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16. Abstract

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A METHODOLOGY FOR THE ASSESSMENT OF
TRUCK LANE NEEDS IN THE TEXAS HIGHWAY NETWORK

by

Hani S. Mahmassani
C. Michael Walton
Kyriacos Mouskos
John J. Massimi
Ira R. Levinton

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A Study of Truck Lane Needs
Research Project 3-18-83-356

conducted for

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FOREWORD

This report summarizes the findings of CTR Research Study 3-18-83-356, entitled "Study of Truck Lane Needs", performed under contract to the Texas State Department of Highways and Public Transportation. The principal accomplishments of this study are the development of a powerful network modelling methodology for the analysis, identification and selection of candidate links in the Texas state highway network for the construction of special truck lanes. The methodology also allows the identification of the type of operations for these additional lanes in conjunction with the existing ones.

The results of the research performed under this contract are presented in three reports. The present one, entitled, "A Methodology for the Assessment of Truck Lane Needs in the Texas Highway Network", provides an overview and summary of the study's accomplishments. It presents the methodology developed in general terms, emphasizing the capabilities of the various procedures and their application to the truck lane needs study. More detailed information on the procedures can be found in two companion reports:

1. CTR 356-1, "Truck Lane Needs Methodology: A Heuristic Approach to Solve a Five-Option Network Design Problem", which presents the model developed to identify and select the highway links that constitute the best candidates for improvement through truck lane addition, for different budget availability constraints.

2. CTR 356-2, "Network Assignment Methods for The Analysis of Truck-Related Highway Improvements" , which describes in detail the results of research on the network traffic assignment procedures developed and implemented in this study.

ABSTRACT

Special truck lanes have been proposed as a measure to deal with the increasing traffic of larger and heavier trucks on the Texas highway system. This report describes an integrated network modelling Methodology for the study of truck lane needs in the Texas highway network. It consists of three major components: critical link programming, network traffic assignment and optimal link selection/network design.

The critical link programs allow the user to diagnose and assess the adequacy of the links in a highway network for handling excessive truck traffic under specified conditions. Geometric, pavement and operational criteria are defined for this purpose, and embedded in interactive critical link screening procedures.

The traffic assignment model is essential for the prediction of link flow patterns and subsequent user costs calculation in response to particular changes in the network corresponding to truck-related link improvements. The assignment problem addressed here allows the asymmetric interaction between car and trucks sharing the roadway in the determination of link travel times. Numerical experiments on the Texas network have confirmed the usefulness of the diagonalization algorithm, modified for computational efficiency, for the study of truck lane needs.

The optimal link improvement selection problem is cast as a discrete network design problem with multiple improvement options per link. One of its main features is the definition of link improvement in terms of both lane addition (capacity expansion) and operating scheme (lane access restrictions to cars or trucks). A branch and bound integer programming approach is adapted and tested for the truck-related link improvement selection problem.

The potential of the network modelling methodology for the study of truck lane needs in the Texas highway network has been demonstrated. Further steps needed for its effective implementation and enhancement as a decision support system for truck-related network planning issues are also discussed.

EXECUTIVE SUMMARY

The motivation for this study arises from the need to plan for and accomodate the of increasing traffic of larger and heavier trucks in the Texas highway system. In particular, the construction of special lanes for the exclusive use of trucks in selected critical parts of the network is receiving consideration as an approach to deal with truck-related highway problems.

This report provides an overview of the principal accomplishments of a CTR study aimed at developing a methodology to support the analysis, identification and selection of specific sections of the highway network that constitute good candidates for the construction and implementation of truck-related improvements, with particular attention to exclusive truck lanes.

The integrated network modelling methodology developed in this study allows engineers and planners at the implementing highway agency to address three main types of decision problems: 1) Evaluation and diagnosis of critical highway links from the standpoint of excessive truck traffic, based on geometric, pavement and operational considerations; 2) Assessment of systemwide impacts of proposed truck-related highway improvements in selected parts of the network, and 3) optimal selection of a subset of truck-related link improvements.

The underlying conceptual framework and structure of the methodology are presented in this report. The methodology consists of three principal components: 1) critical link programming component, 2) network traffic assignment models and 3) optimal link selection/network design model. The logic, features, capabilities and implementation guidelines of each of these components, as well as highlights of their application to the study of truck lane needs in the Texas highway network are described in this report.

The critical link programming component provides a general-purpose procedure for the diagnosis and evaluation of link conditions in a highway. This procedure is implemented in an interactive, user-friendly manner, and relies on a database developed for the Texas network from HPMS files. Warranting procedures and criteria for exclusive lane implementation can be tested and implemented using these procedures.

The network assignment models constitute the core components of the network modelling methodology. Streamlining strategies that improve the computational performance, and enhance the operational usefulness of the "diagonalization" algorithm have been devised, tested and successfully implemented in this study. This traffic assignment algorithm allows the explicit representation of the interaction between cars and trucks in the traffic stream, which is an essential feature in the study of truck-related link improvements in a network. In addition, a special mechanism for the network representation of different link improvement options was devised and implemented for this study.

Link improvement options are defined in terms of both capacity expansion (lane addition) and associated operational scheme, involving lane access restrictions to either cars or trucks, for both new and existing lanes. The optimal combination of links and corresponding improvements options can be obtained using the link selection/network design component of the methodology. A modified branch and bound approach was developed for this procedure. The approach also includes an elaborate set of feasibility rules, consisting of geometric, pavement and operational criteria, which govern the compatibility between each improvement option and a given link's characteristics.

The potential and usefulness of this network modelling methodology to support the planning and engineering of truck-related improvements to selected parts of the highway network has been established. A number of aspects, identified in this report, remain to be addressed or enhanced in future research in order to comprehensively address truck-related problems in the Texas highway network.

IMPLEMENTATION STATEMENT

The methodology developed in this study can assist the SDHPT in dealing with the questions of special lanes or facilities for truck traffic. Its applicability is however not limited to the analysis of exclusive truck lanes. It can handle a variety of highway link improvement options, involving capacity expansion jointly with operating strategies. The latter can include any combination of lane access restrictions to either cars or trucks, of existing as well as new lanes. As such, the network modelling methodology provides a flexible framework and tool to address a wide variety of measures aimed at relieving the problems associated with increasing flows of larger and heavier trucks in the highway system.

The critical link programming procedures developed in this study provides a general-purpose diagnosis and evaluation tool of link conditions in a highway. These procedures are interactive and user-friendly, and rely on a data base derived from HPMS files. They can produce useful information in an interactive format on a variety of planning and engineering questions affecting the highway network.

Naturally, some updating and fine-tuning of the network modelling methodology and its inputs to the specific needs of the implementing agency in any given problem situation is necessary. However, the requisite adaptability for such tasks is built into the structure of the methodology.

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CHAPTER 1. INTRODUCTION

1.1 Motivation

Careful highway planning involves the anticipation of future problems and needs; this requires going beyond mere extrapolation to consider evolving trends that can shape the load and requirements placed on the highway system in Texas in the medium to long run. Actions initiated today to deal effectively with emerging demands must be based on information generated by careful analysis. The magnitude and scale of the problems under consideration and their impact warrant the development and use of advanced state-of-the-art analysis methodology to effectively support the planning and decision-making process in the area of statewide highway investment.

Four major trends, representing significant though gradual changes in the technological, economic and regulatory conditions under which the highway system will operate, provide the principal motivation for this study. First, vehicular traffic of all types will continue to increase, in most parts of the State's highway network, fueled by a continuing and increasingly diversified and spatially dispersed economic activity system.

Second, the trend towards an increasingly deregulated trucking industry translates into larger and heavier trucks, including double and triple trailers, using the highway system. Economic and productivity considerations drive carriers to consolidate commodity flows into these higher capacity vehicles, with federal and state actions generally relaxing existing regulatory obstacles[1].

Third, passenger car models are likely to continue to exhibit a wide diversity in shapes, sizes and performance characteristics, with a growing fleet of compact and subcompact vehicles on the road, and potentially significant inroads into the U.S. car market by low-priced mini and micro automobiles[2]. The result is an increasingly complex mix of vehicles, with widening differentials in size, weight and performance among vehicle categories (perhaps best dramatized by very large combination trucks on one hand and subcompacts on the other), sharing the use of common highway

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facilities.

Fourth, concerns over adequate funding for infrastructure provision and maintenance are likely to remain acute, requiring even further scrutiny in the allocation of scarce resources to various elements of the transportation infrastructure.

The above trends raise a number of questions regarding the adequacy of the existing highway system to address the changing requirements placed on it, as well as the types of solutions that could be conceived and implemented in a timely manner to meet the future needs of the State's economy and the mobility of its residents in a safe and efficient manner. In particular, the following concerns result from the above trends:

1) Very large combination trucks have already begun to jeopardize some geometric design features on many of the State's most traveled highways.

2) Capacity constraints and level of service degradation due to increasing congestion, worsened by the interaction of cars with heavy trucks in the traffic stream, lead to longer travel times and higher user costs.

3) Heavier trucks and higher overall flows accelerate pavement deterioration rates, contributing to further expenditure demands on available funds.

4) Potentially hazardous driving conditions arise from the interaction between smaller cars and larger trucks, with particular concern over the severity of collisions involving vehicles of dissimilar extreme size, weight and performance characteristics.

As noted earlier, these emerging concerns will become more acute over time, as they correspond to economic, socio-demographic and technological trends that are not likely to be reversed in the foreseeable future. For these reasons, it is essential to carefully and systematically plan to alleviate and accomodate these evolving conditions. The non-routine nature of the problem, the accelerating pace at which it is unfolding, and the explicit or implicit constraints within which solutions must be developed and deployed require that responsible mission agencies look beyond familiar approaches. Innovation and creative solutions must be generated and given careful consideration to effectively meet impending challenges in the provision of a quality transportation infrastructure to support the State's economic vitality and the mobility of its residents.

An innovative solution concept for some of the truck-related concerns is

that of special-purpose truck lanes or facilities, which would be implemented in selected corridors of the State highway network. This concept has attracted a good amount of attention in the Texas State Department of Highways and Public Transportation (SDHPT). While recognizing that there are no quick fixes to problems of this scale and magnitude, promising approaches that can contribute to alleviating these problems should be carefully analyzed in terms of their impact on the highway network and the various actors that use it and manage it.

Realizing that decisions and strategies developed at this juncture can have potentially significant long-term consequences, it is imperative that the planning, engineering and decision-making activities with regard to special truck lanes be supported by careful and systematic documentation of their systemwide impacts. This requires the development of powerful network analysis and modelling methodology that draws on the state-of-the-art in this area. Because of the innovative character of the truck lane concept, existing procedures are not directly applicable and require adaptation to the specific requirements of this problem.

1.2 Scope and Objectives

The principal objective of the present study is to develop a methodology to support the analysis, identification and selection of specific sections of the highway network that constitute good candidates for the construction or implementation of particular types of truck-related improvements. This methodology allows: 1) the identification of critical highway sections from the perspective of excessive truck traffic, for a given network configuration operating under current and future demand scenarios, 2) the assessment and evaluation of systemwide impacts of relief and prevention measures aimed at truck traffic problems and 3) the investigation of the effectiveness and implications of alternative criteria (in terms of the physical and operational characteristics of highway links) and warranting procedures for special truck lane facilities.

The present report provides an overview of the principal accomplishments of this study, and describes the overall structure of the methodology, its capabilities and the features of its major components. More detailed information of a more mathematical nature is presented in separate companion reports, as indicated in the foreword to this report.

The next section reviews the general policy and technical background to the problem addressed in this study.

1.3. Background Review

In a recent study conducted at the Center for Transportation Research at the University of Texas at Austin, Yu[3] provides a comprehensive overview of truck sizes and weights trends and legislation at the state and federal levels, as well as related studies conducted over the past two decades, as a background to the proposed designated Intercity Truck Route Network for large combination trucks. Laws and regulations have been enacted over the years to limit the size, weight, tires, axle spacing and other features of trucks allowed on the highway system in order to control the damage inflicted by vehicle axles on the roadway. Trucking firms and shippers have naturally tended to favor larger and heavier trucks, in the interest of economies of scale achievable by larger payloads per trip, which translate in greater net revenues. Regulation is intended to strike a balance between the concerns of truckers and the achievable transport economies on one hand, and potentially negative operational, pavement and environmental impacts on the other. The evolution of size and weight limits in Texas since the 1950's is shown in Table 1.1[3].

At the federal level, the enactment of the Federal Aid Act of 1956 is generally recognized as the first instance of federal intervention in state size and weight legislation. The federally legislated limits applied to the Interstate System, though states with higher limits were still allowed to retain these higher limits. The second major size and weight legislation affecting Interstate Highways was passed by Congress in 1975. The new limits raised the vehicle single axle limits from 18,000 to 20,000 lb., tandem axle limits from 32,000 to 34,000 lb., and gross vehicle weights from 72,000 lb. to 80,000 lb. Also affected was the way gross vehicle weight is regulated: instead of a flat maximum permissible weight, the gross permissible vehicle weight for a given vehicle was determined by the joint consideration of its axle weight and axle spacing according to the so-called "Bridge Formula"[4].

The passage of the STAA of 1982 initiated a new phase in Federal highway legislation. The STAA of 1982 was the first Federal Act to set regulations on vehicle length limits in the highway system. Section 411 (a) of STAA 1982 states that

TABLE 1.1. DEVELOPMENT OF TEXAS MOTOR VEHICLE SIZE LIMIT

	Length Single (Ft)	Other Vehicles (Ft)	Width (In)	Height (Ft -In)	No. of Trailers
1951 & Earlier	35	45	96	13-6	1
1951-1959	35	45	96	13-6	1
1960-1965	35	50	96	13-6	
1965-197(?)	40	55* 65**	96	13-6	
1977	45	65	96	13-6	
1983	45	65	96	13-6	
1984	45	57* 65	102	13-6	

*Truck-trailer semitrailer
**Other combinations

NOTE: This table presents a rough sketch of the size limits in
       Texas since 1951. The table is not exhaustive and thus
       gaps exist. It is only shown here for a rough overview of
       the development of size limits in Texas since the early
       50s.

Source: Ref. 3.

No state shall establish, maintain, or enforce any regulation of commerce which imposes a vehicle length limitation of less than forty-eight feet on the length of the semitrailer unit operating in a truck tractor-semitrailer combination, and of less than twenty-eight feet on the length of any semitrailer or trailer operating in a truck tractor-semitrailer-trailer combination, on any segment of the National System of Interstate and Defense highways and those classes of Interstate and Defense Highways and those classes of qualifying Federal-aid Primary System highways assignated by the secretary ...[5].

The STAA of 1982 prohibits states from establishing, maintaining, or enforcing any overall length limits, and limits the operation of double combinations to those having overall lengths of 65 feet. It also allows the Secretary of Transportation to designate a network of qualifying "Federal-aid Primary System" highways which allows the operation of doubles of overall length less than or equal to 65 feet.

This continual interplay among technological advances, trucking industry trends, and regulation was addressed in a number of studies [6-10], comprehensively reviewed by Yu[3]. The specific findings of these studies are not of direct concern to the present discussion. However, taken together, these studies point to the inevitable increases in truck weight and size limits, perhaps coupled with designated and or restricted facilities. The result is therefore the above-mentioned continuing increase of heavier and larger trucks sharing the right of way with a diverse automobile traffic, which provides the motivation for the present study.

1.4. Overview

This chapter has defined the problem addressed in this research study, outlined the motivation behind it and reviewed previous studies pointing to the significance and potential implications of increasing truck traffic, and the accompanying weight and size increases on the highway system. The principal accomplishments of this study consist of an integrated network modelling methodology, which explicitly recognizes the unique features required by the analysis of truck-related highway improvements.

