transportation. Following current trends, each travel mode would gain additional riders with automobile travel growing most. An expansion of intercity bus service would be profitable under scenarios with low, medium, and high fuel prices. Railroad passenger ridership could more than quadruple with vastly improved service, but the annual operating losses would be very substantial and the total ridership still remains small. The capital construction costs would be enormous. Highway travel is expected to grow between 60 and 200 percent depending on the price of gasoline. During an energy shortage, intercity bus has the greatest potential for moving people with a minimum of fuel. Intercity rail is second best. The automobile and aircraft modes have the lowest fuel efficiency. The Federal Railroad Administration's proposed restructuring of Amtrak will reduce the subcorridor's railroad ridership by one-half.

■ ELASTICITY-BASED METHOD FOR FORECASTING TRAVEL ON CURRENT URBAN TRANSPORTATION ALTERNATIVES

Brand, D.; Benham, J.L.
Charles River Associates, Inc.
Transportation Research Record 895, **pp. 32–37, 1982**

This paper presents a quick-response incremental travel demand forecasting method that uses travel demand elasticities and readily available ground-count travel and land use data. Elasticities are defined and criteria for selecting elasticities are identified. The steps for calculating each component of travel affected by a transportation improvement are described. Personnel and computational requirements for this method are greatly reduced relative to those necessary for forecasting with the conventional four-step sequential process (trip generation, distribution, modal split, and trip assignment). The basic travel behavior assumptions of the method are similar to those inherent in conventional models although, in contrast to sequential derivation and application of these models, internally consistent causal relations are maintained. A range of outputs of interest to policy makers is generated, including changes in total travel, changes in mode-specific travel, and changes in travel on a given route or link. The elasticity-based method was used to forecast patronage on the four major transit alternatives included in the Baltimore north corridor alternatives analysis. This application is described in the paper. It is also compared with forecasts made in a particular application of the conventional four-step sequential travel demand forecasting system for the same alternatives and under the same conditions. This direct comparison of the two forecasting methods provides a unique opportunity to assess the effects on forecast patronage of many assumptions inherent in typical applications of each method.

■ PREDATORY PRICING IN INTERCITY PASSENGER TRANSPORTATION MARKETS: AMTRAK VERSUS GREYHOUND

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Iowa City, Iowa

The author presents arguments for the contention that Amtrak is indeed in competition with private intercity bus carriers, that Amtrak's policy of promoting ridership at the expense of economic efficiency has harmed bus carriers, and that this could adversely affect the traveling public as a whole. He cites data indicating that there is significant cross-elasticity of demand between rail and bus riders and that Amtrak does not maximize revenue given competitive conditions. Concern is expressed that the current situation could lead to cutbacks in bus service to rural areas not served by rail through revenue decreases in the urban corridor bus service subsidization and competition with Amtrak. Such cutbacks would offset the minimal (or nonexistent) social gains effected so far by Amtrak.

■ AN EQUILIBRIUM ANALYSIS OF SELECTED INTERCITY FREIGHT MARKETS: TRUCKS WITH DOUBLE TRAILERS VERSUS TRAILER ON FLATCAR (TOFC) SHUTTLE TRAINS AS ENERGY CONSERVATION ALTERNATIVES

Roberts, P.O.; Brigham, T.B.; Miller, C.A.
MIT Center for Transportation Studies
Sponsor: U.S Department of Transportation, Washington, D.C.
Report No. CTS-77-25; DOT/RSPA/DPB/20-79/2
December 1977

The objective of the research is to determine the transportation market consequences in an environment in which two competitive modes, TOFC shuttle trains and double-trailer

trucks, are allowed to compete freely. The analysis requires looking at both the demand side and the supply side. A model of the decisions made by individual managers responsible for logistics is used on the demand side. For each firm, it is possible to hypothesize a logistics cost for maintaining an inventory of each of the inputs used in the production process. Such a logistics cost function contains elements for placing an order, transporting the goods, distributing and storing them, paying interest on the money invested, and incurring such costs as would accrue with a stockout of these goods. The logistics cost function is minimized by simulating the decision maker's manipulations of certain choice variables. These include the point of purchase or acquisition of the product, the decision when to reorder and in what size of shipment, and, finally, the mode used for its transport. This demand model of individual decision makers is used to analyze a sample of the population of shippers within three major city-pair markets for the year 1967: Philadelphia-Cleveland, San Francisco-Los Angeles, and Chicago-Houston. The decisions of the individual decision makers are aggregated for each of the policy options under consideration, and a comparison is performed with the base case for each market. The results give an indication of the shipper response to each of the options. Fuel use implications of each of the policy options is developed.

■ NORTHWEST TRANSIT CORRIDOR REFINEMENT STUDY

Atlanta Regional Commission
Atlanta, Georgia
March 1992

This study builds on the results of a 1989 future transit corridors study, which identified several potential rail transit corridors, including radial corridors to Cobb and Gwinnett counties and a circumferential corridor in Cobb, Fulton, and DeKalb counties. It encompasses the northwest radial corridor from Atlanta to Cobb County, and the northwest circumferential corridor from Cumberland to Perimeter Center. The overall purpose of this study is to make a more detailed assessment of the costs and benefits of the potential corridors. It includes an assessment of whether new transit facilities in the corridors would meet cost-effective guidelines established by the FTA.

Six system alternatives were analyzed for patronage, costs, and effectiveness—one TSM alternative (HOV lane) and five rail alternatives. New rail technologies were also explored. The study concluded that none of the rail lines meets FTA guidelines for federal funding (using the efficiency measure of cost per new rider). Freeway congestion in I-75 and I-285 has been found not to warrant rail transit lines. Furthermore, extensive structures and substantial right-of-way acquisition make rail development in the area costly. On the other hand, dedicating existing freeway lanes to buses and HOVs were found to be cost-effective, especially if complemented by additional park-ride lots and expanded bus service. Analysis of the potential uses of abandoned freight lines for commuter rail service was proposed.

■ PASSENGER RAIL FEASIBILITY STUDY

Sarasota/Manatee Metropolitan Planning Organization
Sarasota and Manatee Counties, Florida
May 1991

The purpose of this study is to assess the feasibility of passenger rail service and express bus service for Sarasota and Manatee counties in Florida. Three alternatives consisting of combinations of commuter rail, light-rail transit, rapid rail, intercity rail (Amtrak), and express bus were identified: (1) within Sarasota and Manatee counties; (2) in Sarasota and Manatee counties with connections to Tampa; and (3) in Sarasota and Manatee counties with connections to Tampa and Fort Myers. Rail alternatives would use existing freight railroad. Ridership for the years 1995 and 2010 was estimated and used in evaluation. Forecasts are based on existing bus transit ridership, automobile trips attracted to transit, population growth over the next 20 years, and additions of extensions to the Tampa area. It was assumed that a shared-use arrangement for passenger and freight rail services would be established. The alternatives would require significant improvements to the existing railroad base and track. Stations and passing sidings would have to be constructed.