Chapter Two presents the framework for the analysis of truck lane needs and the structure of the above methodology. The principal components are identified in that chapter, along with the interrelation among them, and a brief discussion of their capabilities both separately as well as within the

context of the overall methodology.

Chapter Three describes a procedure developed for the diagnosis of a given highway network, and the screening and identification of critical links in that network. Selection or elimination criteria can be specified in terms of geometric, pavement and operational characteristics of the network's links. In addition to the identification of critical links, this procedure allows the assessment of the systemwide costs and other implications of alternative selection criteria. It can be used in conjunction with the Highway Performance Monitoring System (HPMS) database for the Texas network, as well as with link flow information generated by the traffic assignment procedure in the overall network modelling methodology.

The network traffic assignment procedure is a central component in the overall methodology. Its purpose is the prediction of link flows in response to a particular set of improvements and truck lane additions to the highway network. These flows are essential in the calculation of user costs and benefits incurred with a particular set of improvements. However, because of the nature of these truck-related improvements, it is essential to incorporate the interaction between cars and trucks, on both shared and separated exclusive facilities, in the assignment procedure. Chapter Four describes the particular traffic assignment problems addressed in this study, and the research conducted to develop and operationalize a special algorithm for this purpose. Further details on the mathematical underpinnings of the algorithm and associated computational procedures, as well as on the specific experiments conducted in conjunction with this study, are given in the companion report by Mouskos, Mahmassani and Walton.[11]

Another major methodological component developed in this study is described in Chapter Five. It consists of a network design procedure for the selection of an optimal subset of link improvements to be implemented under given expenditure levels. Its principal feature lies in the definition of the link improvements it can handle. In particular, these improvements are defined to include both the provision of additional capacity, in the form of truck lanes, and the type of operational scheme adopted in conjunction with these additional lanes, particularly in terms of access restriction on the existing and the new lanes to either cars or trucks. These are explained in greater detail in Chapter Five, along with the capabilities and requirements

of this powerful methodology, which uses the above-mentioned traffic assignment procedure in its search for the best combination of candidate link improvements. The mathematical and computer-related aspects of this network design methodology are presented in a separate companion technical report.[12]

Finally, Chapter Six concludes this report with a summary of research accomplishments, and a discussion of various aspects related to the successful implementation and effective use of the network modelling methodology developed in this study. In particular, the development of various inputs outside the scope of the present study is discussed. Recommendations and suggestions for continuing research and implementation of this methodology are also given, in order to effectively support the development of truck-related strategies for the Texas highway network.

CHAPTER 2. CONCEPTUAL FRAMEWORK AND METHODOLOGICAL STRUCTURE

This chapter describes the conceptual framework underlying the analysis of truck lane needs using the network modelling methodology developed in this study. It also presents the overall structure of the methodology, highlighting the function of its principal components, and explaining how these components are interrelated to perform the desired analysis. The result is a flexible decision support tool that can be used to examine a variety of questions related to special truck lanes in sections of the State highway network, as well as other truck related measures. It is first useful to describe the types of decision problems that can be addressed by this methodology.

2.1. Types of Decision Problems

Three principal classes of related decision problems or tasks can be addressed and effectively supported with the aid of the present network modelling methodology:

P1. **Evaluation and diagnosis of critical highway links:** Given the highway network, with given physical and operational link characteristics, including flows of different vehicle categories on each link, the problem is to identify those links which can be considered "critical" from the perspective of truck traffic. This task is performed using a set of criteria or screens that flag out those links which do not seem adequate for serving the given truck flow levels. In addition, it is possible to screen links for various improvement types, and subsequently calculate the costs to the responsible agency of implementing such improvements.

P2. **Assessment of impacts of proposed improvements:** The problem here is to analyze the impacts of providing new truck lanes, to be operated according to some specified scheme, on proposed selected links of the network. This allows the evaluation of various proposals, both independently or jointly, that may be submitted by the districts, or through internal and/or external screening, for consideration by the SDHPT. This task

involves the determination of the redistributed flow patterns in the network, which form the input to the calculation of most user cost elements in the analysis. It can be noted that after the flow prediction and impact assessment activities, the model user may need to solve the first decision problem type P1 for the improved network and its associated link flows.

P3. **Optimal link subset selection:** Given an initial highway network, find the subset of links to be improved, and the corresponding optimal improvement type (defined in terms of the scheme of operations on the improved facility). This selection is performed so as to minimize total costs, subject to feasibility constraints (in terms of the link's physical characteristics) and to a specified maximum level of expenditures. In other words, given limited resources, where should special truck lanes be built, and how should these be operated, so as to yield the maximum overall benefits. The principal difference between decision problem P3 and the two previous ones is that P3 involves the (automated) search for the best combination of links to be improved, whereas P1 and P2 primarily analyze and diagnose potential problems associated with a particular network configuration (possibly including pre-specified improvements).

While different methodological components come to bear on each of the above three problem types, these are integrated within the overall network modelling methodology, where they draw on the same core components. The underlying conceptual framework for addressing all three problem classes is presented next.

2.2 Conceptual Framework

All three activities identified in the previous section require knowledge of the network links' physical and operational characteristics, including the flow patterns of cars and trucks (preferably broken down by size/weight category) in the network. Flow patterns are essential to the computation of all user costs and benefits due to various improvement schemes, and are generated by the network assignment model for a particular combination of proposed link improvements.

Let X_i^A denote the flow of cars on link i and X_i^T the flow of trucks on that same link, i = 1,...,n, where n is the total number of highway links under consideration; let the vector $X_i = (X_i^A, X_i^T)$. Furthermore, with each

link i we associate a vector of physical characteristics (geometrics, pavement, structural) $A_i = \{A_{i1}, A_{i2}, --A_{im}\}$, where A_{ij} is the j-th feature for link i, j=1,---,m. One additional feature associated with link i is the link performance function, which gives the travel time as a function of the flow vector on that link. The characteristics of the link are captured in that function through a set of parameters unique to each link type. Since cars and trucks experience different travel times, two performance functions can be defined for each physical highway link, namely:

$$t_i^A = f_i^A(X_i^A, X_i^T \mid A_i)$$

$$t_i^T = f_i^T (X_i^A, X_i^T \mid A_i) \qquad ,$$

where t_i^A and t_i^T denote the average travel time on link i of cars and trucks respectively, and $f_i^A(.)$ and $f_i^T(.)$ therefore denote the corresponding link performance functions. It can be noted that these travel time functions incorporate the interaction between these two classes of vehicles, meaning that cars' travel time will be affected not only by the flow of cars on that link but also by that of trucks. This interaction is an essential feature in the network modelling methodology developed in this study; further details on the performance function are found in Chapter Four of the present report, as well as in the companion report by Mouskos et al.[1]

In order to obtain the flow X_i for all links i = 1,___,n, and the associated travel times, the traffic assignment model requires two principal types of inputs:

1) The highway network's characteristics, namely the physical and operational features of its links and nodes, specified in the form of the vectors A_i (which include the number of lanes, functional classification, length and free mean speed) for all i =1,... n, and the link performance functions (usually specified by a code number referring to the type of facility).

2) Passenger travel and commodity transport needs, specified in the form of two origin-destination (O-D) matrices OD^A and OD^T, giving the number of daily trips between all node pairs in the network, for passenger cars and trucks respectively.

The traffic assignment model determines the paths selected by the O-D

trips through the network, resulting in the link flow pattern X_i, $i = 1,...,n$. It should be noted that the assignment process must recognize two key phenomena: 1) the (generally non-linear) dependence of link travel times on the flow levels on that link and 2) the interaction between cars and trucks in determining the travel time performance on a highway link. The first of these phenomena requires the simultaneous determination of flow levels and travel times on the links of the network, also known as (demand-performance) equilibration. The second phenomenon is of particular importance to the study of truck lane needs, as it is essential to the representation of the operation and performance of exclusive truck lanes and related access-restriction measures. Due to its importance in the overall methodological framework, the assignment model has been the subject of extensive development, testing and adaptation to the unique features of this particular study.

The link flows and travel times determined by the assignment procedure form the basis for the calculation of the various user costs for a particular network configuration (possibly including selected link improvements such as special truck lanes) under given traffic growth scenarios, translated in terms of the O-D matrices OD^A and OD^T. The various performance measures and costs derived from the assigned flows are determined both at the link level as well as on a network-wide basis. Link-level indicators serve in the link diagnosis and improvement identification activities, while network-wide figures are useful for overall evaluation purposes, and to provide a basis for the comparison of different combinations of link improvements in the network.

The above link-level and network-wide measures therefore constitute the principal considerations in addressing any one of the three decision problems defined in Section 2.1. The solution process beyond the computation of these figures of merit depends to a large extent on which of the three problems is under consideration. In this framework, the procedures for processing the above figures of merit, for whatever decision problem, are collectively referred to as the "decision component" of the methodology.

Figure 2.1 provides a schematic representation of the overall conceptual framework. As discussed earlier, the car and truck link flows, performance

measures and user costs generated by the traffic assignment model are subjected to "diagnosis, assessment and evaluation" (see Fig. 2.1), the exact nature of which depends on the decision problem type addressed. For problem P1, where the objective is to identify critical links, it is necessary to define a set of criteria on the basis of which a particular link is considered to be critical. Three categories of criteria are considered:

1. Traffic and operational criteria, which include truck and car flows on the link, the fraction of trucks and V/C (volume/capacity) ratio, as an index of congestion.

2. Geometric criteria, which pertain to the adequacy of certain links for truck traffic as well as their possible appropriateness for special truck lanes. These criteria include the number and width of lanes, the shoulder width, the presence, type and width of median, the degree of curvature and the availability of right of way for widening, among others.

3. Structural criteria, which include the pavement type and condition, the shoulder type, and others.

Further details on the specific criteria that have been incorporated in the critical link identification methodology, or that could be considered by the engineer or analyst, are given in Chapter 3; an overview of the logic of the diagnosis and elimination activities is also given in the next section.

It can be noted that only the first of the above three categories of criteria consists of flow-dependent characteristics. In other words, they depend on the actual flow level on the link, thereby requiring the output of the traffic assignment model.

The evaluation and diagnosis of critical links also suggests remedial measures, mostly in the nature of special truck lanes or related measures to cope with excessive truck traffic. Naturally, each of these options has an implementation cost associated with it. Thus Fig. 2.1 shows a budget which can act as a constraint in this process, as indicated by the arrow from the "budget" to the "diagnosis, assessment, evaluation" boxes in the figure.

Once improvements are suggested for specific links based on warranting procedures in terms of the previously mentioned criteria, the assessment of their systemwide implications, especially in terms of user costs as well as on a link basis, requires the execution of the traffic assignment model. Here, a problem of type P2 (stated in Section 2.1) is encountered. The

proposed improvements are translated to changes into the highway network's features, and the origin-destination trip matrices are reassigned to the modified network configuration, resulting in the systemwide and link-specific figures of merit that form the basis for the evaluation of that particular combination of improvements. The need to reassign traffic to estimate the costs and benefits associated with particular link improvements is essential when one is dealing with a network of highway links. While links can be screened individually, a correct assessment of the effectiveness of proposed improvement on a particular link cannot be made without consideration of the response of traffic to the modified network conditions, thus requiring the re-assignment of traffic to the network.

While the engineer or analyst using the methodology can specify alternative proposed combinations of link improvements and conduct a comparative evaluation of their respective impact, it is desirable to have the capability to automate the search through the possible combinations to identify the most promising (or "optimal") one in terms of maximizing some measure of overall benefit. This is the purpose of problem P3, which seeks a subset of link improvements (defined in terms of lane addition and special truck-related operational scheme) that minimize total user costs in the network subject to a maximum expenditure level. In Fig. 2.1, this optimal link subset selection is controlled by the "search" box, which controls the interfact between the improvements suggested by the "diagnosis, assessment and evaluation" activities and the specification of these improvements as changes to the network's features than can be understood and processed by the traffic assignment model.

The complexity of the above search problem, which is akin to a discrete network design problem with multiple link options, arises from the combinational nature of the problem and the need to solve a network traffic assignment problem to evaluate the objective function (user costs) for each combination of improvements. Chapter Five presents additional information on the solution algorithm, with further detail reported in the companion publication by Massimi, Mahmassani and Walton[3].

The structure of the methodology is presented next.

2.3. Methodological Structure

The integrated network modelling methodology developed in this study

consists of three major components:

1) The critical link identification and diagnosis program, which identifies highway segments with critical deficiencies, or that warrant various types of improvements. Essentially, this component performs the "diagnosis, assessment and evaluation" functions in the conceptual framework articulated in the previous section and shown in Fig. 2.1. This procedure can operate under different modes of elimination and screening logic, as discussed in Chapter Three.

2) The network traffic assignment model, which determines the link flow pattern in a given network resulting from given origin-destination trip matrices. The role of this component was detailed in the previous section. Note that two different assignment programs have been developed in this study, reflecting two different principles according to which users are presumed to select their routes in the network: the user equilibrium principle, and the system optimal principle, respectively. These are discussed in greater detail in Chapter Four and in the companion report by Mouskos, Mahmassani and Walton[1]. The user equilibrium formulation is the more appropriate one for all applications requiring flow prediction and impact assessment in this study. The system optimal program is however necessary in the context of the optimal link subset selection methodology (equivalent to a network design problem) to calculate the lower bound in the branch and bound algorithm (see Chapter Five and the companion report by Massimi, Mahmassani and Walton[2]). In both formulations, the problem involves asymmetric interactions between cars and trucks sharing common highway links, as noted previously.

3) The link selection/network design model, which performs the "search" function in the above conceptual framework and all interfaces between the appropriate components of the methodology. It allows the selection of an optimal subset of link improvements (including operating scheme), given a budget constraint, so as to minimize total user costs in the network. Four improvement options are possible for each link, corresponding to different combinations of lane access restrictions to cars and/or trucks; these options are described in Chapter Five.

The link selection/network design model is the most elaborate of the

three components, as it requires the other two components within its structure. In particular, both user equilibrium and system optimal assignment models must be called repeatedly by the link improvement selection program. While the critical link diagnosis programs are not directly called by the network design algorithm, the latter has embedded an elaborate set of elimination and screening rules that effectively perform that same function.

The rationale for providing the assignment and critical link diagnosis components as separate entities from the network design methodology is to have a flexible planning and decision support tool that can be used to respond to more than simply one type of structured, well-posed decision problem. As shown in Section 2.1, at least three types of decision problems can be meaningfully supported by this methodology.

The principal tool to address a problem of type P1 is the critical links program(s), which requires a given network with associated link flow pattern, and database on the physical characteristics of the highway links. A database of the pertinent characteristics has been developed in this study for the Texas highway network, relying primarily on the Highway Performance and Monitoring System (HPMS) files, appropriately complemented from other sources as needed. However, to identify critical deficiencies under future conditions, one needs to generate the component of the input database that comprises the traffic and operational characteristics of each link that would result from projected changes in the O-D patterns or in the features of certain portions of the highway network. As such, it would be necessary to first exercise the traffic assignment model for the projected conditions in order to obtain the requisite link flows. Furthermore, if, as a result of the critical links identification process, improvements are specified or proposed to remedy certain deficiencies, then the effectiveness of these improvements can be assessed by solving a problem of type P2.

As noted earlier, the user equilibrium network traffic assignment model is the principal tool for addressing problems of type P2. The link-level flows, travel times and performance measures could be further analyzed using the critical link identification programs, which would be used in a post-processing capacity with respect to the traffic assignment model.