Estimates of operating cost per rider for the intercity train and commuter rail alternatives are very high, exceeding $100 per rider. The operating cost for the light-rail transit is lower, but the capital costs are more than seven times greater than the other rail alternatives. Bus operating costs are closer to the feasible range.

Based on the feasibility assessment for rail and bus alternatives, none of the options appears to be justified by cost per rider indices because of low ridership and high capital cost and unavailability of funding. However, population growth, employment growth along the corridor, fuel costs, and parking costs may require reassessment of feasibility of rail alternatives. The study came up with a table that shows the typical population densities required to support various transit technologies.

■ LONG-RANGE SYSTEM PLAN

Mid-Ohio Regional Planning Commission
June 1993

Growth in central Ohio continues to exceed previous forecasts and expectations. Transportation projections show that the transportation planning area will have 1.3 million people by the year 2010, supported by an additional 225,000 jobs in the same time period. Large increases in population and employment will cause corresponding growth in travel, estimated at 37 percent of the total vehicle miles. The average v/c ratio for the region is projected to be 0.88 (LOS E), indicating higher travel times and congestion during weekdays.

The north corridor shows the highest number of projected person and work trips of all the eight travel corridors identified. Studies indicate that an enhanced bus system combined with fixed guideway rapid transit such as light

rail will improve travel conditions in this and the west and northwest corridors. It will also furnish an alternative to highway travel. The components of this corridor are commercial thoroughfares, industrial freeways, interstate highways, and a double track right-of-way owned by Conrail.

Specifically, three transit alternatives were explored:

- No-build alternative—Use of the current bus fleet,
- TSM improvement—Consisting of all-bus improvements, and
- Light-rail transit—Proposed alignment utilizes a portion of the current railroad right-of-way.

Based on estimates, the TSM will serve approximately 47 percent more riders than the null alternative, and light-rail transit will serve nearly 60 percent. In order to determine whether an alternatives analysis will be approved by FTA, cost-effectiveness indices were calculated (the corridor currently has 19,000 daily trips, satisfying the first FTA requirement). Light-rail transit indices were determined to be close to $10 per rider, indicating that the fixed guideway system should be adopted. At a minimum, TSM bus alternatives were recommended.

■ FEASIBILITY STUDY REPORT (On Route 710 Freeway from Long Beach to Route 5 Freeway)

California Department of Transportation
February 1993

Route 710, from the Port of Long Beach to Route 5, is a major interstate freeway that runs north and south and serves as one of the main arteries for inter- and intraregional commuting and shipping through an urbanized corridor. Truck traffic accounts for 20 percent of the traffic on the south end of the corridor and 10 percent on the north end. A number of cities, government agencies, and the Port of Long Beach recognize that the ever-increasing volumes of cargo moving through the Port and onto Route 710 will increase traffic congestion. This study examined the feasibility of providing an exclusive and separated truckway facility along the corridor to carry the projected traffic in year 2020.

Three alternatives were studied:

- Do nothing and allow progressive deterioration of LOS to F for major corridor components,
- Provide a barrier-separated truck facility combined with a viaduct in the median at specific locations (involves widening the existing freeway), and
- Provide a viaduct for the entire length of the project directly adjacent to the levee of the Los Angeles River.

Evaluations of these alternatives indicate that the second alternative is feasible, with the viaduct option used in those areas where right-of-way constraints make it difficult to widen existing freeways. In those areas where sufficient ROWs exist, conventional freeway widening is proposed to accommodate the proposed truckway. The third alternative is also feasible although it will incur a high cost due to extensive structural work and ROW acquisition, it completely separates truck from the mixed flow traffic.

■ US-70 CORRIDOR STUDY (from Durham County Line to Duraleigh Road Wake County, North Carolina)

March 1992

This study concerns a 7-mi minor arterial highway (US-70) in Wake County, North Carolina. It focuses on measures of controlling access and optimizing intersection efficiency along the corridor to protect the traffic-carrying capacity of the roadway, with particular emphasis on minimizing stops and delay for through traffic on US-70. Capacity analysis for peak-hour traffic volumes in the year 2010 indicated an unsatisfactory level of service at all of the major intersections along the corridor. Based on this analysis it was determined that a higher level of traffic design, with more interchanges and fewer signalized intersections, would be needed to meet future traffic demand. Collector roads were also proposed to be relocated to be compatible with traffic needs, development, and topography. Alternative analyses of corridor improvements show that all the signalized intersections along US-70 are projected to operate at LOS D (considered acceptable) or better. Phasing recommendations for the improvements were based on availability of funds, traffic growth rate, and developments in the corridor area. Greenways and visual resources were also carefully examined and areas that may be affected by proposed improvements were identified.

■ SACRAMENTO SYSTEMS PLANNING STUDY

Sacramento Regional Transit District
February 28, 1991

If current Sacramento Council of Governments projections are correct, Sacramento County will continue to grow rapidly. Projected population and employment growth will combine to increase overall tripmaking in the region by the year 2010 to a level 57 percent greater than it was in 1991. Given this projected increase in travel, jurisdictions within the Sacramento area need to take significant action including the construction of new fixed guideway transit lines to accommodate the travel demands. This study recommends actions that would improve public transit services, reduce congestion, and improve air quality.

Eight corridors were identified in the system study area. For these corridors, eight system alternatives were examined and compared in terms of projected 2010 patronage, costs, cost-effectiveness, operational characteristics, land use impact, environmental impact, and impact on air quality. These alternatives are as follows:

- No-build,
- TSM (best or expanded bus),
- HOV/busway system,
- Commuter rail, and
- Light-rail transit (four options).

The study indicated that light-rail transit corridors are most desirable based on projected patronage and cost-effectiveness.

Because the implementation of light rail and other system alternatives requires right-of-way, the study indicated that whenever possible, right-of-way should be acquired early to preserve the options for future fixed guideway and relatively high-speed public transit lines, even in areas where the need has not yet been fully demonstrated. Right-of-way should also be acquired early to establish locations for future transit lines so that land use planners and policy makers can organize adequate development in ways to encourage transit use. It was recommended that as soon as the various fixed guideway alignments are known and appropriate funding, private or otherwise, becomes available, right-of-way should be acquired or otherwise preserved for the corridors.

A comprehensive, high-quality light-rail transit system, backed up by a good bus system, can serve as an excellent alternative to the automobile. However, demand management strategies such as parking restrictions, pricing, telecommuting, and land use planning should accompany the expansion of light-rail transit systems.

■ CORRIDOR STUDY

Strategic Implementation Plan
Marin and Sonoma County, California
June 1989

In an effort to respond to the projected 50 percent increase, by 2005, in commuting traffic in North Bay, California, representatives from Marin County, San Francisco, Sonoma County, 11 cities in Marin County, and 7 cities in Sonoma County met in 1983 with representatives of ABAG, the Metropolitan Transportation Commission, Caltrans, and North Bay transit operators to form the 101 Corridor Action Committee. In 1984, the committee reached a consensus on the types of transportation projects and services that should be implemented in the corridor. After several years of analyses, evaluation, and comparison of projects and corridor components, the committee adopted the 101 Corridor Plan in 1989. The plan is a balanced highway and transit program designed specifically to meet the transportation needs in the 101 corridor over the next 20 years. The plan responds to the growing travel demand in the corridor in an environmentally sound manner that is supportive of desired land use policies and responsive to public opinion throughout the North Bay area. The plan consists of the following components:

- Widen lanes from four to six and add HOV lanes for a continuous 52-mi HOV lane;
- Implement a continuous commuter rail transit system in Sonoma County and a light-rail system in Marin County;
- Implement a high-speed catamaran ferry service to San Francisco;
- Increase transbay bus service from south Marin County to San Francisco;
- Construct, widen, and extend seven arterial and connector roads; and
- Leave peak-hour highway capacity on Golden Gate Bridge and Doyle Drive unchanged.

A key element of the corridor plan is the passenger rail service, which would cost approximately $426 million (1989) in capital and operating costs. Funding sources include sales taxes, the FTA, State Rail Bond, HR 2, and bridge tolls to subsidize transbay rail riders. The annual cost for the commuter train service was estimated at $5.7 million in operations and maintenance, expected to be offset by $2.8 million in passenger fares, resulting in a net public cost of $2.9 million. Annual cost for the light-rail transit was estimated at $8.8 million, with passenger revenues covering some $4.9 million, leaving $3.9 million in annual public cost.

Half of the forecasted rail passengers will be taking the ferry service for a transbay trip to San Francisco. Frequency of ferry service will have to be increased to accommodate these passengers during both peak and off-peak hours. Large and faster catamaran vessels (with 400-passenger capacity) are expected to cruise the 11.3-mi distance in 35 min. Other ferry services will also be upgraded. The total capital cost of the improved ferry operations is $43.2 million, the annual cost is $13.7 million, and the annual passenger revenue is $9.6 million, leaving an annual public cost of $4.1 million.

Bus services will be expanded to serve rail stations and schedules will be coordinated with the train arrival and departure times. Forty-six buses will be added to the existing fleet of 281, resulting in capital costs of $13 million.

Fifty-two miles of the 101 corridor will have HOV lanes as a result of widening highway segments and/or modifying the interchanges throughout the corridor. Capital costs for these improvements are estimated at $467 million. Alternate and parallel routes and connector roads will be improved to provide motorists additional routes to 101, thereby removing some of the local or short-distance trips from the freeway.

The rationale for leaving the capacity of the Golden Gate Bridge and Doyle Drive unchanged stems from the limitation of downstream roadways to accommodate additional traffic volumes; the desire to increase the use of public transit, carpools, and vanpools; and the prediction that 90 percent of the increased commuting by Marin and Sonoma residents will be to jobs located in the North Bay area rather than in San Francisco.

■ STATE ROUTE 240 TRANSPORTATION STUDY

Benton-Franklin Regional County, Washington
July 1993

Route 240 in Richland, Washington, is the area's busiest traffic corridor. In the past years a steady increase of traffic has been experienced along the corridor. Much of this increase can be attributed to recent employment surges along the corridor. This traffic volume increase has resulted in operational problems on Route 240 bypass and other roadways and intersections along the corridor. Travel forecasts for the year 2012 show substantial increases from base year figures, reducing the system operating speed and increasing the v/c ratios in the next 20 years.

Traffic studies for the corridor showed a low percentage of multiple occupancy (> 1) usage at 13 percent, a 30 percent to 50 percent load factor for commuter buses, excessive vehicle delays, and low LOS for many signalized and unsignalized intersections, ramps, and roadway segments. The study investigated the following potential solutions to current and future capacity problems:

- TIP—minor improvements,
- Reconstruction and widening of existing roads,
- Construction of a new route to divert traffic from Route 240,
- Construction of a new bridge that will directly connect two areas, and
- TDM solutions such as the Washington State Trip Reduction Ordinance.

Several performance measures were used to compare the impacts of the options including VMT, vehicle hours traveled (VHT), number of trips taken, operating speed, v/c ratio, lane miles, and lane miles for v/c greater than 0.8 (represents congested conditions). The conclusions drawn from the analysis are that all construction options indicated improvement over the no-build option. (However, the analysis indicated that construction of the freeway increased the amount of travel to the point where it was congested.) VMT was lowest for the TDM strategies and construction of the toll bridge. Implementation costs and funding sources were identified for comparative purposes.

The feasibility of a shuttle rail system using a heavy rail line through the area was previously studied. However, maintenance and upgrade needed on the railroad tracks and ballasts would require a significant amount of ridership to warrant the repairs and keep the service operating within fiscal limits, making the option nonviable.

Biking, walking, and other nonmotorized transportation were also explored because the work trips in the corridor were relatively short, and the climate and relatively flat terrain in the area are inducements. The study reported that safe, clear, delineated, and well-maintained bike routes and bicycle parking and locker facilities at the workplace are incentives for biking.

■ TRANSPORTATION DEMAND MANAGEMENT IN THE NEW YORK REGION

Regional Plan Association for the New York Metropolitan Planning Council
June 1991

This report by the Regional Plan Association defines and explains various TDM actions and how they can be used for transportation planning and specifically for the New York region. TDM strategies were evaluated for three study areas: the Staten Island Expressway (SIE), Long Island, and Westchester County.

The 9-mi, six-lane SIE through northern Staten Island connects the Goethals Bridge on the west with the Verrazano-Narrows Bridge (VNB) on the east. The SIE, also known as I-278, provides a critical circumferential link in the regional highway network and, with the VNB, provides a way to travel between central New Jersey and the four counties of Long Island. This through-travel function and the function of serving the growth on Staten Island results in increased traffic and the inevitable congestion that follows. Five of the seven easternmost miles of the SIE in the eastbound direction have LOS E to F from 6:00 to 8:00 a.m.

■ TWO AIRPORT ISSUES IN THE NEW YORK REGION

Regional Plan Association for the New York Metropolitan Transportation Council
October 1991

The report examines the options of building a fourth airport to serve the New York region and of improving access to the existing airports.

■ URBAN TRANSPORTATION: ISSUES RELATED TO THE SOUTH CORRIDOR (CHICAGO) STUDY

U.S. General Accounting Office Report
August 1993

Chicago's Regional Transportation Authority initiated the South Corridor Transit Study to obtain a comprehensive analysis of transit service in the area. The study reviews the four major transit lines in the area that carry commuters downtown and are operated by the following agencies:

- Metra—Provides commuter rail service that transports commuters from the South Side and suburban areas to downtown Chicago, and
- Chicago Transit Authority (CTA)—Provides rapid transit on two elevated train lines and express bus service.

Rationalization of transit service (in terms of operating cost per rider) was the principal objective of the study. Alternatives evaluated in the south corridor study follow:

Null Alternative

- Maintain existing transit system.

Short-Term Alternatives

- Fare integration—Coordinate the fare structures and transfer policies of CTA and Metra,
- Rail station modifications—Consolidate lower volume rail stations on Metra lines and improve parking and access to the remaining stations, and
- Express bus conversion—From direct bus access to Chicago to local rail feeder buses.