Finally, to solve decision problem P3, all the necessary methodological components have been chained together to conduct the search for an optimal subset of link improvements. The optimal link selection/network design model

would then be the principal tool for this problem, and inputs in the form of O-D matrices, budget constraint, implementation costs, elimination criteria, and identification and diagnosis rules would then be supplied directly to the solution algorithm. The specific inputs developed for the application of the model to the Texas truck lane study are given in Chapter Five and in the companion report by Mahmassani et al.[12].
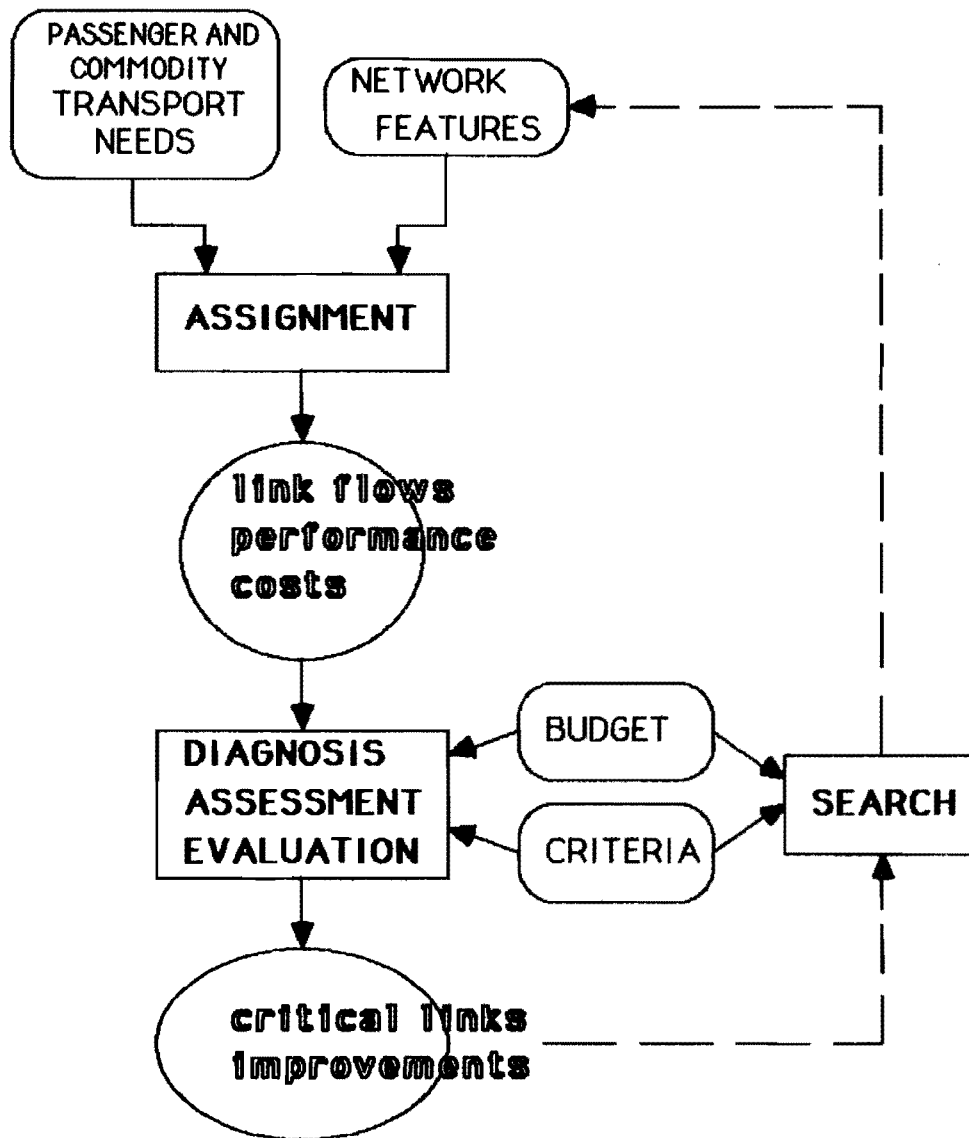
Figure 2.1. Conceptual framework.

CHAPTER 3   CRITICAL LINK PROGRAMMING

This chapter describes the procedures developed for the identification and diagnosis of critical highway links, from the perspective of truck traffic, in a given network. The links that are identified become candidates for capital improvements. The main concern in this study is how these highways are impacted by heavy truck usage, and whether they should be considered for the construction of special truck lanes. The function and role of the critical link programming procedures and the type of decision problems that they are intended for, were presented in the previous chapter. First, the identification logic is presented, followed by the definition of the principal aspects or criteria for this process. The various programs and their capabilities are presented in section 2.3. The specifics of the application to the truck lane needs study for the Texas highway system are described in section 2.4.

2.1. Identification Logic

The links are tested for criticality on each of a given set of features or attributes, referred to hereafter as aspects. Each aspect corresponds to a particular condition that must be met by the link under consideration. Such conditions are generally expressed using one or more variables describing the link, which are tested against a parameter value. The procedures developed in this project allow the user to specify these parameter values, since for most of the variables in this problem, precise standards do not exist. In many cases, the parameter values cannot be set independently for each variable, but require the joint consideration of several factors. In this study, suggested parameter values have been specified for all variables; however, the capability to examine alternative values to define criteria (reflecting warranting procedures) for identifying candidates for special truck lanes is one of the objectives of this study.

Note that aspects or criteria can be considered individually, one at a time, or simultaneously in any combination. For instance, let $CRIT_{ij}$ be a binary variable such that $CRIT_{ij} = 1$ if link i is critical from the standpoint of aspect j, and $CRIT_{ij} = 0$ otherwise where $i = 1,...,n$ and

$j = 1,\ldots,m$. With each link i, we associate a scalar $CRIT_i = 1$ if that link is considered critical or $CRIT_i = 0$ otherwise. Given the vector $CR_i = \{CRIT_{ij}, \; j = 1,\cdots,m\}$ of 0's and 1's obtained for each aspect for link i, then the link can be declared critical (i.e. $CRIT_i = 1$) under one of three possible situations:

1. It is critical on at least one aspect, i.e. $CRIT_i = 1$ if and only if $CRIT_{ij} = 1$ for at least one aspect j, $j = 1,\ldots,m$.

2. It is critical on all aspects, i.e. $CRIT_i = 1$ if and only if $CRIT_{ij} = 1$ for all aspects $j = 1,\ldots,m$.

3. It is critical on a specified combination of aspects (contained in subset A^c of aspects), i.e. $CRIT_i = 1$ if and only if $CRIT_{ij} = 1$ for all aspects j in A^c. This third situation is more general than the first two, and actually covers the wide range between the first two special cases.

The flexibility needed to operate under either of the above three situations is maintained and implemented by forming the matrix $\{CRIT_{ij}, \; i = 1,\ldots,n$ and $j = 1,\ldots,m\}$ and operating on its 0 or 1 elements according to the desired logic.

It can be noted that the above logic is similar to that followed in most Artificial Intelligence applications in knowledge-based expert systems, where so-called IF-THEN rules provide the principal inferential mechanism (referred to as "inference engine").

3.2 Definition of Aspects

Three categories of aspects are considered, pertaining respectively to geometric, pavement and operational characteristics of a given highway link. In defining an aspect for the critical link identification logic, it is necessary to specify whether it corresponds to a minimum or maximum cut-off value for the particular link variable defining this aspect. In some instances, an aspect may involve two or more variables, with conditional cut-off values (i.e. contingent upon the value of a variable other than that for which the cut-off is defined).

The principal geometric aspects included in the procedure include:

a. Minimum number of through lanes: it is suggested that highways

intended for heavy truck usage have a minimum of four through lanes (two in each direction).

b. Minimum lane width: highways with lane widths of less than 12 ft. would not adequately serve traffic with large trucks in the vehicle mix.

c. Minimum median width: these minimum values are contingent on median type. It is naturally desirable for multilane highways carrying heavy truck flows to be divided by a median. Highways with no median are considered critical from the perspective of handling large trucks. For highways with curbed or unprotected medians, criticality is based on width; less width may be needed for curbed medians compared to unprotected ones, as summarized in Table 2.1. These values, like those of any of the other critical threshold parameter values can of course be modified to reflect the specific concern of the implementing agency.

d. Minimum shoulder width; AASHTO specifies minimum 10 ft. shoulders on high volume roads, which is taken here as the minimum needed on roads with large truck traffic.

e. Critical shoulder type: using the HPMS ordinal classification, with fully surfaced rated (1) and none rated (5), a specified cut-off value can be set to flag links with inadequate shoulder type.

f. Horizontal curves: The degree of curvature that can be reasonably and safely negotiated depends on the superelevation and vehicle velocity. Tables of maximum degrees of curvature are given in the ASSHTO geometric design book, for given speeds and superelevations. Links are considered critical on this aspect if the specified degree of curvature is exceeded; cut-off values are given for the three speed limits of 55 mph, 50 mph and under 50 mph (the design speed is generally about 15 mph higher than the speed limit on high speed facilities).

Where curvature data is not available, the HPMS provides a "horizontal adequacy rating", defined on an ordinal scale where 1 indicates that all adequacy standards are met, 2 indicates that standards are not fully met, but the highway should be adequate for heavy trucks, and 4 is the worst rating, indicating an unsatisfactory condition. Cut-off values in this category can also be imposed.

g. Grade: Grades present a particular concern with regard to truck usage of the facility, especially for larger and heavier trucks. Maximum thresholds can be set directly on the percent grade, or a "relative speed

reduction function" can be used.

In the absence of data on grade for a particular link, the HPMS supplies a vertical adequacy rating, similar in concept to the above-mentioned horizontal adequacy rating. Cut-off values for this index can similarly be set.

h. Minimum passing sight distance: on highways with less than four lanes, passing sight distance is an important consideration. The HPMS data contains the percent of a given highway section with adequate passing sight distance. A minimum percent of adequacy can be set for critical link identification purposes.

The second category of aspects, addressing primarily pavement related considerations, includes the following:

a. Minimum pavement type: naturally, high-type pavements, which include rigid (HPMS code No. 70) and high flexible (HPMS code NO. 60), are desirable for sections carrying large volumes of heavy trucks. Low bituminous type pavements (code Nos. 51, 52, 53) are considered critical on major highways.

b. Minimum pavement condition: also based on HPMS pavement condition rating; conditions above 30 are considered good, between 20 and 30 fair and below 20 poor. A suggested cut-off value here is a minimum of 30, though 20 may be more realistic in terms of severe criticality.

c. Pavement section: highway links with light pavement sections are critical for heavy truck traffic, as are links with low pavement. Medium pavement sections are considered critical if a specified maximum hourly truck volume is exceeded.

The following operational and traffic-related aspects are considered in the critical link analysis:

a. Maximum AADT Volume: used primarily for diagnosing existing conditions, this is a logical indicator of the demand level on the facility, and one that is used primarily in combination with other link features to determine criticality.

b. Maximum peak hourly truck volume and maximum percent of trucks: these two aspects are essential to the central concern of this study, and particularly important in the diagnosis of the network's links under future conditions, following the results of the assignment procedure. A cut-off

value of 15% for the percent of trucks is currently suggested, though one may wish to vary this value to examine its network-wide implications.

c. Maximum volume/capacity ratio: a useful indicator of congestion and delay, this is another flow-dependent aspect that is important in analyzing the flow patterns generated by the traffic assignment model. A cut-off value of 0.8 is currently suggested as a basis for identifying critical links.

Table 3.1 summarizes the above aspects and their corresponding suggested critical values. As noted previously, these values are not intended as standards but rather as examples of the type of input to the methodology. To facilitate the input process and enhance the ability to examine alternative cut-off values, the computer programs developed for this purpose have been made user-friendly, allowing the interactive selection of aspects and input of the corresponding critical values, as discussed hereafter.

3.3 Critical Link Programs

Three computer versions of the above procedures have been developed. All are based on the same underlying principles, but differ in their capabilities and in the embedded logic for declaring a particular link critical. These three versions, referred to as critical aspect matrix, conjunctive screening, and sequential interactive screening respectively, are presented hereafter.

3.3.1. Critical Aspect Matrix Program

This program is the most basic and most general of the three. It produces the matrix {$CRIT_{ij}$, i = 1,...,n and j = 1,...,m), where $CRIT_{ij}$ is, as defined in Section 3.1, a binary variable equal to 1 if link i is critical (i.e. does not meet the cut-off value) on aspect j; otherwise, $CRIT_{ij}$ = 0. For each link then, a performance profile on all m aspects is obtained.

This output affords the greatest degree of flexibility in terms of interpreting and processing the status of each link with respect to all aspects under consideration. One can then add a simple post-processing code to either eliminate or select links according to any combination of aspects, and accordingly control the output. However, two particularly useful procedures have been developed and embedded in the other two programs, described hereafter.

TABLE 3.1. SUMMARY OF CRITICAL LINK ASPECTS

VARIABLE	IDENTIFICATION	POSSIBLE CRITICAL VALUES	CONDITIONS
Lane Width		<12 ft	All
No. Thru Lanes		<4	All
Volume/Capacity Ratio or v/c		>.80	All
Pavement Type	70-rigid (High) 60-flexible (High) 51, 52, 53 (Low) - Bituminous	<60	All
Pavement Section	0-unpaved 5-light 1-SN known 2-D known 4-medium	=0 =5 $SN \leq 30$ $D \leq 7$ =4 $SN \leq 45$ $D \leq 9$	All All All All Trucks>400 vph Trucks>400 vph Trucks>400 vph
Pavement Condition	20's-fair 30's-good	<30	All
Shoulder Type	1-full surfaced 2-stabilized 3-earth 4-curb 5-none	>1	All
Shoulder Width		<10 ft	All
Medians	1 curbed 2 barrier 3 unprotected 4 none	=1 =3 =4	Width<6 ft Width<10 ft All
Passing Sight Distance		<50 pct.	Lanes<4

TABLE 3.1. (Continued)

VARIABLE	IDENTIFICATION	POSSIBLE CRITICAL VALUES	CONDITIONS
Horizontal Adequacy	0-for principal arterials 1-good 2- substandard	>1	All
Vertical Adequacy	0-principal arterials 1-good 2-4 substandard	>1	All
Curves		>3 degrees >4 degrees >5 degrees	Speed limit=55 mph Speed limit=50 mph Speed limit<50 mph
Grades		10 mph speed reduction (DIST+.1)(GRADE)>.9 15 mph speed reduction (DIST+.1)(GRADE)>1.1 (miles)　　(%)	Speed limit=55 mph Speed limit<55 mph
Grades		>4%	All

3.3.2. Conjunctive Screening Program

In this program, data is printed out for links that have critical values in at least one of a selected set of aspects. In other words, for a link to not be considered critical, it must pass on all selected aspects. Mathematically, the value of $CRIT_i$, defined in Section 3.1 as a binary variable equal to 1 if link i is considered critical, and equal to 0 otherwise, is set as follows:

$CRIT_i$ - 1 if and only if $CRIT_{ij}$ - 1 for at least one j in A^c, where A^c is the subset of selected aspects, conversely, $CRIT_i$ - 0 if and only if $CRIT_{ij}$ - 0 for all j in A^c.

The user selects the aspects and the associated parameter values interactively over the computer terminal. Aspects are taken one at a time; for each aspect, links are tested with respect to that aspect. For each test of criticality along a particular aspect, only those links that have not been indicated as critical on any test up to that point in the execution are passed to the next test.

Initially the variable $CRIT_i$ - 0 for all links. When a test indicates criticality for a link on a certain aspect, then $CRIT_i$ is set - 1. Once $CRIT_i$ - 1 following a given test, the corresponding link is not retested, but is kept in the critical set. After all selected aspects are tested, the link is printed out if $CRIT_i$ - 1. This indicates that a given critical condition was found. The output includes route number, county, node 1, node 2, AADT, maximum hourly trucks, and number of lanes.

The process can be rerun with all links retested for a different set of conditions.