Long-Term Alternatives

- Light-rail line—Eliminate some rapid transit lines and express buses, and
- Rapid rail extension.

Implementation of one or more of these alternatives was judged unlikely for the following reasons:

- The transit agency would have to pay back the FTA for improvements made on some transit lines that were proposed to be eliminated.
- Any change in transit service would have to be reviewed for compliance with the Civil Rights Act of 1964 . The Act requires a transit agency to hold a public hearing, at which any possible discriminatory effects of the change could be identified and addressed.
- The funds to implement any of the null and long-term alternatives may not be forthcoming.
- Long-range alternatives for the south corridor would have to be consistent with the region's long-range transportation plan.

■ RAPID CITY I-90 CORRIDOR STUDY, 1987-2005

South Dakota Department of Transportation
February 1988

This study identifies 1987 and forecasted 2005 capacity and LOS operations for I-90 between Ellsworth Air Force Base and Deadwood Avenue in Rapid City, South Dakota. Based on trend analysis, an average of 10 percent growth per decade within the Rapid City urbanized area is expected. South Dakota DOT will accept the current LOS C and forecasted LOS D on interstate ramps during peak-hour operations. The study proposed resurfacing and nonconstruction alternatives such as work shift changes for Ellsworth Air Force Base (the major area employer) in order to provide an adequate LOS until the interstate highway is reconstructed in the year 2000. It also recommended that the corridor should be preserved to allow management and designers the choice of constructing a six-lane freeway facility in the year 2000, because the existing four lanes will function at acceptable LOS only until 2005. Specifically, rights-of-way along frontage roads and interchanges will have to be preserved. No cost comparisons were made.

■ 21st CENTURY PARKWAY

Design Concept Study
Johnson County, Kansas
May 1992

The 21st Century Parkway in Kansas is a proposed public works improvement that is intended to meet growing transportation needs in Johnson County. The Parkway is conceived as a framework for increased mobility, linking regional transportation facilities, airports, development areas, employment centers, recreation amenities, and communities. The proposed roadway will replace the function of a circumferential highway system consisting of several routes that has become ineffective due to the urban growth in the county. If the functional replacement is desirable, a definite commitment to preserve right-of-way had to be made as soon as possible while open space is still available.

Since 1940, the Kansas City population has grown from about 780,000 to 1.5 million in 1990. Johnson County's population and employment, as percentages of the total regional figures, increased from 4.3 percent to 22.7 percent and from 11.2 percent to 25.2 percent, respectively, during the period. The county is projected to capture 53 percent of the increase in metropolitan population and 45 percent of the regional job growth between 1990 and 2010. The 21st Century Parkway is seen as a way to maintain future mobility of persons and goods in the county.

The objectives of the study were to provide a sufficient amount of data for the county commissioners to make a "go" or "no go" decision on development of the parkway, to evaluate and recommend alternative and preferred alignment locations within the previously established corridor, and to provide forecasted travel demand information to explain the need for the parkway corridor. Right-of-way costs for the 35.5-mi alignment were estimated at $5.4 million, and total construction costs for a four-lane highway are approximately $143.5 million. Displacements amount to five residences and three businesses plus relocation of several mobile homes. The study also evaluated the environmental impacts of alternatives and found no setbacks.

■ US-30 SUBAREA STUDY

Northwestern Indiana Regional Planning Commission
February 1993

The study was a response to the problem of traffic congestion on Route 30 (arterial) in Central Lake County, Indiana. The congestion is a result of the high rate of growth of land development, the US-30 area became the CBD of northwestern Indiana. US-30 is the only road in the area capable of carrying a large volume of traffic, making it overburdened.

Analysis of traffic accident data and testing of various alternatives to reduce projected growth in traffic volume on congested portions of US-30 were undertaken in the study. Specific goals were as follows:

- Reduce accident rates,
- Increase overall system LOS,
- Reduce motorist delay,
- Increase area accessibility,
- Coordinate developmental schemes to provide a more consistent land use pattern,
- Develop and provide reserve capacity (supply) to satisfy current and expected future travel demands, and
- Increase the market area and/or provide capability for new market development.

The basic problem identified in the study is lack of a comprehensive plan for the area, including coordinated transportation and land use components, which resulted in residential and commercial developments along US-30 and throughout the area that generated many more vehicle trips than the transportation system could effectively serve. US-30 has been widely perceived at a congested facility, particularly at signalized intersections. Access between US-30 and the adjacent land reduces its ability to serve as a principal arterial route.

A transportation planning package (QRSII, which uses the four-step model) was employed to estimate traffic volumes and delays on highway links and nodes. Travel projections for the year 2010 were determined using forecasts of 2010 socioeconomic data. Four alternatives were analyzed:

1. Do-nothing—Undertake only those improvements that have already been committed for implementation,
2. Improve roads in the area other than US-30 and US-41,
3. Add two public transit services (express and shuttle bus), and
4. Improve US-30 and US-41.

Based on the results of model analysis, Alternative 2 will result in the lowest traffic volume on US-30. The study recommends that improvements be made to the street system, including the construction of alternative routes to accommodate local traffic and access management techniques for US-30 such as elimination of direct access between US-30 and adjacent land, elimination of median openings except at signalized intersections, and improved channelizations of turning movements.

■ THE PARKWAY WEST MULTIMODAL CORRIDOR STUDY

Prepared for Southwestern Pennsylvania Regional Planning Commission

August 1989

The study area is delineated by the eastern and western limits of the Parkway West: downtown Pittsburgh and the Greater Pittsburgh International Airport. In all, the area is composed of 40 municipalities in Allegheny County plus 18 wards in the city of Pittsburgh. The area is projected to account for 54 percent of the population growth in Allegheny county and 21 percent of the growth in the region for 2010.

Parkway West consists of selected existing major expressways and arterial highways, bus routes, and a fixed transit system considered to have systemwide significance. The study investigated existing (1985) and future (2010) travel conditions. Future conditions are based on 2010 travel data for the existing plus committed transportation facilities. A corridor profile that examines the traffic patterns and LOSs for various components of the Parkway West study area was developed in order to identify how well the system is accommodating travel and how well it will accommodate travel by the target year 2010. More specifically, the intent was to identify deficiencies in the corridor that would be the target for improvements. The deficiencies took the form of 213 highway segments that are currently operating, or will operate in the future, at an unacceptable LOS. Because virtually all transit service in the area consists of bus service that operates on existing highways, the unacceptable LOS segments represent deficiencies in the transit system as well. Causes of deficiencies are as follows:

- The three major highway bridges and tunnels serving traffic from the study area to downtown Pittsburgh are major constraints to capacity leading to the CBD.
- The interchanges on the corridor are either incomplete or poorly designed.
- More trips are made to downtown Pittsburgh than the present system capacity can accommodate.
- Every major radial route to downtown is or will be operating at LOS E or F.
- Many of these routes cannot be widened or are constrained by a bridge or a tunnel.
- The increase in the employment in the Central Parkway and airport (Pittsburgh's Midfield International Airport is already operating) will cause the LOS of the corridor to drop.

Following are some of the alternatives considered for correcting these capacity deficiencies:

- Redirect traffic on bridges serving the corridor to other bridges.
- Add new bridges.
- Shift substantial portion of trips to transit (busways).
- Reconstruct existing interchanges or add new ones.
- Widen the parkway, and
- Provide a new alternate radial route to downtown.

These alternatives (involving several components of the corridor) were evaluated and screened both in quantitative and qualitative measures that include capital cost, speed, LOS (decrease in VMT and VHT or increase in v/c ratio),

environmental impacts, and nontransportation objectives such as development. The "screening" of these options resulted in five alternative, multimodal programs, each consisting of a package or suite of highway and transit projects. These packages were further evaluated and compared to identify the most effective solution to the transportation issues in the study area.

The general conclusion of the study was that the cost of rail transit compared to busway is not justified; however, fixed rail is not precluded from any future analysis.

■ IMPROVING ACCESS TO CALIFORNIA PORTS

California Transportation Commission
Caltrans and California Association of Port Authorities
February 1990

California's commercial ports are major generators of jobs and income and provide a vital link to the U.S. trading partners in the Pacific Rim and throughout the world. During fiscal year 1988, over 166 metric revenue tons of cargo flowed through California's ports. This volume is expected to grow to over 524 million metric tons by 2020. Expanding harbor facilities to meet the projected demand is meaningless without adequate highway and railroad access to move the cargo to and from the docks. Congestion on California's highways and roads is threatening landside access to marine ports, and the magnitude of congestion throughout the state has been characterized by the following:

- Hours per day are lost on freeways, and the delay is projected to increase 74 percent by 1995 and climb another 65 percent by 2005.
- Many miles of the state freeway system suffer from recurring congestion, compared with an average of 30 mi in 1963.
- Congestion on Los Angeles and San Francisco freeways is increasing at annual rates of 15 to 27 percent.

International shippers and port-related businesses are quick to relocate to other West Coast states if California's transportation system is not expanded and modernized to increase landside access to rail, highway, and other facilities. Cargo could be diverted to Pacific Northwest ports. Of particular concern is the overland common point cargo—foreign intermodal (containerized) freight shipped by rail to or from points east of the Rocky Mountains.

Some of the proposed solutions to the problems are as follows:

- Provide on-dock and near-dock intermodal rail yards to reduce the amount of trucks on the highways (one obstacle is the vertical clearances of key railroad tunnels that do not allow double-stack trains).
- Consolidate all train traffic in one corridor or rail line so that it does not impact highway traffic at major at-grade intersections and so that all environmental impacts are concentrated into this one corridor (e.g., Alameda corridor).
- Explore barge system (for inland transport) as an alternative to truck transportation.
- Employ TSM actions including (1) coordinating truck and train traffic to avoid heavy commute hours and (2) developing rideshare programs and flextime working schedules for employees.

Funding is a major constraint identified, and the study proposed that some of the port improvement and access projects be placed in the Regional Transportation Improvement Plan, the state TIP, and the county's congestion management program.

■ HIGH OCCUPANCY VEHICLE LANES (I-495: Capital Beltway to MD-121, Clarksburg Road)

Informational Workshop and Public Hearing
Maryland Department of Transportation
May 1993

Development along the I-270 Corridor outside of the Beltway near Washington, D.C., has grown and will continue to grow well into the 21st century. The significant increases in traffic volume historically show the effect of this growth and the reasons for most of the traffic congestion experienced today. Maryland DOT conducted a workshop and a public hearing to inform the public and obtain public opinion regarding proposed use of HOV lanes on the I-270 corridor to alleviate congestion. Three alternatives were presented:

- Provide no HOV lanes, and undertake only some improvement projects that would widen portions of I-270;
- Open new constructed lanes as HOV lanes; and
- Provide continuous HOV lanes throughout the corridor.

It was anticipated that no significant environmental impacts will result from the introduction of the HOV lanes.

■ ROUTE 5 CORRIDOR STUDY (West Springfield/Holyoke, Massachusetts)

Pioneer Valley Planning Commission
West Springfield, Massachusetts
June 1993

From September 1990 to December 1991, the Pioneer Valley Planning Commission performed a comprehensive analysis of traffic and land use within the Route 5 transportation corridor interconnecting Holyoke and West Springfield, Massachusetts. Based on recent development trends the study area can expect substantial increases in the

number of average daily trips unless steps are taken to reduce the number of new trips. Extensive land use data about every parcel included in the corridor study area were collected. Similarly, data on existing traffic conditions were gathered. Trends in land development and traffic growth were identified, and their impacts on the capacity of the roadway in the corridor were analyzed. Projections of future development were made, and estimates of future traffic were derived, which, in turn, were evaluated to determine if the corridor could accommodate future traffic. Deficiencies in the capacity and safety conditions of the road under future traffic volumes were identified, and recommendations to improve land use regulations and traffic controls along the corridor were made.

The recommended land use strategies include the following:

- Establish planned business zones.
- Protect environmentally significant land parcels.
- Control infill development in existing large commercial shopping centers.
- Upgrade site plan review regulations.
- Update local sign regulations.
- Improve municipal parking and landscaping regulations.
- Improve pedestrian safety.
- Establish standardized development fees.
- Establish a corridor advisory committee.

The recommended transportation improvement measures are classified as short-term or long-term and include the following:

- Intersection operations (signal timing, phasing, etc.), and
- Channelization (for through and turning lanes).

■ THE OAHU REGIONAL TRANSPORTATION PLAN

Oahu Metropolitan Planning Organization
June 1991

The Regional Transportation Plan sets forth the transportation plans and policies to address the Island of Oahu's travel needs. The plan identifies the facilities and programs that have been selected to meet increased travel demands through the year 2005 and addresses potential programs that may extend beyond 2005 to meet needs brought about by continuing major development and redevelopment efforts targeted for various areas of Oahu. The plans and programs encompass the major surface modes of intraisland circulation—automobile, transit, paratransit, bicycles, and water transportation.

The plan includes major new facilities and capacity expansion to existing facilities. However, physical and funding constraints limit capacity expansion to levels that may not be able to satisfy unrestrained increases in travel demands. Given the recognition that Oahu cannot build its way out of increasing congestion problems, emphasis must also be placed on redirecting land use policies to reducing travel needs and on more effectively managing travel demand and use of transportation facilities.

The development of the Regional Transportation Plan also recognizes the need to coordinate the plans and programs for the various travel modes to provide an integrated transportation system. This coordination is essential to provide a transportation system that efficiently serves travel demands and that serves the diversity of travel needs on Oahu. Provision of an integrated system will require coordination in areas such as the following:

- Development of terminals for transfers between travel modes,
- Planning for HOV lanes and bus services, and
- Development of programs to encourage ridesharing, and the provision of facilities and services to accommodate the added transit, carpool, and vanpool riders.