3.3.3. Sequential Interactive Screening Program

The processing logic embedded in this program is to print data out only for links that have critical values on all of a selected set of aspects (denoted by A^c). Mathematically, $CRIT_i$ - 1 if and only if $CRIT_{ij}$ - 1 for all selected j in A^c; conversely, $CRIT_i$ - 0 if and only if $CRIT_{ij}$ - 0 on at least one j in A^c.

The user selects the aspects and the associated cut-off parameter values interactively over the computer terminal. For each test of criticality on a particular aspect, only those links that are indicated as critical (i.e. that

have failed all selected aspects tested up to that point) pass to the next test.

There are a few exceptions, however, where links are kept even though they are not indicated as critical for a given aspect. This occurs when either a given aspect is not applicable, or the link was indicated as critical for a similar aspect. These exceptions are as follows:

1) Medians are not evaluated for highways with fewer than four lanes.

2) Percent passing sight distance is not applicable to highways with at least four lanes.

3) If the shoulder width and shoulder type are both selected aspects, only one needs to be critical.

4) If horizontal adequacy and curves are both selected aspects, only one needs to be critical. In general, meaningful data is not given for both categories.

5) If vertical adequacy and grades are both selected aspects, only one needs to be critical. In general, meaningful data is not given for both categories.

The program logic is such that if $CRIT_{ij} = 1$ after aspect j is tested, link i is passed to the next aspect $(j + 1)$. However, if $CRIT_{ij} = 0$, then $CRIT_i = 0$ and link is is not even considered for aspect $(j + 1)$. If $CRIT_{ij} = 1$ and link i is found to be critical on aspect $(j + 1)$, then it is passed along to the next aspect $(j + 2)$, and so on. The process continues until either all $CRIT_i = 0$ for all links i (meaning that no link is found to be critical on all the selected aspects), or, more likely, after all selected aspects j in A^c have been exhausted. $CRIT_i$ will then be set to 1 only for those links i that have been declared critical on the last considered aspect (meaning that link i has also been found critical on all preceding aspects). A special mechanism is used in the program to implement the five exceptions listed above, that arise because of intrinsically related aspects.

At the end of each iteration (testing for selected subset of aspects), all links i with $CRIT_i = 1$ are shown on the terminal and printed. The user can then choose, interactively, to reiterate with only the remaining set of links from the previous iteration, but employing a previously unused set of aspects, or a revised set of cut-off parameter values for the previously selected aspects, in any combination. This allows the user to further reduce the set of critical links by imposing additional conditions. If it is

desired to test the original set of links with a previously unused set of aspects, then the program must be rerun, instead of continuing with additional iterations affecting only the remaining links from the previous iteration.

This is a very easy to use program, where aspects and corresponding cut-off values can be input and run one at a time or in any combination, affording the user considerable flexibility in specifying and experimenting with criticality criteria.

The input to all three of the above critical link programs consists of two types of information: 1) the selected aspects and associated cut-off parameter values, which, as seen above, can be input easily and interactively by the model user and 2) the network link data base, which contains all the relevant characteristics of the tested links. As noted earlier, all data elements which are flow-dependent need to be supplied by the traffic assignment model; however, the majority of the rest of the data is based on the HPMS data files. However, these had to be modified, as HPMS highway sections were combined to form network links that are compatible with the remainder of the network modelling methodology developed for this study. The development of the data base in appropriate format for the Texas highway network is presented in the next section.

3.4. Network Data Base Development for Critical Link Programming

This section presents some "nitty-gritty" details of the data base development process. As such, it can be skipped without loss in continuity by the reader seeking a conceptual understanding of the methodology and its capabilities.

3.4.1 Selection of HPMS Link Records

The network link data base input in the critical link programs was developed from HPMS data. Initially, HPMS data files containing all Texas links was copied, and subsequently reduced by eliminating links judged by the analysis team to be inconsequential to the truck lane needs study, which involves consideration of truck traffic routing in the statewide highway network. However, care was exercised not to eliminate reasonable alternate routes that could be used by shifting automobile traffic in response to

excessive truck interference on their present routes. Essentially, links with a strong local character, that are not nor likely to be potentially involved to any meaningful degree in intercity movement, were deleted.

All links with a maximum hourly truck volume of at least 190 vehicles (two-way) per hour were included. Also included were all links on a selected set of possible highway routes. Intercity highway route sections were chosen if: 1) at least one HPMS link record from that highway had maximum hourly truck volume in excess of 190, or 2) several links had maximum hourly trucks in excess of 100, or 3) the route is an interstate or connected multilane highway, or 4) it is important to maintain connectivity in the network. In other words, the initial screening involved some rather loose criteria as well as engineering common sense. A total of 710 HPMS link records were thus included in the data base development.

Note that "maximum hourly truck volume", as used above, was obtained as the maximum of hourly truck volume during the peak, and hourly truck volume during the off-peak. Peak hourly trucks is found using the following expression:

PEAK TRUCKS = AADT * (K-FACTOR/100) * (PEAK TRUCK PERCENT/100),

where the K-FACTOR is an HPMS multiplier applied to the AADT to obtain the corresponding peak hourly traffic volume (percent of 30th peak hour to AADT). However, because the peak hourly traffic is in terms of both trucks and general passenger car traffic, it need not correspond to the time period where the maximum hourly flow of trucks is observed. Thus the additional calculation of hourly truck volume during the off-peak, as follows:

OFF-PEAK TRUCKS = AADT * 0.07 * (OFF-PEAK TRUCK PERCENT/100).

Naturally, not all variables found in the HPMS data files were needed. Link characteristics defining the aspects described in Section 2.2 were included in the critical link programming data base, along with other characteristics that might reasonably be considered at some future date for defining critical aspects. In this manner, the critical link data base was limited to 137 columns per record (link), which is the maximum number of columns that can be printed on a single line. While this latter constraint was motivated primarily by convenience, and thus could be circumvented if necessary, there was no need for additional link characteristics to be included in the data base, as a good amount of "redundancy" has already been

built in by including any variable that could even remotely be useful to the analysis. The list of HPMS variables included in the data base, along with some derived or calculated quantities, is given in Table 3.2.

3.4.2. Curves and Grades Data

The HPMS data for curves and grades were modified and condensed in the data base development process. Since a given HPMS section may include more than one horizontal curve, the data was condensed into the maximum degree of curvature for each highway link. It is obtained by simply identifying the curve with the highest curvature category among those curves associated with a given link, and considering its category as that of the maximum degree curve associated with that link. Table 3.3 summarizes the curvature categories.

The grade data was set up in the critical links data base to test for speed reduction of heavy trucks on grades. The percent grade and length of grade is needed. The HPMS data gives sums of lengths of all link segments in a given grade category. The length of the longest section must be at least the length of the average section if two or more sections are included.

The procedure for the grade data is as follows:
1) Find the highest observed grade category and its associated percent grade.
2) For the highest grade category,

LENGTH $\leq$ (Total grade length of sections)/(Number of sections).
3) Find the second highest grade category and its associated percent grade.
4) Find the length of the second highest grade category by the same formulation as in step 2.

The grade categories are summarized below:

Category	%Grade	Programmed
A	0	0
B	1-2	2
C	3-4	4
D	5-6	6
E	7-8	8
F	>8.5	10

3.4.3 Combining HPMS Links Into Network Links

The process of combining HPM links to form Texas network links must be consistent with the objectives of the critical link programming, as well as with the other components of the network modelling methodology, particularly

TABLE 3.2. LIST OF HPMS VARIABLES INCLUDED IN DATA BASE

Variable	HPMS Item Number
Section 1D - first 4 characters	7 (characters 1-4)
Section 1D continued	7 (characters 5-8)
Route number	3
County	4
Function class	8
Lanes	26
Section length miles	23
AADT	24
Peak hour to day percent	55
Peak hour truck percent	54
Off peak hour truck percent	54
Peak direction factor percent	56
Lane width	39
Peak hour capacity (one direction)	57
Volume to capacity	calculated
Speed limit (mph)	52
Rural - Urban	4
Access control	38
Signalization	58
Pavement type	32
Pavement section	34
Structure number or slab thickness	35
Pavement condition	36
Terrain type	63
Shoulder type	41
Right shoulder width	42
Median type	43
Median width	44
Horizontal adequacy	47
Maximum degree curve	derived from 48
Vertical adequacy	49
Maximum percent grade	derived from 50
Maximum grade distance	derived from 50
Second maximum percent grade	derived from 50
Second maximum grade distance	derived from 50
Percent passing sight distance	51
Future AADT	61
Widening feasible	46
ROW width	45
Maximum hourly trucks	calculated
HOV or reversible lanes	21
Skid resistance	37
Off peak capacity	57
Urban area code	5
Left shoulder width	42

TABLE 3.3. DEGREE OF CURVATURE CATEGORIES

Category	Degree of Curvature (Percent)
A	0
B	1
C	2
D	3
E	4
F	5
G	6
H	8
I	10
J	13
K	18
L	25
M	30

the traffic assignment programming. This process is necessary so that the network can be created for the traffic assignment program, and to allow for coordination between the critical links and traffic assignment program. The component HPMS link records for a given network link should have identical speed limits, number of lanes, and similar capacities. Therefore, a given intercity highway link could result in several network links.

For the critical links analysis, the primary concern is with the worst case. Therefore the narrowest lanes, shoulders, and median widths, the highest volume to capacity, the lowest pavement condition rating, etc, of all the component HPMS links would be used for the combined network link.

The network links used in the traffic assignment process are directed links, corresponding to one direction of flow only. A two-directional highway section is thus typically represented by two directed links, one in each direction. Since HPMS sections are all two-directional, it is necessary to replace the HPMS section identification numbers by network node numbers, and to effectively duplicate each HPMS record into two network link records, with appropriate adjustments to such variables as number of lanes, two-way volumes, and so on. It is also necessary to replace HPMS section lengths with the corresponding network link lengths. In some cases, it was possible to calculate these by summing the component section lengths, while in other cases, distances were measured off Texas highway maps.

3.5. Summary

This chapter has presented the procedures developed for the identification and diagnosis of critical highway links, from the perspective of truck traffic in the Texas highway network. The logic followed in the development of the critical link programming procedures was presented. Essentially, each link is screened on a set of aspects, whereby some cut-off parameter value must be met on a selected number of link characteristics. Three types of aspects are considered: geometric, pavement and operational aspects. Detailed descriptions of these aspects were given in section 2.4. However, it is intended that these be refined by engineers and planners using the procedures developed in this study, to examine the implications of various warranting procedures and criteria for truck lane implementation. For this reason, three versions of the critical link programming logic were developed, allowing for user-friendly, interactive input of aspects and

corresponding cut-off parameter values. Details of the development of the link data base, for the Texas highway network, as required by the critical link programs, were given in Section 2.4. The next chapter describes the traffic assignment procedures developed in this study.

CHAPTER 4 NETWORK TRAFFIC ASSIGNMENT

As noted in the conceptual framework of Chapter 2, the network traffic assignment methodology is an essential component of the overall network modelling methodology developed for the study of truck lane needs in the Texas highway network. Its function is to determine the link flow patterns resulting from the allocation of origin-destination trip matrices (for cars and trucks respectively), corresponding to present or future conditions, to a given highway network. By changing the configuration of the latter, or by modifying the characteristics of some of its links, the traffic assignment procedures allow the assessment of the impact in all parts of the network of selected truck-related improvements, such as special truck lanes or facilities in designated corridors or highway sections. This impact is of interest at the individual link level, as well as for the network as a whole, as discussed in Chapter 2.

To be useful in this study, the network traffic assignment model should possess the following capabilities:

1. It should yield truck flows as well as passenger car flows on every network link.

2. It should capture the non-linear dependence of the travel time (or cost) incurred by link users on the total flow using that link.

3. It should recognize the interaction between vehicle classes sharing the same right-of-way; in this case, passenger cars and trucks are the vehicle classes of interest.

4. It should be policy-sensitive, in that it should allow the representation of the contemplated truck-related countermeasures.

Items 2 and 3 above are generally captured in the link performance functions, which yield the travel time as a function of the flow of each vehicle class on that link, or more generally as a function of the entire link flow pattern, as discussed in Chapter 2.

The procedures developed in this study have succeeded in implementing an approach that possesses all of the above capabilities. Because of the need to simultaneously solve for the link flows (which determine link travel times) and the link travel times (which in turn affect the routes chosen by

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motorists in the network, and therefore link flows), the problem is known as a network equilibrium problem. Since each user is assumed to choose the route that minimizes his/her own travel time, the formulation is known as a user equilibrium problem. Furthermore, when interactions among vehicle classes are explicitly represented, they are effectively equivalent to interactions among links (where different conceptual links are defined for each user class). Such interactions are asymmetric, meaning that the marginal contribution of a vehicle belonging to a given category to the other class' travel time is different from the marginal contribution of a vehicle in the latter category to the former's travel time. In this study, interactions between cars and trucks are generally asymmetric, yielding a user equilibrium network assignment problem with asymmetric link interactions.

A more detailed presentation of the mathematical and algorithmic background of this problem and solution approach is given in the companion report by Mouskos, Mahmassani and Walton[11]. Essentially, there are no guaranteed procedures to solve the network user equilibrium problem with asymmetric link interactions. However, an approach known as the diagonalization algorithm has recently received attention as a promising one to solve for network equilibrium in the presence of asymmetric link interactions, [13,14,15]. Because the necessary conditions for its convergence to the desired equilibrium solution are not well understood in the transportation science literature, while known sufficient conditions are recognized as being too strict and often far from necessary, it is necessary to test the approach in the specific context in which it is to be employed[15]. Furthermore, in its complete version, the algorithm is rather demanding computationally. However, some shortcuts have been suggested to improve its performance in this regard[13]. However, these approaches remain to be tested, as numerical experience to date seems to have been limited to small unrealistic networks. A major objective of this effort is therefore to test these approaches and develop computational experience in realistic networks, comparable to that used in the truck lane needs study. This then forms the basis for recommendations in view of its use as an operational tool in the analysis of truck-related improvements in a highway network. The special network representation adopted to handle interaction among vehicle classes is presented next, followed by a brief description of the steps of

the diagonalization algorithm, along with the principal streamlining strategies considered.

4.1 Network Representation

Two types of nodes are specified in the representation of the traffic system under consideration. First, centroids represent points from which trips originate or terminate. In an intercity network, centroids will correspond to the principal urban areas and communities that generate and receive the passenger cars and commodities transported in the network. Centroids are connected to the rest of the network using hypothetical links known as centroid connectors. The other category of nodes do not generate or receive trips or commodities, but serve as link start and end nodes. All links in this network are directed links, carrying flow in one direction only.

As noted previously, each highway link is used by two classes of vehicles; cars and trucks, which interact, through their use of the common shared right of way, in determining the travel time incurred by vehicles of both classes using that link. The interaction between the two classes or a highway link is represented through the use of identical networks (referred to as "copies" of each other) for each class. Each physical highway is thus decomposed into two "conceptual" links. Each link has its own performance function, and the flow on any given link consists of one or the other designated class only. Interaction among the various classes using a particular physical link thus translates into interaction among links in this network representation (which is why the problem addressed here was referred to as involving asymmetric link interactions).

Special Representation of Truck Lane Additions

In order to test the effect of truck-related improvements to a particular highway link, it is necessary to devise a general purpose mechanism that allows the representation of this improvement not only in terms of lane addition, but also in terms of how this new lane might be operated in conjunction with the existing lanes (e.g. access restriction of a given lane to certain vehicle classes). Essentially, with each given physical highway section, with start node i and end node j, we have already seen that two conceptual link copies are defined, one for trucks and one for

cars, with the "coupling" accomplished through a special numbering scheme as well as through the respective link performance functions, as described in Mouskos et al[11]. Furthermore, to allow for the addition of a lane that may be for the exclusive use of trucks, or to compare this exclusive truck lane to other possible uses of that potential lane, such as shared use by both classes of vehicles, or exclusive use by cars only, one additional node (dummy node) and two additional links are defined, for each of the car and truck copies, as shown graphically in Fig. 4.1.