■ CSX CORRIDOR STUDY

Hampton Roads Planning District Commission
Chesapeake, Virginia
June 1993

The city of Newport News, Virginia, is elongated in shape, with two major roadways carrying traffic the length of the city. There is concern about the future high volumes of traffic traveling those thoroughfares. In addition, I-64 parallels these facilities. Some capacity improvements are planned for these facilities but not enough to adequately carry the projected traffic. The city would like to determine whether the CSX railroad right-of-way, which runs between the two major highways, should be reserved for future use as a transportation corridor and determine the feasibility of light-rail service and other forms of public transit.

This study examines the feasibility of transit and HOV service in the CSX right-of-way. A previous analysis performed for the Peninsula Area Transportation Study, Year 2010 Major Thoroughfare Needs, indicated that this right-of-way should be protected and reserved as a future transportation corridor. The projected traffic volumes on the parallel roadways indicate another corridor will be needed in the future. The annualized cost not covered by fares of operating a light-rail transit in the corridor would be $22.2 million per year, or roughly $15 per passenger. The cost of constructing and operating an elevated HOV system would be approximately $75.4 million per year, or $22.50 per passenger for HOV and $14.20 for HOV and single-occupant vehicle.

Alternative uses for the CSX right-of-way include dedicated bus lanes and express bus services.

■ US-30 MULTIMODAL STUDY—LOWER COLUMBIA RIVER CORRIDOR (Technical and Final Reports)

Oregon Department of Transportation
May 1991

The Lower Columbia Basin in Oregon, which forms a confluence with the Pacific Ocean, is strategically located with respect to Pacific Rim trade. Transportation facilities in the US-30 corridor from Portland to Astoria—including the state highway, the Burlington Northern rail line, and the Columbia River—are major resources that influence economic development in the basin. Because of the unique nature of the corridor and the diversity of transportation modes and their impacts on the area's economy, the corridor is a prime example of a multimodal corridor in Oregon. This study was undertaken to identify the best and most efficient transportation investment strategy for the corridor based on the analysis of the region's economy.

Freight and passenger traffic moves on the Columbia River, on the Burlington Northern Railroad, and on US-30 and its access roads within and through the Columbia River basin. Improvements are required in each of these transportation systems to support the economic development potential of the region:

- US-30. Traffic volumes were projected on this highway for the years 2000 and 2010 using baseline (1989) increases and economic development effects. LOS analysis was conducted, which identified required corridor improvements such as additional travel lanes, widened travel lanes, widened shoulders, and roadway realignments. These improvements were compared with and evaluated against the proposed Oregon DOT needs list for the highway. The ratios of discounted savings in travel time, operating cost, and accident cost versus the construction and right-of-way costs were used as measures of effectiveness. Improvements in local access roads were also identified.
- Railroad. Sufficient capacity exists to accommodate expected growth in rail freight traffic (mostly containerized for the Port of Portland) along the US-30 corridor through the year 2010, as long as Burlington Northern railroad maintains the railway and site access improvements are made for efficient delivery of raw products and finished materials. Shippers benefit from rail improvements that enable them to ship by rail versus truck. Higher operating speeds would reduce Burlington Northern's crew wages, locomotive ownership costs, and fuel costs for railroads, resulting in benefits for shippers in the form of lower contract rail rates, reduced inventory costs while products are in transit, and more timely services for customers. Additional use of rail versus trucks also reduces potential damage to the highway.

  The idea of using the existing rail line for passenger service was also examined, and it was determined that it was not feasible because of low demand, high upgrade costs, high operating costs that cannot be covered by fares, conflict between passenger and freight, and the superiority of bus service for mass transit.
- Marine. Vessel traffic to and from Portland will continue to grow at about 2 percent in 2010 if Columbia River dredging accommodates ship drafts that carry grain, wood products, and containers between the northwest United States and Pacific Rim countries. Marine construction projects (i.e., piers, dolphin rescue, dredging, etc.) would result in benefits due to reduced travel times and cost of moving materials, products, and people from a project site to a destination.

Some of the issues discussed in the study follow:

- Requesting state and federal funding for highway and marine improvements;
- Gaining support from Burlington Northern and rail shippers in upgrading the rail lines;
- Dealing with environmental regulations such as wetlands preservation, disposal of dredged materials, and protection of endangered species that could delay or block economic development in the basin; and
- Financing infrastructure improvements through revenue bonds, which will be limited because marketplace competition dictated that infrastructure investments will not amortize themselves.

■ STAMPEDE PASS RAIL CORRIDOR PRESERVATION FEASIBILITY STUDY (Final Evaluation)

Washington State Department of Transportation (WASDOT)
May 1991

The Washington State Air Transportation Commission, in cooperation with WASDOT, completed a study of the feasibility of acquiring the Stampede Pass rail line for use as a utility corridor or intermodal high-speed transportation corridor or for other transportation purposes. The corridor was evaluated for its potential for rail uses (freight, conventional passenger, and high-speed passenger service) and for nonrail corridor uses (roadway, public utility, and recreational). The complete feasibility study consists of freight traffic demand analysis, state rail plan recommendations, track valuation and right-of-way appraisal, analysis of utility and other transportation uses, and final evaluation of preservation feasibility. The feasibility of preserving the corridor in the face of probable abandonment by Burlington Northern was the focus of the study.

Conclusions and recommendations are as follows:

- The railway corridor should be preserved as possible for future freight rail or other uses that may prove feasible and desirable based on further analysis.
- The railway infrastructure, as well as right-of-way, should be preserved (at an estimated acquisition cost of $5.2 million) to obviate the possible future need for its replacement at great economic cost (more than $30 million) and to ensure the ability to retain the right-of-way.
- The essential rail banking account should be funded to an amount at least equal to that required to acquire both the right-of-way and trackage.
- Organized labor should be consulted in any future negotiations regarding the reactivation of the line for freight rail purposes.
- The city of Tacoma should be consulted regarding any future uses of the corridor for purposes other than rail, where crossing affects its watershed.
- Consideration of other potential uses, such as high-speed rail (even though this is not currently an attractive option), should be continued.
- If abandoned by its owner (Burlington Northern), the corridor, right-of-way, or trackage should be acquired.
- Actions taken to preserve and use the corridor should be reviewed within 6 years, as required by statute, in light of changed circumstances, needs, or expectations.

The study examined how future actions to protect endangered species on the Snake River can disrupt the barge traffic on the river; hence alternative transportation options such as rail through the Stampede Pass should be explored.

■ US-15-501 TRANSPORTATION CORRIDOR STUDY (Findings and Recommendations/ Minutes of the Steering Committee Meeting)

North Carolina
June 1993

The US-15-501 is the primary transportation facility connecting Durham, Chapel Hill, and I-40 in North Carolina. The corridor provides predominantly local access to development within the corridor. The objective of the study is to develop a transportation master plan that will accommodate full development (build-out) within the area and the forecasted traffic growth for the year 2010. Upgrading the corridor into a freeway or expressway will not provide enough capacity to accommodate the projected demand and the intensity of development in the area. The problem is also characterized by high turning volumes at streets intersecting the corridor.

The study identified and evaluated alternative solutions to the future capacity problems of the corridor as follows:

- Land Use. Reduce land use intensity through rezoning and land use planning and promote a balanced mix and better arrangement of land uses to increase the level of internal trip making (to facilitate pedestrian and bicycle use), thus reducing the need to access the corridor.
- TDM and Transit Options. Discourage single-occupant vehicles, implement trip reduction ordinances, extend regional and local transit to the corridor, increase bus service, and provide complimentary park and ride in addition to fixed guideway service.
- Provide additional capacity on parallel corridors and streets.

Public and steering committee meetings identified other needs as follows:

- Adequate right-of-way should be reserved for corridor improvements, including freeway and fixed guideway and HOV lanes.
- Projects should be phased in so that improvements are implemented when and if required.

Following are conclusions drawn from the study:

- Designate the US-15-501 corridor as a freeway by providing grade separations for the entire length within the study area.
- Right-of-way within the study area (not necessarily along the corridor) should be reserved to accommodate fixed guideway or HOV lanes. The corridor should be designated as an overlay zone by ordinance to protect the footprint of the freeway and preserve right-of-way.
- To the extent possible, implement TDM and transit strategies to delay or possibly avoid a freeway facility. The strategies include encouraging ridesharing, restricting parking, improving transit services and facilities, and forming a transportation management association whose mission is spearheaded by this endeavor.
- Implement the master plan in phases, according to demand and the effectiveness of TDM strategies, and adopt the internal circular system for multimodal use.

■ SR 12/SR 395 CORRIDOR STUDY: FINAL REPORT

Benton-Franklin Governmental Conference
Richland, Washington
May 1991

Local agencies such as Franklin County, city of Pasco, and the Benton-Franklin Governmental Conference in Washington were concerned that the growth of the region, including anticipated development in the area east of SR 395 and north of SR 12, and the high frequency of accidents occurring along the corridor indicated the need to study the corridor and plan for circulation improvements. This study includes

identification of alternative locations for new interchanges and overcrossings that would eliminate existing at-grade intersections and provide full access control on the two state routes. Improvements are expected to occur in phases as growth occurs in the area.

Traffic volumes for the year 2010 were projected using the future land use and development. Traffic generated by new development was determined using the 1987 Trip Generation Manual published by the Institute of Transportation Engineers. Base traffic volumes for the year 2010 were calculated based on 1990 traffic volumes increased by 3 percent per year. Truck traffic volumes were assumed to account for a high percentage of vehicle stream for 2010.

The existing highways have high LOSs, but the crossing roads are below acceptable. LOSs for 2010 are estimated to be below F. Future accident rates (which are not captured in LOS) were calculated for intersections and road segments using 1990 base rates. The high accident rate is the driving force for the decision to convert the state routes into controlled access roads.

Public meetings were also held and suggestions and comments raised were included in the evaluation.

The study recommended an alternative consisting of five interchanges and 53 mi of roadway and ramp construction. The complete action is expected to be implemented in phases over the 20-year horizon.

■ CALIFORNIA RAIL PASSENGER DEVELOPMENT PLANS

California Department of Transportation
July 1991

The 1991 Rail Passenger Development Plan of the state of California provides an overview of the development of intercity and commuter rail passenger service throughout the state. It describes the services on various individual routes and corridors (both existing and potential) and presents the department's recommendations concerning state-supported service on specific routes.

Los Angeles-Fresno-Bay Area/Sacramento High-Speed Rail Corridor Study

This study focused on determining the necessary incremental improvements to increase speeds to the 110 to 125 mph range and the improvements required to increase speeds to much higher ranges. More than 20 million people live in the catchment area of the Los Angeles-Fresno-Bay Area/Sacramento corridor, which is about two-thirds of the state's population. The study finds that state-of-the-art passenger and freight train service are as important to the state as highways and safe airways. A reduction in highway automobile pollution in the state depends on having passenger trains whose travel times are less than automobile and a rail freight end-to-end service that is faster than trucks. In order to provide a fully integrated system in the California corridor, service should ultimately be provided to the valley along the Southern Pacific, Santa Fe, and Union Pacific rail lines. The study also recommended the need to use many existing rail rights-of-way for substantial parts of the corridor, guide the development and financing of high-speed corridor through entirely new institutional arrangements, and the development of a network of local transportation and regional rail passenger services to support the high-speed rail service.

■ REPORT ON THE FEASIBILITY OF IMPLEMENTING HARTFORD-ENFIELD COMMUTER RAIL SERVICE

Connecticut Department of Transportation
Bureau of Policy and Planning
January 1992

The Hartford-Enfield rail corridor is located in Connecticut's I-91 corridor. The railroad right-of-way is owned by Amtrak and is part of the Northeast Corridor service known as the inland route. Amtrak operates 18 trains daily, 9 in each direction, on the New Haven-Springfield line, with all the trains being through trains to and from New York, Philadelphia, and Washington. Hartford is an active Amtrak station, but Enfield is not.

Travel forecasts were estimated using TRANPLAN travel forecasting software and a mode split model. The proposed rail line was added to the 2010 proposed transit network and assigned service characteristics. Modeling was done for commuter work trips in the year 2010 and assumed implementation of TSM strategies (e.g., employer subsidies for transit fares, automobile insurance reductions for transit riders, and encourage transit use). Mode split allocates forecasted person trips to four modes of travel: single-occupant vehicle, carpools, bus, and rail.

Forecasts revealed low-level rail ridership due to competing bus service operating on HOV lanes in the I-91 corridor. Bus ridership was expected to grow and the choice of bus over rail is a result of lower fares, more frequent service, faster service due to HOV, and the elimination of transfers to bus for distribution. The report indicates that to operate a peak period commuter rail service between Enfield and Hartford on one-half hour headway, a capital investment of $43.6 million is needed including rolling stock, maintenance, storage facilities, track and right-of-way improvement costs, and station and parking costs. An annual operating deficit of $6.5 million was estimated, requiring an annual operating subsidy of $72 per passenger or $118 per passenger if annualized cost of capital were applied.

The report recommends that the implementation of the commuter rail service not be pursued and that the department focus instead on expanding corridor express bus operations and aggressively market the service.

■ REPORT ON THE FEASIBILITY OF IMPLEMENTING WATERBURY-HARTFORD COMMUTER RAIL SERVICE

Connecticut Department of Transportation
Bureau of Policy and Planning
April 1992

Another rail corridor evaluated for commuter service in Connecticut is the Waterbury-Hartford line. The rail line between the two cities is approximately 31 mi long, and the rights-of-way are owned by four different parties: the state of Connecticut, Boston and Maine Corp., Conrail, and Amtrak. The corridor was previously identified in the Connecticut statewide transit study as a corridor with the potential for providing commuter service.

The proposed service is a peak-period service only. Ridership estimates were developed utilizing future land use for a year 2010 market-based plan. Transit modeling was based on future congested highway travel times with no highway capacity improvements in the corridor except for some segments. The modified transit network (with the commuter rail service) was used to created LOS files for input to the mode split model (which allocates riderships to single-occupant vehicle, carpools, bus, and rail).