The two additional links consist of: 1) a dummy link, from the start node i to the dummy node, and 2) a link, from the dummy node to the end node j, representing the actual lane addition, included in each copy to allow either cars or trucks (or both) to use it. However, if it is desired to restrict its usage to trucks only, then the preceding dummy link in the car network copy will be associated with a very large positive cost (travel time), effectively prohibiting cars from accessing it (and thereby getting onto the added lane). If, on the other hand, it is desired to allow cars to use this new lane, then the cost is set equal to zero, and cars are therefore allowed to consider using the additional lane in their route choice. Of course, the travel time that they will experience on that link (representing the new lane) is given by the associated performance function, which properly accounts for the interaction with the existing lanes as well as with the truck flows on the existing and new lanes (represented by the links defining the truck network copy). Further details on this representation in conjunction with the improvements that can be handled by the link selection/network design model are given in Chapter five, as well as in companion technical reports [11,12].

4.2. Steps of the Diagonalization Algorithm

The diagonalization algorithm is an iterative procedure which involves solving a series of tractable single-class user equilibrium programs.

Let $t_a^n = f_a(X_a^n, X_{\bar{a}}^n)$ denote the performance function for link a, where t_a^n is the travel time and X_a^n is the flow on link a at the n-th iteration of the algorithm, while $X_{\bar{a}}^n$ is a vector of flows on all links other than a that affect the travel time on that link. The vector $X_{\bar{a}}^n$ will typically contain at least the flow on the link corresponding to the "other" vehicle class

Actual Directed Link (Shared Use)

Car Copy

Truck Copy

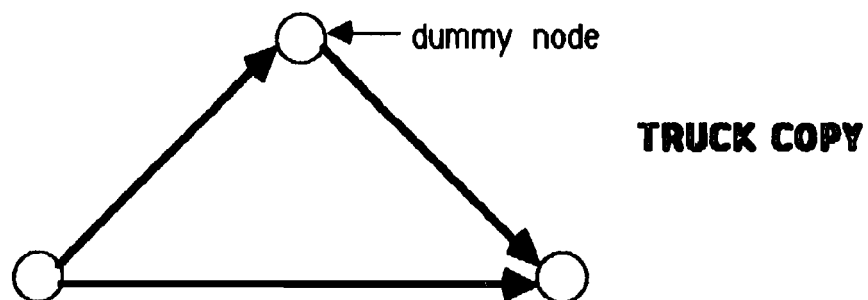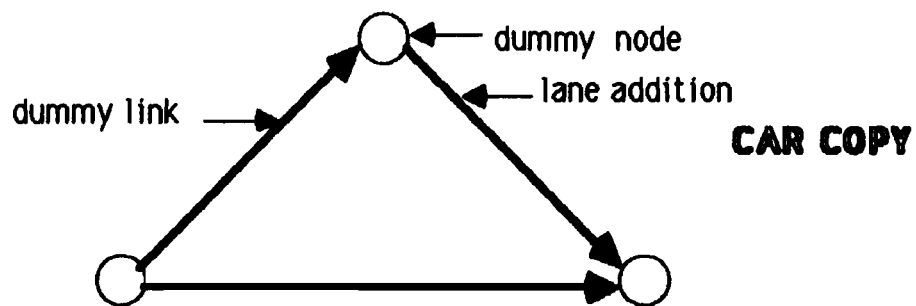Improvement Involving Lane Addition

CAR COPY

dummy node
lane addition
dummy link

TRUCK COPY

dummy node

Figure 4.1. Special Network Representation of Truck Lane Addition

sharing the physical right-of-way of link 2; i.e. if a is the passenger car copy of a particular highway link then X_a^n will include at least the flow on the truck copy of that same physical highway link. In addition, X_a^n may also contain flows on links defined especially to study the impact of truck lanes and other truck-related improvement options, as described in the next chapter in conjunction with the link improvement selection/network design problem introduced in Chapter 2.

Note that the effect of X_a on t_a is referred to as a main effect, whereas the effect of the components of $X_{\bar{a}}$ on t_a are called cross-link effects. The diagonalization algorithm requires, at the n-th iteration, that all cross-link effects be fixed at their current levels, with only the main effect allowed to vary in the solution of the equilibrium problem at any given iteration. In other words, at the n-th iteration of the diagonalization algorithm, we solve jointly for t_a^n and X_a^n such that $t_a^n = f_a(X_a^r, X_{\bar{a}}^{n-1})$ and user equilibrium conditions are satisfied assuming that the cross-link effects are fixed at their values from the (n-1)-th iteration. The next iteration, if convergence is not yet achieved, will then fix the cross-link effects at their values from the n-th iteration in solving for t_a^{n+1} and X_a^{n+1}.

The steps of the algorithm can be summarized as:

Step 0: Initialization; find a feasible link flow vector.

Step 1: Diagonalization; at the n-th iteration, solve a user equilibrium subproblem assuming that cross-link effects are fixed. This yields a link flow pattern X_a^n, and associated link travel times t_a^n, for all links a.

Step 2: Convergence test; if X_2^n is approximately equal to X_a^{n-1}, for all a, then convergence is reached. X_a^n is the desired solution. Otherwise, set n = n=1 and go to step 1.

As can be seen, the diagonalization algorithm involves a number of iterations, referred to as _outer_ iterations, to distinguish them from the _inner_ iterations that one must perform in solving the subproblem in Step 2. This subproblem is solved using the Frank-Wolfe or Convex Combinations algorithm.[13] The steps of this algorithm can be summarized as:

Step 0: Initialization; perform all-or-nothing assignment (by assigning all flows from a given origin to a particular destination to the shortest path

between the two points) based on the free flow or uncongested link travel times.

Step 1: Update travel times, using the link performance functions, with only the main effects due to each link's own flow allowed to affect that link's travel time. Cross-link effects remain constant, throughout the solution of this subproblem, fixed at their values from the previous _outer_ iteration.

Step 2: Direction finding; perform all-or-nothing assignment, after solving a shortest path problem based on the updated travel times from Step 1.

Step 3: Line search; find a move size parameter to update the current link flows by "optimally" combining them with the flows generated in the direction finding Step (Step 2).

Step 4: Update the link flows, using the move size parameter calculated in Step 3.

Step 5: Convergence test; if the link flows generated in Step 4 are about equal to the flows from the previous iteration, convergence is reached and the subproblem is solved; otherwise, increment the iteration counter and go to step 1.

A more detailed mathematical presentation of the algorithm can be found in the companion report by Mouskos et al. [11]. The main point for this discussion is that at each (outer) iteration of the diagonalization algorithm, a number of inner iterations need to be performed. Each of these inner iterations requires the solution of a shortest path problem, from each origin to all destinations. Computationally, this can be quite demanding. However, by noting that only the last outer iteration's flow pattern needs to be determined accurately, and that the accuracy of the solution to that subproblem improves only marginally with each additional inner iteration, a streamlining of the algorithm has been proposed by Sheffi[13], whereby only one inner iteration is performed per outer iteration. This streamlined version has not however been adequately tested for accuracy nor computational efficiency.

Actually, a more general streamlining strategy is investigated here, whereby we seek to determine the best number of inner iterations for each outer iteration. This has been conducted for the specific context of the

truck lane needs study, using the Texas network as well as related networks or abstractions thereof. Furthermore, another objective was to establish that the algorithm does indeed converge to the desired equilibrium solution for this type of problem involving interactions between cars and trucks. In the next section, the tests conducted in this study are briefly described.

4.3 Implementation and Computational Tests

The streamlining strategies considered in this study consisted of varying the maximum number of inner iterations allowed per outer iteration. The trade-off is as follows: more inner iterations result in greater accuracy in the solution of the subproblem (of step 2 of the diagonalization algorithm) and in fewer outer iterations, whereas reducing the number of inner iterations may require more outer iterations. However, the key concern here is the total number of iterations that require the solution of a shortest path problem, since the latter is the principal contributor to the computational cost of the overall algorithm. The total number of iterations is simply the product of the number of inner iterations by the number of outer iterations. The principal motivation for streamlining strategies is the observation that, while reducing the number of inner iterations would probably increase the number of outer iterations, the resulting total number of iterations would be less than that obtained with more inner iterations (but fewer outer iterations). In other words, the additional outer iterations seem to be more than offset by the decrease in the inner iterations.

This observation is a very important one from the standpoint of implementing a network modelling methodology to the study of truck lane needs in the Texas network. However, it is necessary to test it in the specific context of this study, since, as noted earlier, no general results exist in that regard, and the operational validity of the approach seems to be context-specific. To this end, computational experiments were conducted for four different test networks, as follows:

1. Test network 1 is a condensed abstraction of the Texas highway network. It was developed as the principal network for methodological development and testing. It was sought to retain the general features of the Texas network, in terms of the location of the major origins and destinations, as well as the principal intercity transport routes. At the

CENTROID

NODE

TYPICAL TWO-WAY LINK

EGRESS-LINK
ACCESS-LINK
CENTROID CONNECTOR
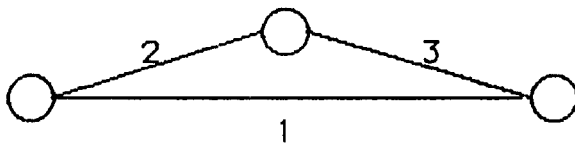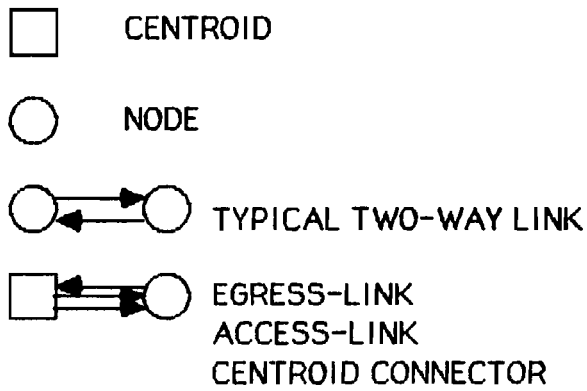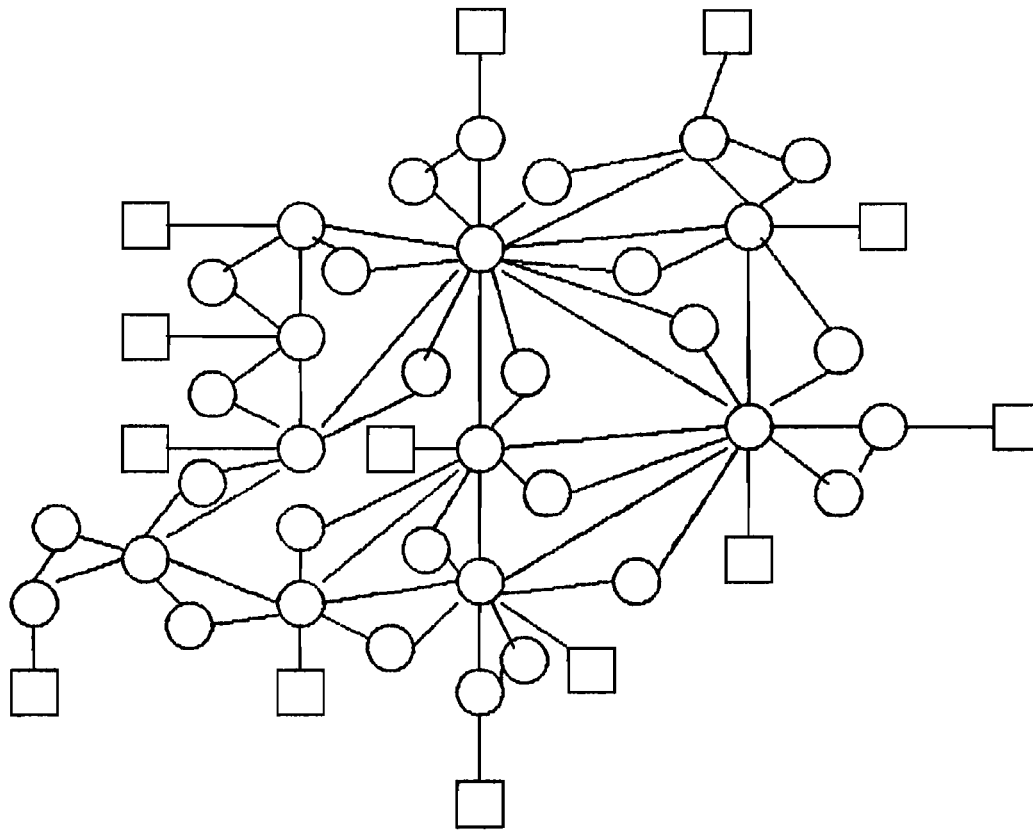
1: COMMON LINK
2: DUMMY LINK
3: EXCLUSIVE AUTO OR TRUCK LINK

Figure 4.2. Test Network 1.

same time, it was desirable to avoid excessive detail that would contribute needlessly to the development cost. The motivation for this condensed Texas test network is of course to limit cost and keep the methodological development process at a manageable level, yet obtain sufficiently meaningful insights for the large-scale implementation of the algorithm. These insights would of course be tested on the full-scale network; however, the test network would provide the research team with a much more effective starting point than working with the large network from the start.

Test network 1 consists of 14 centroids, 42 common links (i.e. shared by cars and trucks), 42 dummy links and 42 exclusive use lane addition links. Two copies of this network were coded, one for trucks and one for cars, as described previously. It does allow the addition of a lane, and the control of its use, to each of the existing highway links. Figure 4.2 shows a graphical representation of this network (single copy only).

2. Test network 2 is similar to test network 1, except that it is not equipped with the special exclusive lane addition mechanism. Therefore, no dummy links and nodes are included, but only the common links (see Fig. 4.3). The motivation for including such a network in these experiments is to provide a basis for comparison between networks with and without the particular lane addition configuration.

3. Test network 3 is an arbitrary network included in this analysis to provide comparability of our results to those of other researchers.

4. Test network 4 is the full-scale Texas highway network intended for initial implementation of the network modelling methodology to the study of truck lane needs.

Further detail on the test networks can be found in the report by Mouskos et al.[1].

For each test network, the diagonalization algorithm was run under all combinations of the levels of two factors:

1. The maximum number of inner iterations; which was varied over all integer values between 1 and 10 (inclusive).

2. The congestion level, defined in terms of the link capacity parameter, as used in the link performance functions (see next section). Letting C denote the reference value for capacity per lane, four different levels for these factors were used: 0.5C, 0.8C, C and 4C. The intent was to examine the performance of the algorithm, given maximum number of inner

CENTROID

NODE

TYPICAL TWO-WAY LINK

EGRESS-LINK
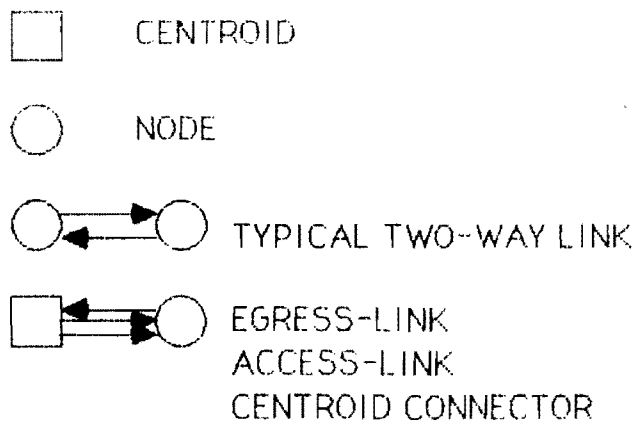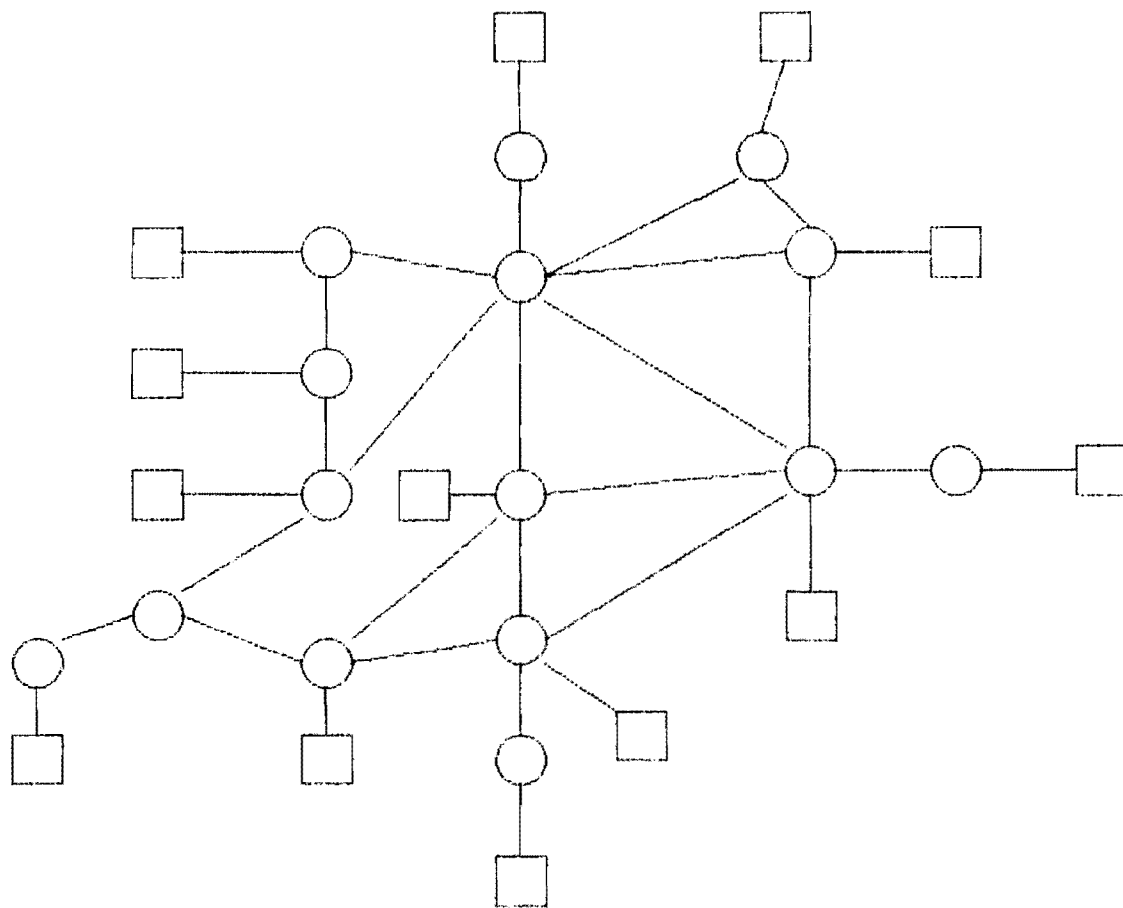ACCESS-LINK
CENTROID CONNECTOR

Figure 4.3.   Test Network 2.

iterations, under widely varying congestion conditions.

For each run, two principal figures of merit were examined: the total number of iterations until convergence, and the C.P.U time, in seconds, required to achieve convergence. Note also that convergence was reached, in all cases, alleviating the concern mentioned earlier about convergence in this context, and further suggesting that the above-mentioned sufficient conditions are too strict. The results are summarized in Tables 4.1 and 4.2 for test networks 1 and 2 respectively. These are included for illustrative purposes. The complete results for all the test networks can be found in the report by Mouskos et al.[11]. Figures 4.4 and 4.5 depict the CPU time versus the maximum number of inner iterations, under the four capacity levels, for networks 1 and 2 respectively.

The principal conclusions from these experiments are that:

1) considerable reduction in computational effort can be achieved by constraining the maximum number of inner iterations per outer iteration of the diagonalization algorithm.

2) While the "best" number of maximum inner iterations varies from one case to another, there is no need to go beyond three inner iterations under any circumstance. Two is the recommended number based on a synthesis of the result.

3) The streamlining approach with only one inner iteration, as proposed by Sheffi[3], is almost never the most efficient strategy. It is however second best in many cases and definitely provides an improvement over the complete version of the algorithm.

4) The diagonalization approach, with the recommended maximum of two on the number of inner iterations, provides an operationally useful tool for solving the network equilibrium assignment problem with asymmetric interactions encountered in the study of truck lane needs in the Texas highway network.

4.4. The Link Performance Functions

An essential element of the methodology to assess the effect of truck lanes and select candidate links for such improvement is an equation that represents the interaction among cars and trucks, at various flow levels, in determining the travel time on the facility, as experienced by cars and trucks. This is captured in the link performance functions, which yield the

TABLE 4.1. RESULTS FOR NETWORK #1

CPU Time (Seconds)

		1*C	0.8*C	0.5*C	4.0*C
		**************************************			
	1	10.049	8.428	9.032	43.401
	2	9.464	7.339	12.646	27.852
	3	14.257	9.940	8.337	41.451
Maximum #	4	16.390	15.924	11.570	14.454
of Internal	5	12.568	14.223	12.625	41.386
Iterations	6	14.161	12.073	13.169	13.432
	7	15.320	15.289	15.298	51.316
	8	14.692	13.146	15.247	35.507
	9	17.539	15.815	14.101	46.011
	10	13.664	14.809	15.308	44.034

Corresponding Total # of Iterations

		1*C	0.8*C	0.5*C	4.0*C
		**************************************			
	1	16	13	14	79
	2	15	11	21	49
	3	24	16	13	76
Maximum #	4	28	25	19	25
of Internal	5	21	24	21	76
Iterations	6	24	20	22	23
	7	26	26	26	95
	8	25	22	26	65
	9	30	27	24	85
	10	23	25	26	81

TABLE 4.2. RESULTS FOR NETWORK #2

CPU Time (Seconds)

		1*C	0.8*C	0.5*C	4.0*C
	1	11.924	13.926	13.451	6.360
	2	7.873	9.915	9.934	3.687
	3	15.364	14.389	18.362	3.161
Maximum #	4	20.387	16.371	18.858	13.666
of Internal	5	23.291	22.303	26.803	7.157
Iterations	6	25.779	22.293	35.264	9.141
	7	24.815	24.305	22.344	7.107
	8	20.850	32.761	21.863	7.087
	9	24.811	27.352	30.758	7.096
	10	30.801	33.792	32.335	7.116

Corresponding Total # of Iterations

		1*C	0.8*C	0.5*C	4.0*C
	1	21	25	24	10
	2	13	17	17	5
	3	28	26	34	4
Maximum #	4	38	30	35	25
of Internal	5	44	42	51	12
Iterations	6	49	42	68	16
	7	47	46	42	12
	8	39	63	41	12
	9	47	52	59	12
	10	59	65	62	12

CPU Time vs Maximum # of Internal Iterations
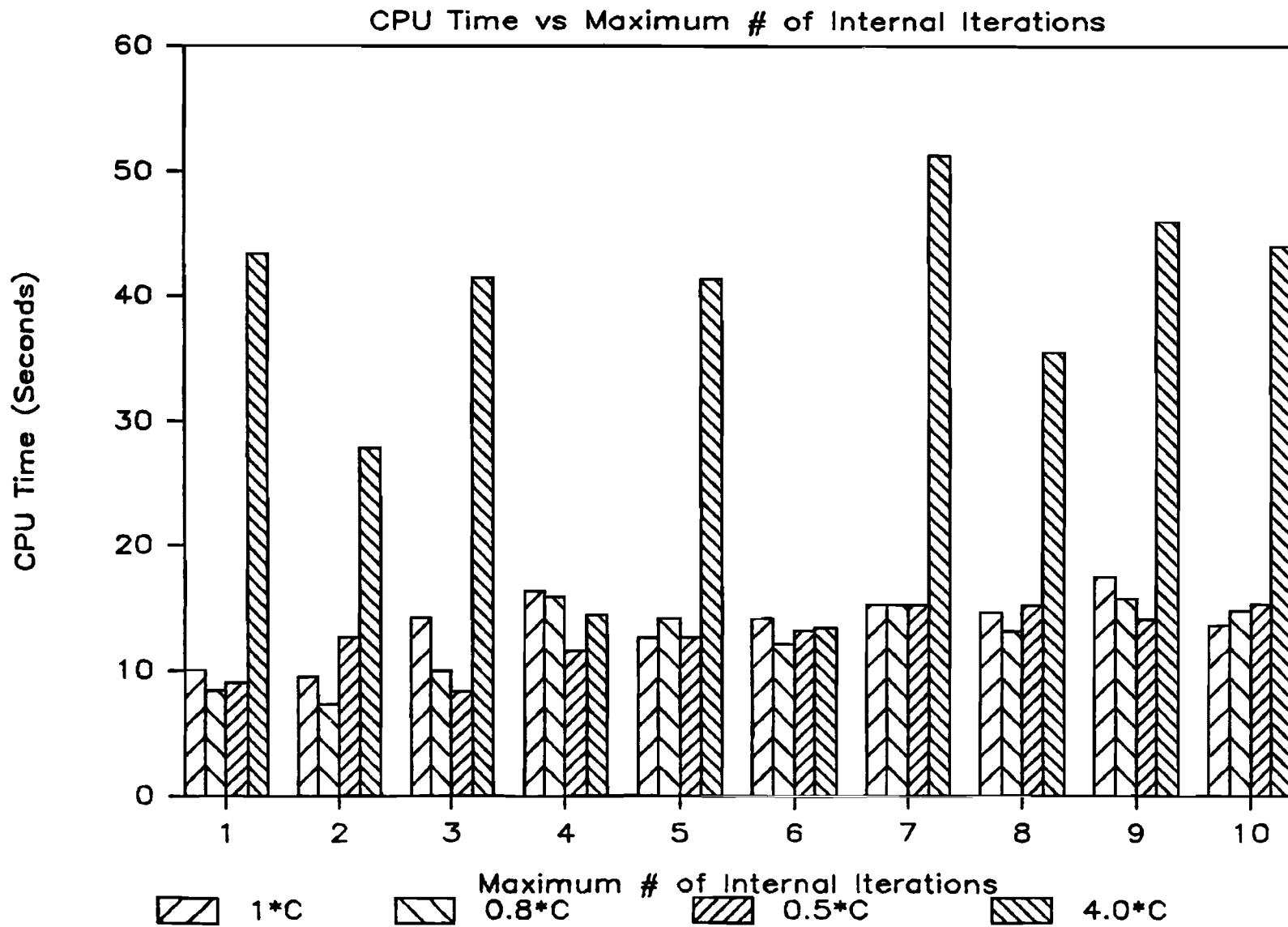
Figure 4.4.   Results for Network #1.

CPU Time vs Maximum # of Internal Iterations
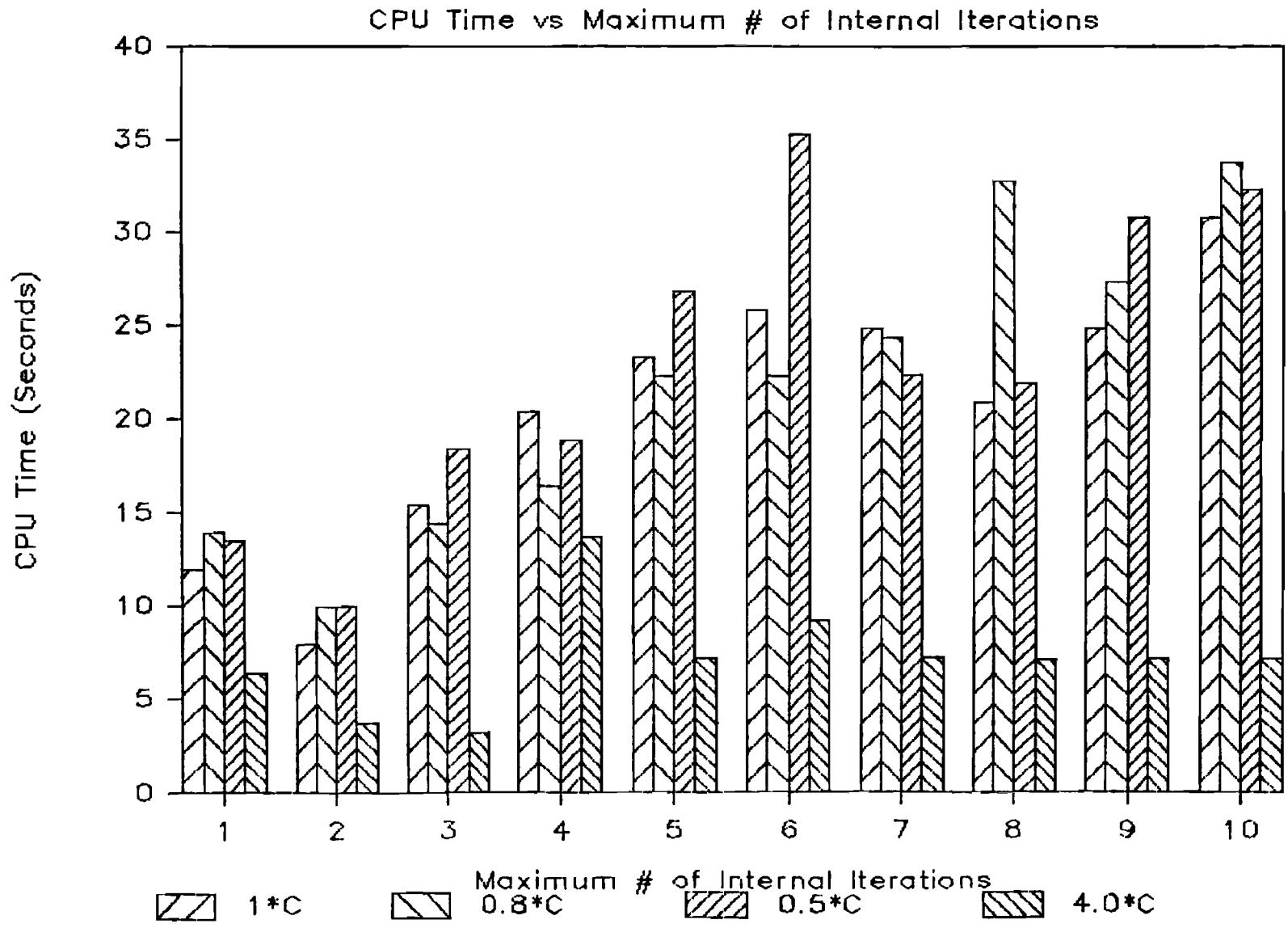
Figure 4.5. Results for Network #2.

average travel time on a highway link as a function of average car and truck flows.

The link performance functions used in the development of the network modelling methodology were obtained primarily from theoretical and engineering practice considerations. Their functional form was selected to be close to the Bureau of Public Roads (BPR) curves that are widely used in traffic assignment practice,[3,6,7] as shown below:

$$t_i^A = t_{oi}[1 + A_1([X_i^A + E. \ X_i^T]/C_i) \quad]$$

$$t_i^T = t_{oi}[1 + A_2([X_i^A + E. \ X_i^T]/C_i) \quad] \quad ,$$

where

t_i^A and t_i^T are the average travel time on link i for cars and trucks respectively

X_i^A and X_i^T are the respective flows of cars and trucks on link i

t_{oi} is the free flow travel time on link i

C_i is the capacity of link i

E is an equivalency factor to convert trucks into cars

A_1, A_2, B_1 and B_2 are link specific and user class specific parameters.