The study revealed that to operate peak period commuter rail service between Waterbury and Hartford on half-hour headways, a capital investment of $96 million would be required. The annual operating deficit was estimated at $8.65 million resulting in an annual operating subsidy of $14 per passenger ($28 per passenger if capital costs are annualized).

The report recommends that the Waterbury-Hartford commuter rail service is a feasible transportation alternative and that the majority of the ridership would be generated between Hartford and Bristol. However, whether it is the best or preferred alternative would still need to be evaluated in an alternative analysis/environmental analysis phase. Various rail and transportation alternatives include express bus and HOV lanes, TSM actions, and transitway or busways along the railroad right-of-way.

■ REPORT OF THE GOVERNOR'S RAIL TASK FORCE

North Carolina Department of Transportation
January 1993

The governor's rail task force was formed in 1988 to study the present, near-term, and future needs for rail transit service connecting major cities in North Carolina. The task force determined that there was a demand for new passenger train service between Rocky Mount, Raleigh, and Charlotte and worked with Amtrak to institute this service. The Carolinian, a New York-Charlotte train, began operating in 1990, and its ridership exceeded all expectations. Operating arrangements for additional trains between Raleigh and Charlotte are being negotiated with Amtrak.

Some of important findings of the task force study follow:

- Changes in land use would foster rail passenger transportation. Land use policies that lead to higher densities of population will tend to foster the development of such systems since mass transportation systems depend on gathering enough passengers to make operation of a train or vehicle economically feasible.
- Train speeds can and should be increased. Trips by automobile are shorter than trips by train.
- Improve the Raleigh-Charlotte route. North Carolina's most heavily traveled transportation corridor extends along I-85 and I-40 from Raleigh and Durham through Greensboro to Charlotte. The corridor links seven urbanized areas, four of which fail to meet air quality standards. Approximately half of the state's population now resides within a band extending 15 mi on either side of this corridor. Congestion and air quality problems will be exacerbated by increased automobile traffic and highway reconstruction along this corridor. The improvements proposed are increased speeds through cities and towns, realignment of track switches and installation of higher speed switches, and increased superelevation on curves and new signal systems.
- Place the rail industry on a "level playing field" with other transportation modes.
- Continue the study on high-speed ground transportation (Charlotte-Raleigh designated Maglev corridor by U.S. DOT).
- Essential rail corridors should be preserved for future use. The Rail Corridor Preservation Act passed by the Assembly in 1988 gave the DOT the power to purchase railroads and preserve rail corridors for future rail use and interim compatible uses.

■ INTERMODAL MOBILITY DESIGN CONCEPTS AND COMPETITION (Final Report)

Prepared for Pennsylvania Department of Transportation
Ebasco Infrastructure
July 1991

Interstate 95 is arguably the nation's most significant transportation artery. Extending the entire length of the east coast, I-95 traverses 14 states and Washington, D.C. The interstate highway's alignment serves and affects the nation's busiest and most populated transportation corridor, and it is called on to satisfy a wide range of mobility needs. Within the busy Northeast Corridor, these needs range from long-distance interstate trips to the long-distance and local distribution of goods. The corridor also accommodates relatively short home-to-work commuter trips. Although this interstate once was synonymous with high-speed travel, today many segments provide less than adequate service, with usage far exceeding the original intended capacity. Recognizing the impacts on eastern Pennsylvania (and indeed the Northeast Corridor) from the steady deterioration of I-95, PennDOT

has acted to develop a complete, systematic, and implementable multimodal corridor improvement program. Three teams were asked to participate in a design competition to develop a multimodal transportation plan and to make I-95 in the state the pre-eminent 21st century urban transportation corridor. The specific objectives are as follows:

- Restore I-95 pavement and bridge decks,
- Modernize I-95 and improve safety,
- Alleviate congestion in the corridor,
- Integrate mass transit and automobile travel,
- Minimize air and noise pollution, and
- Showcase advanced transportation technology.

Corridor needs were summarized in the study as follows:

- Congestion. Capacity-induced congestion is most pronounced in the central segment (in the vicinity of Center City Philadelphia) although both the northern and southern segments of the highway are also plagued with problems. The primary cause of peak period delays is heavy traffic volume, merging and weaving traffic, and substandard ramp configurations.
- Roadway and Bridge Deterioration. Physical infrastructure, similar to that in many areas in the northeast, has not received the level of maintenance required. Many of the interchanges are not up to current standards and require upgrading.
- Safety. I-95 in Pennsylvania experiences a high frequency of accidents, with more than 1,000 reported per year (or an average of 3 per day). Trucks are involved in 25 percent of the accidents even though only 10 percent of the vehicles in the stream are trucks.
- Transit. The extensive transit in the corridor is characterized by an extensive rail and bus system that primarily serves Center City Philadelphia. Despite this extensive network of routes, transit is predicted to experience only moderate growth in ridership (1.7 percent) between 1987 and 2015, compared with approximately 18 percent growth in internal automobile trips in the Delaware Valley.
- Goods Movement. Traffic congestion and inadequate intermodal rail facilities delay shipments and add cost to the delivery of goods (by as much as $35 per hour of delay). This is especially critical at trans-Delaware crossings, such as the Walt Whitman Bridge, which have significant port-related truck traffic. Lack of a modern, convenient rail intermodal transfer facility and supporting infrastructure caused only 13 percent of port containers to be transferred to rail for distribution.
- Environment/Air Quality. The Philadelphia metropolitan area has exhibited measured levels of air pollution that exceed standards set by the U.S. Environmental Protection Agency. The Clean Air Act Amendments of 1990 call for actions to bring air quality in the corridor into compliance by (1) a 25 percent increase in average vehicle occupancy for large employers, (2) a reduction in VMT (which is expected to increase by 25 percent for the area and by 20 percent for the corridor from 1987 to 2015), and conformity of transportation plans and programs with the air quality implementation plans.

A traffic demand model that defined 741 traffic analysis zones and 22,530 network links along the I-95 corridor was developed. This model was used to predict the 2015 travel patterns and volumes for the corridor and to evaluate improvement strategies consisting of the following:

TDM

- Park and ride locations,
- Regional multimodal transportation centers,
- Impact of HOV lanes on selected segments of I-95,
- Ramp metering,
- Reversible travel lanes,
- Widening other regional transportation facilities,
- Corridorwide construction management strategies or staging and their impacts on I-95 diversion and congestion,
- Incident management,
- Traffic monitoring,
- Traffic control,
- Ridesharing, and
- IVHS.

Highway Modernization

- Scheduled bridge and highway improvements,
- Interchange improvements,
- Bridge rehabilitation and construction,
- Arterial roadway improvements,
- Arterial improvements for transportation center access, and
- Priority access roadway.

Transit

- Expanded regional rail service and improvements,
- Existing rail line parking expansion,
- Development of three new regional transportation centers,
- New express bus services to serve nontraditional markets,
- Improvements to existing local transit and feeder services, and
- New fare technology.

Goods Movement

- Interstate ramps to access Port of Pennsylvania and regional intermodal transfer facilities,
- Truck-only lanes, and
- Information and trucker amenities.