Unfortunately, virtually no prior research has addressed the proper functional form of the interaction between cars and trucks sharing the same right-of-way; nor have general purpose parameters for these functions, when cars and trucks are present, been calibrated. Therefore, the functions used here are not based on actual observation of traffic behavior, though such observationally-derived functions would be highly desirable. Such a task was outside the scope of the present study, especially since proper observations of exclusive truck lane operations are simply not available. In the course of this study, a data set of freeway operations for selected facilities in the country was identified and obtained from the Federal Highway Administration. However, this data cannot answer all the questions related to this problem. It is hoped that the present methodology will be updated to reflect advances in the development of these functions. In particular, two promising sources of observations can be used: 1) the above mentioned FHWA data and 2) observations that can be obtained from demonstration projects, currently under preparation by the Texas SDHPT. It is recommended that

proper monitoring of traffic characteristics and facility travel time performance be placed in operation in conjunction with such demonstration projects. At any rate, the present network modelling methodology already has built in the mechanism for easy updating of the link performance functions.

4.5. System Optimal Assignment

The prediction of user response to changes in the highway network (in the form of selected link improvements) is accomplished by assigning users to the network according to the user equilibrium principle. However, a computer program to assign traffic according to another rule, namely the system optimal principle, has also been developed for this study. The system optimum formulation assigns users to the network so as to minimize the total travel. time of all users in the network, even if some individual users could improve their own travel time by switching to a shorter route. While the user equilibrium formulation is generally recognized as more realistic in terms of individual route choice behavior, thereby making it a more appropriate descriptive tool than the system optimal model, the latter is quite important for its role in network design models.

The optimal link improvement selection/network design methodology presented in the next chapter requires the use of a system optimal assignment model to calculate appropriate "lower bounds" in the branch and bound algorithm. This need has provided the motivation for pursuing the system optimal formulation in this study, in addition to the user equilibrium assignment model which remains the principal tool for predicting link flow patterns and associated user costs.

The system optimal formulation still recognizes the asymmetric interaction between the two user classes sharing the roadway, using the same link performance functions and network representation strategy discussed earlier in this chapter. In the companion report by Mouskos et al.[11], the mathematical programming formulation of this problem is given, and the first order for the existence of a stationary point (i.e. solution) are derived, establishing the existence of this solution. Its uniqueness is however not guaranteed, just as in the user equilibrium case. The diagonalization algorithm is also useful for this problem. A simple modification in the "direction finding" step of the convex combinations algorithm, used to solve

the subproblem encountered in step 2 of the diagonalization algorithm, is needed, as shown by Mouskos et al.[11]. This modification has been implemented and is currently operational.

Because the issues associated with the diagonalization algorithm for the system optimal assignment problem remain the same as in the user equilibrium formulation discussed earlier, numerical experiments have also been conducted to test the computational aspects of the algorithm for the system optimal case. These experiments parallel those conducted for the user equilibrium case, presented in section 4.3, and will not be repeated here. The general conclusions are also similar to those given earlier. A more complete discussion of these results is given in Mouskos et al.[11].

4.6. Recommendations

This chapter has described the network assignment models developed in conjunction with the network modelling methodology for the truck lane needs. An essential feature of this problem is the interaction between cars and trucks sharing the same roadway. The network representation developed in this study to model the truck-related link improvements under consideration, leads to asymmetric interactions among links. This interaction must be captured in the performance functions governing the dependence of link travel time on the link flow pattern. The special mechanisms presented for this purpose are essential to the usefulness of the overall procedure.

Extensive algorithmic development was conducted in this study, to address the special features of the truck lane improvements in a network. This development focused on the diagonalization algorithm. More importantly, systematic testing of strategies to improve the computational performance of this algorithm, and thereby enhance its operationalability, was conducted. These experiments were performed on four test networks including a full-scale Texas highway network (at the appropriate level of detail for the truck lane needs question), as well as a condensed version that served as a laboratory tool in the methodological development process. The results are extremely encouraging, and confirm the usefulness of the model for the truck lane needs study in the Texas highway network.

It is recommended that the following questions be examined to ensure the full effectiveness of the methodology developed here. First, there is the matter of the appropriate functional form and parameters of the link

performance functions that capture the interaction between vehicle classes. Suggestions along these lines were given in section 4.4. This question should be a high priority item in subsequent related research.

Second, the perennial question of proper origin-designation information must be addressed. This information is needed for both car trips as well as truck movements. The data gaps in this area are quite severe, and require a specially targeted research effort, which is clearly outside the scope of the present study. A crude heuristic approach was used here to generate O-D information for the purpose of developing and testing the network modelling methodology. This information was judged to be adequate for that purpose. However, policy, planning and engineering decisions require better accuracy in this regard. A number of useful approaches that combine information from a variety of sources, including observed link flows, to synthesize O-D matrices were identified in this study, and should be pursued in future work.

CHAPTER 5 OPTIMAL LINK SELECTION/NETWORK DESIGN METHODOLOGY

This chapter describes the procedures developed to identify an optimal subset of truck-related link improvements in the highway network, so as to minimize overall system costs (including costs incurred by car and truck users), subject to a specified maximum level of expenditures over the selected planning horizon. This procedure is thus developed to solve decision problem type P3, discussed in Chapter 2. Essentially, this procedure combines the traffic assignment model and subsequent evaluation, diagnosis and assessment activities with the search for a best combination of link improvements within a specified budget.

The principal features of this network methodology are such that it allows the consideration of:

a - congestion on links resulting from the volume of vehicles

b - interaction of cars and trucks in the traffic stream and its effect on link travel time

c - selection of which links are to be improved as well as the type of improvement

d - link improvement in terms of not only capacity expansion (lane addition) but also operating scheme (exclusive lane use by either vehicle class vs. shared use of both new and existing lanes)

e - an elaborate set of feasibility rules, including geometric, pavement and operational criteria for the addition of special truck lanes to existing highway links.

The purpose of this chapter is to provide an overview of this methodology, its principal features and capabilities. Only brief attention is given to the algorithmic aspects, as these are covered in great depth in the companion report by Massimi, Mahmassani and Walton[12]. The major concern in this chapter is with the types of improvements that can be handled by the model, and therefore employed by the implementing agency. These options are described in the next section, followed by the logic of their network representation. Section 5.3 discusses the elaborate set of elimination rules devised to exclude certain links with particular characteristics from

receiving certain improvement types. Section 5.4 provides a brief overview of key features of the solution approach, followed by concluding comments and recommendations in Section 5.5.

5.1. Definition of Link Improvement Options

Four types of improvements are defined, each involving the addition of a new lane, but differing in terms of the rules governing the access of both the new and the existing lanes by the two categories of vehicles under consideration. In particular, the new lane can be used by either 1) trucks only (exclusive truck lane), 2) passenger cars only (restricted lane) or 3) all traffic. Similarly, the existing lanes can be used by either 1) all traffic or 2) car traffic only. Note that the conversion of all existing lanes of a facility to exclusive truck usage was not considered to be a viable option warranting inclusion in the methodology. Four different combinations of these factors define the following mutually exclusive options for each link:

Option 1: Expand the link by one lane and allow all traffic on entire link.

Option 2: Expand the link by one lane, but allow only truck traffic on new lane with all traffic allowed on old lanes.

Option 3: Expand the link by one lane, but all truck traffic must use new lane with all car traffic allowed on old lanes only.

Option 4: Expand the link by one lane, but allow only car traffic on new lane with all traffic allowed on old lanes. Note that this option is equivalent to building a new lane which would be open to both cars and trucks, and at the same time restricting trucks from using the left-most lane.

Figure 5.1. illustrates the implementation of each of the four options on a link which presently has three lanes.

Noting that all links are directed in the network representation followed here, as discussed in the previous chapter in conjunction with the traffic assignment model, it is assumed that if such a (directed) link is improved by a given option, then the sister link (i.e. the paired link in the opposite direction, corresponding to the same physical two-directional highway section) is improved by the same option.

Present   Proposed

Option 1:   - | - | -   - | - | - | -

                 - | - | -   - | - | - | -

                 - | - | -   - | - | - | -

Option 2:

                 - | - | -   x | - | - | -

                 - | - | -   x | - | - | -

                 - | - | -   x | - | - | -

Option 3:

                 - | - | -   x | o | o | o

                 - | - | -   x | o | o | o

                 - | - | -   x | o | o | o

Option 4:

                 - | - | -   o | - | - | -

                 - | - | -   o | - | - | -

                 - | - | -   o | - | - | -

Legend

-   Designates lane open to all traffic

x   Designates lane open to truck traffic only

o   Designates lane open to car traffic only.

Figure 5.1 Link Improvement Options

5.2. Representation of Link Improvement Options

Having specified the truck-related improvement options of interest in this study, it is meaningful to further describe the special mechanism, introduced in Section 4.2, devised to represent these link improvements. As mentioned in that section, two principal elements are used in this mechanism: 1) the dummy node and link configuration, shown in Fig. 4.1, and 2) the parameters of the link performance functions associated with each of the links comprising this configuration.

Consider existing directed link a, and let:

a_A denote the copy of link a for car traffic

a_T denote the copy of link a for truck traffic

a'_A denote the potential lane addition link for cars

a'_T denote the potential lane addition link for trucks

and a_{Ad} and a_{Td} the corresponding dummy links in the car and truck copies, respectively.

Furthermore, define the link travel times t_{aA}, t_{aT}, $t_{a'A}$, $t_{a'T}$, t_{aAd}, t_{aTd} on the corresponding links defined above (see Fig. 5.2). Then travel times are, in the general case, related to the flow vector $X_a = [X_{aA}, X_{aT}, X_{a'A}, X_{a'T}]$ comprising the respective flows on the above-defined links. Note that t_{aAd} and t_{aTd} are equal to either M (a very large positive number) or 0, depending on the access rule for the additional lane, as seen hereafter. The performance functions for the non-dummy links are denoted by $t_{aA}(.)$, $t_{a'A}(.)$, $t_{aT}(.)$ and $t_{a'T}(.)$ respectively. The operational schemes associated with each improvement option are translated through the specific dependence of the above link travel times on the components of the flow vector X_a.

Option 1: Under option 1, all traffic is allowed on the new lane, with no changes (i.e. still all traffic) on the existing lanes. Therefore:

$$t_{aA} = t_{a'A} = t^*_{aA}(X_{aA} + X_{a'A}, X_{aT} + X_{a'T})$$

$$t_{aT} = t_{a'T} = t^*_{aT}(X_{aA} + X_{a'A}, X_{aT} + X_{a'T})$$

$$t_{aAd} = t_{aTd} = 0$$

In other words, the average travel time on links a_A and a'_A is effectively the same (i.e. there is no basis for distinguishing between the
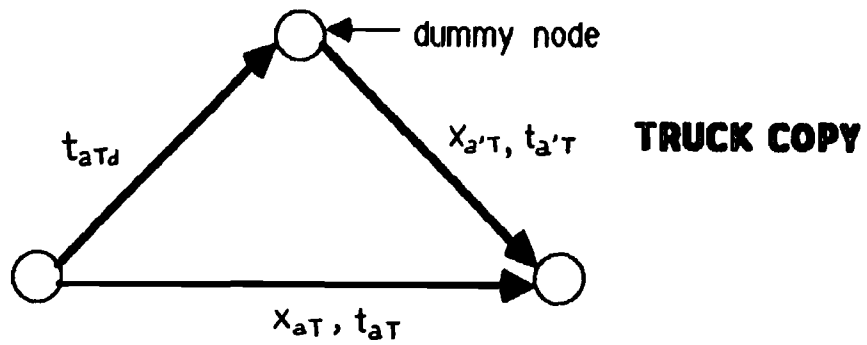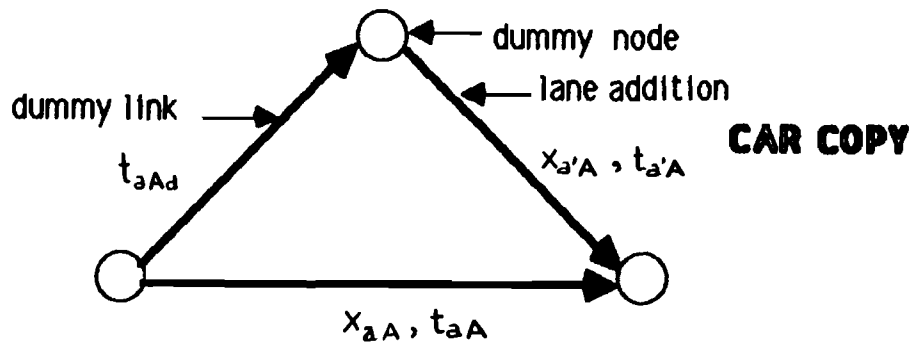
Figure 5.2. Notation for Link Improvement Representation.

performance of these lanes), and dependent on the total auto and total truck flows, respectively, on the upgraded highway link a; similarly for a_T and a'_T. The functions $t^*_{aA}(.)$ and $t^*_{aT}(.)$ denote the modified performance functions for the upgraded facility.

Option 2: Under option 2, the new lane is an exclusive truck lane, with no car traffic allowed on that lane. No other restrictions apply on the existing lanes. This translates into:

$$t_{aA} = t_{aA} (X_{aA} , X_{aT})$$

$$t_{a'A} = t_{aAd} = M \text{ [very large positive number]}$$

$$t_{aT} = t_{aT} (X_{aA}, X_{aT})$$

$$t_{a'T} = t_{a'T} (X_{a'T}) \text{ and } t_{aTd} = 0$$

Effectively then, the new exclusive truck facility is assumed to operate virtually independently from the existing lanes. Therefore, travel time for trucks in the truck facility depends only on the flow of trucks using that facility. Naturally, travel time for cars in that facility (as well as on the corresponding dummy link) is set to a very large positive number to prohibit its use by cars.

Option 3: Under this option, the new lane operates as an exclusive truck facility. However, this is coupled with the restriction of truck traffic from using the other (existing) lanes of the highway. The corresponding relationships are:

$$t_{aA} = t_{aA} (X_{aA}) \quad \text{and} \quad t_{aT} = 0$$

$$t_{a'A} = t_{aAd} = M$$

$$t_{a'T} = t_{a'T} (X_{a'T}) \quad \text{and} \quad t_{aTd} = 0$$

Here, the two "facilities" (existing lanes on one hand and new exclusive truck lane) operate virtually independently from each other, thus the absence of cross-link effects in the corresponding performance functions.

Option 4: Under this option, an exclusive new car-only lane is built, with no trucks allowed; no other restrictions apply. This is represented by:

$$t_{aA} = t_{aA} (X_{aA}, X_{aT})$$

$$t_{a'A} = t_{a'A} (X_{a'A}) \quad \text{and} \quad t_{aAd} = 0$$

$$t_{aT} = t_{aT} (X_{aA}, X_{aT})$$

$$t_{a'T} = t_{aTd} = M.$$

In essence, the new exclusive car lane is assumed to operate virtually independently of the existing lanes, with no truck interference, whereas the same relationships remain in effect in the existing, shared-use lanes.

The above equations illustrate the functional dependence between the various travel time and flow components associated with the particular network configuration introduced in this study to represent the truck-related link improvements of interest. The specific functional forms follow those presented in Section 4.2. In addition, the specifics of implementing changes in the network configuration, corresponding to particular link improvements, within the network design model, are given in conjunction with the description of subroutine CHANGES in the program documentation by Massimi et al.[12].

The next section presents the feasibility rules that govern the compatibility of each improvement option with the characteristics of any given link.

5.3. Feasibility/Elimination Rules

These are patterned after the aspects defined in the critical link programming procedures described in Chapter 3. Geometric, pavement and operational characteristics of each link, obtained from the data base described in Section 3.4, are invoked to determine if any given link has the dimensions or features to be expanded. In addition, links are checked for any particular characteristics that make them likely candidates for a particular type of improvement.

Following are the possible elimination rules currently coded in the network design model. Not all of these are activated in the present version of the model. However, the mechanism is already built in for the user to exercise such criteria. Note that the detailed codes associated with each of the following variables can be found in the technical report by Massimi

et al.[12].

1. <u>Rural/urban designation</u>: Describes land use intensity in the area surrounding a particular highway link. Three categories (as per HPMS) are defined: rural, small urban and urbanized. This variable primarily is used to check feasibility of using shoulders in urban areas.

2. <u>Functional Class</u>: Describes the designated function of a particular highway link. Six urban and six rural classes are defined. The model user can restrict the search to any subset of these twelve classes. In particular, it might be desirable to limit consideration to principal urban and rural arterials. Any such restrictions would likely result in considerable computational cost savings.

3. <u>Trucks/commercial vehicles access</u>: Describes the degree of access of a particular link to trucks and commercial vehicles. Four categories are defined in the HPMS, reflecting total or partial restriction of access to heavy vehicles. Such restricted links are usually parkways or facilities where restrictions are imposed primarily for environmental considerations. For this reason, links where such prohibitions are currently in place are not considered as candidates for truck-related lane addition. This stipulation could be deactivated by the model user, but such action is not particularly recommended.

4. <u>Number of through Lanes</u>: This allows the restriction of the search to only major facilities, such as those with at least three lanes in each direction, if desired by the model user.

5. <u>surface/Pavement Type</u>: If the pavement type is not of sufficiently high quality (e.g. high flexible or high rigid), one may wish to restrict the applicability of lane addition options for that particular link.

6. <u>Widening feasibility</u>: An elaborate formula for checking the feasibility of widening a particular facility has been implemented. It considers the respective widths of the following elements: right-of-way, median, shoulders and lanes in this check. It is of particular interest in urban areas where land availability is likely to be a major constraint for lane additions.

The above criteria provide an illustration of the types of elimination

rules that ensure feasibility and compatibility between link features and improvement options, while at the same time reducing the search space for the solution, thereby contributing to computational effort savings.

5.4 Overview of Algorithmic Approach

The optimal link improvement selection problem is cast as a discrete network design problem with multiple improvement options per link. It is solved using a branch and bound integer programming approach that recognizes the special features of the problem under consideration. The conventional discrete network design problem is a 0-1 integer programming problem (where the choice for each link is to either build or not build). In that case, there are 2^n possible solution sets (combinations of links to be improved). However, there are five options per link (the no addition option, plus the four improvement options) in the truck-related improvement selection problem, thus increasing the number of possible solution sets to 5^n; this is clearly a computationally demanding task, further motivating the need for elimination rules that can somewhat reduce the search space for the optimal solution.

A further complication due to the five-options per link formulation arise in the computation of a lower bound for the values of the objective function (consisting of the total user costs) for the "successors" of any given node in the tree structure of the branch and bound search process. First note that the computation of the objective function at a given node requires the solution of a user equilibrium network assignment problem. Each node of the branch and bound tree corresponds to a solution (or subset of link improvements). This solution is "complete" if all links are set at a value denoting some improvement type or no improvement; a "partial" solution is one where some links remain to be set, and are therefore called free links. The principal difficulty in computing lower bounds in the network design problem arises from the well-known "Braess' paradox", which says that the total travel cost associated with the user equilibrium flows on a network may increase when one or more links (or link improvements) are added to a network (see Sheffi[13] for a discussion of this phenomenon). To circumvent this difficulty, in the standard 0-1 network design problem, Leblanc[18] proposed to compute lower bounds by relaxing the budget constraint and allowing all free links to be built (or improved), and then solving the

system optimal traffic assignment on the resultant network configuration. The system optimal travel costs, for a given configuration and given origin-destination trip patterns, are always less than or equal to the corresponding user equilibrium travel costs.

The appropriate lower bounding strategy is not as evident in the problem addressed here, where five options (instead of two) are possible per link. Fortunately, it is possible to find an equally simple strategy in this problem. This strategy is based on the observation that improvement option 1 (all traffic allowed on new lane) yields the least constrained problem. It is actually possible to obtain the patterns that would exist under the other improvement options in the solution to the system optimal assignment problem (using option 1 for all free links), if such a solution is indeed optimal. Option 1 was therefore adopted for all free variables when solving the relaxed problem to obtain the desired lower bound. the principal components of the algorithm are therefore as follows:

1. Initialization and set up, whereby the various elements of the problem are specified, including feasibility rules, available improvement options, and so on.

2. Elimination rules, which screen links individually to ensure feasibility and compatibility with proposed improvement types.

3. Upper and lower bound calculations: Within the branch and bound process, it is necessary to evaluate the objective function at each stage of the process, and obtain both upper and lower bounds for this function. In the network design problem, calculating the objective function requires the solution of a traffic assignment problem. Depending on whether it is a lower bound or an upper bound that needs to be calculated, the system optimal assignment rule (on a "fully improved" network, as discussed above), or the user equilibrium rule are adopted, respectively, for traffic assignment.

4. Branching rule: At each stage of the search process, it is necessary to specify a mechanism for proceeding in the search. This is typically handled by selecting the variable that appears to yield the largest local improvement in the objective function. In this problem, this rule provides an important lever for accelerating the research process. In its current version, the program accepts rules based on respective link

flows of cars, trucks or combined, fraction of truck traffic or user-specified heuristics. The currently operational version is based on total link flow (i.e. select free link with highest link flow). However, this is one area that can benefit from more elaborate testing and experimentation.

5. Network configuration modification: This is an essential interface between the search logic and the traffic assignment model. Link improvements must be translated into inputs that the traffic assignment models can recognize. This interface is accomplished, as noted earlier, via the link performance functions. However, this interface must be flawlessly programmed in order to automate the search for the optimal link improvement combination.

5.5. Recommendations

The link improvement selection methodology presented in this chapter can be very useful in assisting highway agencies plan for the provision of special lanes or facilities for truck traffic. However, its applicability is not limited to the analysis of exclusive truck lanes, as it can handle a variety of highway improvement options, involving capacity expansion jointly with lane use restrictions on either cars or trucks, for both new and existing facilities.

The methodology described in this chapter has been successfully implemented and tested on the Texas highway network. However, the computational requirements of this algorithm can be extensive. For this reason it is recommended that "shortcuts" be actively pursued to reduce these requirements without significantly sacrificing accuracy. Such heuristic rules have been explored in this study; however, there remains much to be done in this area, particularly along the lines of the numerical testing of possible rules that are thought to have a potentially significant impact on computational cost.

A particularly interesting extension of this work would be to formulate and solve the link improvement selection problem as a multi-objective problem. Two principal objectives are the travel cost incurred by trucks versus that incurred by passenger cars. In the current model, those are given equal weight in the total cost objective function. It would be informative to vary these weights, or to examine the two objectives separately, assessing the degree to which they might be in conflict. This would allow the consideration of questions of equity and distributional impacts,

particularly in the context of cost allocation studies.

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

This concluding chapter summarizes the principal accomplishments of this study, and presents recommendations for further steps towards the effective implementation of the network modelling methodology, as well as for enhancements that would increase the applicability of the methodology to a wider range of truck-related improvement options.

6.1 Summary

This study has successfully achieved its primary objective of developing a methodology to support the analysis, identification and selection of specific sections of the highway network that constitute good candidates for the construction and implementation of particular types of truck-related improvements, with particular attention to exclusive truck lanes. The present report has provided an overview of the principal accomplishments of the study, describing the overall structure and organization of the methodology, its capabilities and the features of its principal components. The result is an integrated network modelling methodology, that allows SDHPT engineers and planners to address different types of decision problems that arise in conjunction with the truck lanes issue, and more generally, with excessive heavy truck traffic.

Three principal types of decision problems can be addressed by this methodology:

1) The evaluation and diagnosis of critical highway links, where criticality is determined relative to the link's ability to handle heavy truck traffic. The critical link programming component of the methodology is the principal tool for problems of this type.

2) The assessment of the impacts of proposed truck-related highway improvements in selected parts of the network. Improvements here are defined in terms of lane addition as well as the operating scheme associated with both the new and existing lanes. The network assignment component of the methodology provides the principal tool for problems of this type.

3) The optimal selection of a subset of link improvements, so as to minimize total costs, subject to a specified maximum expenditures level. It

allows, for example, the determination of where to construct exclusive truck lanes given limited resources. The principal tool to address problems of this type is the link selection/network design component of the methodology. This component integrates the other methodological components in the search for the optimal combination of link improvements.

The critical link programming procedures implement a link screening process according to a variety of aspects, taken individually or jointly in any specified combination. Aspects are defined in terms of link characteristics, corresponding to geometric, pavement of operational criteria. The procedures were implemented on an extensive data base, derived from HPMS files of the Texas highway network links. Warranting procedures and criteria for exclusive truck lane implementation can thus be examined and implemented.

The network assignment models constitute the core component of the network modelling methodology, the function of which is to predict link flow patterns and associated user costs/benefits resulting from proposed truck-related improvements to the network. Principal features of the assignment model developed for this study include: 1) the explicit treatment of the interaction between cars and trucks in the traffic stream and 2) the mechanisms devised for the network representation of the truck-related improvements of interest.

Extensive algorithmic development, and subsequent numerical testing on a number of test networks, including the Texas highway network set up for this study, have led to the following conclusions: 1) the diagonalization algorithm for the network equilibrium problem in the presence of (asymmetric) interactions between cars and trucks provides a useful operational tool for the analysis of truck-related improvements and truck lane needs study; 2) the computational performance of this algorithm, in the problem context of interest to this study, can be greatly improved using the streamlining strategies proposed and demonstrated in this study, thereby greatly enhancing its operational usefulness.

Finally, the link improvement selection/network design methodology developed in this study provides a powerful approach for identifying the most cost effective combinations of truck lane improvements in the highway network. Its key features include 1) the capability to consider link improvements in terms of both capacity expansion and operating strategy (in

the form of lane access restrictions to either cars or trucks, for both new and existing lanes), 2) the above-mentioned capabilities of the embedded assignment models to handle the interaction between multiple vehicle classes and 3) the incorporation of an elaborate set of feasibility rules, including geometric pavement and operational criteria governing the compatibility of particular improvement options with a given link's characteristics. A modified branch and bound approach was devised, programmed and successfully demonstrated in this study.

Naturally, a number of questions can benefit from additional attention, as discussed in the next section.

6.2. Recommendations for Further Development

The network modelling methodology developed and implemented in this study represents a significant step towards a comprehensive capability to analyze and develop solutions to questions regarding the ability of the Texas highway network to meet present and future passenger mobility and commodity transport demands. In order for these tools to be effective in supporting the planning, policy-making and engineering processes, and to fulfill their potential usefulness, there are a number of aspects of the methodology and related issues that can benefit from further investigation. Many of these should be high priority items if the critical problems related to truck traffic in the State are to be addressed in a technically sound and timely manner.

As is usually the case with methods designed to deal with large-scale complex transportation network problems, various components of the system under consideration and associated phenomena are understood to different degrees. Perhaps the highest priority item for problems involving trucks is the nature of the interaction in the traffic stream among various types of vehicles with widely different performance characteristics. Despite some studies to define the passenger-car-equivalents of various vehicle types, primarily for capacity analysis purposes, this remains a poorly understood phenomenon in the transportation engineering field. This interaction manifests itself primarily in the link performance functions employed in the traffic assignment model. This issue was discussed in Section 4.4., along with recommendations for additional research. While outside the scope of the

present study, a pilot effort along these lines was initiated in conjunction with this work. In particular, a promising data set from the U.S. Federal Highway Administration was acquired and subjected to a preliminary assessment. The conclusion is that this data set can form the basis for a more focused and highly needed study of this problem.

A significant obstacle that has hampered virtually all research efforts aimed at truck traffic has been the absence of adequate information on the movement of people and goods in the State. In the present methodology, the information in question consists of the origin-destination trip matrices, for both cars and trucks. The data gaps in this area are quite severe, at a time where more and better information is most needed. The severity of the problem and its urgency require a specially targeted research effort, which was clearly outside the scope of the present study.

As noted in Chapter 4, the relatively crude approach used in this work to generate O-D information for the purpose of testing the network modelling procedures is not likely to be adequate for planning and engineering decisions. Greater accuracy is required in this regard. A number of approaches can be followed to meet the above needs. Conventional survey procedures are naturally preferred in terms of accuracy and coverage. However, the large scale of the system under consideration is a clear disincentive for approaches that rely exclusively on "direct" survey data. A more practically viable approach would realize the wealth of information contained in related data. State-of-the-art advances in estimating O-D matrices from partial information should be given careful consideration. In particular, the use of link flows to infer trip matrices that replicate the observed link flows provides a promising avenue for further research. Some algorithmic development along these lines was initiated in this study, especially since it involves only minor modification to the network assignment model. Considerably more attention ought to be accorded to this problem. Furthermore, procedures to systematically combine data from a variety of sources such as commodity transportation files, with link flow information, hold a good deal of promise for developing a reliable data base on O-D trip patterns by people and commodities.

Some specific aspects of the network design/link selection model can also be usefully pursued, as noted in Section 5.5. In particular, it is recommended that heuristic search rules or "shortcuts" be systematically

investigated to reduce otherwise extensive computational requirements without significantly sacrificing accuracy. This requires numerical experiments designed to test the effectiveness of various shortcuts and selection rules, and to yield better insights into the robustness of the optimal solution. Statistical optimization techniques may also prove useful. Ultimately, this can generate good predictor variables for the quick identification of the best candidate improvements.

A particularly challenging extension of the network design methodology would be to pursue a multi-objective formulation of the problem. The principal objectives in this problem are the total travel cost incurred by trucks versus that experienced by cars in the highway network. In the current formulation, these two objectives are given equal weight in the overall total cost in the objective function. It would be informative to vary these weights, to explore how the resulting network improvement strategy might be different, as greater emphasis is placed on one vehicle class relative to the other(s). Such a formulation would allow the consideration of questions of equity and distributional impacts, particularly in the context of cost allocation studies.

Turning to broader questions, it has been noted earlier that the applicability of the network modelling methodology is not limited to the analysis of exclusive truck lanes, though the latter has provided the principal motivation for its development. As indicated, a variety of highway link improvement options can be handled. Link improvements are defined not only as capacity expansion, but also in terms of the operating scheme adopted for the new and existing lanes. Such schemes are usually in the form of lane access restrictions(s) to either cars or trucks. As such, the methodology provides a flexible tool to address a variety of measures aimed at dealing with the inevitable increases in heavy truck traffic in the Texas highway network. It would be desirable to further expand the capability of the present methodology, to include a possibly wider array of truck-related measures. Similarly, a finer categorization of vehicle types is possible, allowing the consideration of different truck types with different size and weight characteristics. However, requisite advances in link performance functions are necessary to meaningfully support a finer categorization of vehicle types.

Finally, a general research issue with direct implication for the input O.D. information is that of the strategies followed by truckers in routing their vehicles through the network. In other words, the route choice followed by truckers must be better understood in order to properly assess what is going on in the highway network, and to be able to generate meaningful estimates of the impact of truck-related regulations and policies. Truckers often rely on break-bulk terminals in order to focus flows and achieve economies of scale. This destroys the assumption that truckers act to minimize total transit time from origin to destination. Better understanding of truckers' operating strategies is therefore an important element in the overall capability to plan for truck-related improvement problems.

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