TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. SWUTC/94/60011-1	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Evaluating Mobility and Energy Efficiency	5. Report Date August 1994
	6. Performing Organization Code
7. Author(s) Timothy Lomax, Vergil Stover, Gary Carlin, Ron Jensen, David Landmark, Johnnie Pate, David Schrank, Edward Sulak, Shawn Turner	8. Performing Organization Report No. Research Report 60011
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No.
	11. Contract or Grant No. 0079
12. Sponsoring Agency Name and Address Southwest Region University Transportation Center Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	13. Type of Report and Period Covered Final June 1990-August 1994
	14. Sponsoring Agency Code

15. Supplementary Notes

Supported by a grant from the Office of the Governor of the State of Texas, Energy Office

16. Abstract

Over the past two decades there has been an increasing awareness of the need to develop a more energy efficient transportation system. This research explored the relationship between energy efficiency and transportation by analyzing the relationship between energy efficiency and specific aspects of transportation. This research analyzed the relationship between land use patterns and transportation energy use, urban congestion and excess energy use, local bus operations and energy efficiency, park-and-ride services and energy efficiency, and vehicle speeds in an urban environment and energy efficiency. This report also provides an example of an analysis of fuel efficiency and vehicle delay under various transportation scenarios in Houston, Texas.

This research highlighted a number of findings that can have a significant impact on energy savings to the citizens of Texas. If the results of this research are utilized to develop policies that encourage energy efficient land development, and policies that encourage the placement of transit routes in corridors with favorable socioeconomic characteristics, increased energy efficiency may be expected to result. Similarly, if the findings of this research, which illustrate that fuel savings are associated with decreased congestion, provide the impetus for operational and other measures that reduce congestion to be implemented, then increased energy efficiency may be expected to result. Finally, if the methodology presented for the analysis of potential fuel savings is incorporated into procedures to analyze transportation alternatives, than significant energy savings may be expected to result.

17. Key Words Energy Efficiency Urban Mobility	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 162	22. Price

Form DOT F 1700.7 (8-69)

EVALUATING MOBILITY AND ENERGY EFFICIENCY

by

Timothy Lomax
Research Engineer

Vergil Stover
Research Engineer

and

Gary Carlin, Ron Jensen, David Landmark,
Johnnie Pate, David Schrank, Edward Sulak, and Shawn Turner

Technical Report 60011

Sponsored by

The Office of the Governor of the State of Texas, Energy Office
Southwest Region University Transportation Center
Texas Transportation Institute
The Texas A&M University System
College Station, TX 77843-3135

August 1994

ABSTRACT

Over the past two decades there has been an increasing awareness of the need to develop a more energy efficient transportation system. This research explored the relationship between energy efficiency and transportation by analyzing the relationship between energy efficiency and specific aspects of transportation. This research analyzed the relationship between land use patterns and transportation energy use, urban congestion and excess energy use, local bus operations and energy efficiency, park-and-ride services and energy efficiency, and vehicle speeds in an urban environment and energy efficiency. This report also provides an example of an analysis of fuel efficiency and vehicle delay under various transportation scenarios in Houston, Texas.

This research highlighted a number of findings that can have a significant impact on energy savings to the citizens of Texas. If the results of this research are utilized to develop policies that encourage energy efficient land development, and policies that encourage the placement of transit routes in corridors with favorable socioeconomic characteristics, increased energy efficiency may be expected to result. Similarly, if the findings of this research, which illustrate that fuel savings are associated with decreased congestion, provide the impetus for operational and other measures that reduce congestion to be implemented, then increased energy efficiency may be expected to result. Finally, if the methodology presented for the analysis of potential fuel savings is incorporated into procedures to analyze transportation alternatives, than significant energy savings may be expected to result.

ACKNOWLEDGEMENTS

This publication was developed as a part of the University Transportation Centers Program which is funded 50% in oil overcharge funds from the Stripper Well Settlement as provided by the State of Texas Governor's Energy Office and approved by the US Department of Energy. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This research was conducted under the oversight and direction of Timothy Lomax and Vergil Stover. Significant contibutions were made by number of people. David Landmark was primarily responsible for Chapters 2 and 6, Shawn Turner was primarily responsible for Chapter 3, David Schrank was primarily responsible for Chapters 4 and 5, and Gary Carlin, Johnnie Pate and Edward Sulak were primarily responsible for Chapter 7. Sarah Hubbard provided editorial assistance. Dave Barry, Kim Duren, and Brad Morello, provided assistance with the editing and and graphics.

EXECUTIVE SUMMARY

Since the 1973 oil embargo crisis, considerable attention has been focused on the availability and rising cost of energy, specifically energy derived from crude oil sources. The oil crisis shattered previous misconceptions about the guaranteed availability of inexpensive energy and highlighted the precarious position of the nation's transportation system as being highly dependent on the import of foreign crude oil. More recent events in the Persian Gulf reinforce this view.

The United States has no peer with respect to its energy appetite, consuming approximately 30 percent of the world's energy while comprising only six percent of the world population. Transportation energy consumption is estimated to account for as much as 25 percent of the total energy consumed, and more than half of the total oil consumed. Automobile fuel consumption accounts for half of the total United States transportation energy consumption and approximately 30 percent of all United States oil consumption. This is exacerbated when the trend of oil consumption is considered, oil consumption has risen 75 percent over the last 20 years while the population has increased by only 22 percent.

Increased energy consumption has stimulated other, related concerns, including the negative environmental impacts of energy consumption. In response to concerns over air pollution, a variety of Federal legislation has been promulgated, including the Clean Air Act Amendments of 1970, 1977, and 1990, the Energy Policy and Conservation Act of 1975, the Motor Vehicle Fuel Efficiency Act of 1990, and the 1991 Intermodal Surface Transportation Efficiency Act. Provisions of these laws have attempted to reduce levels of air pollution and energy consumption simultaneously.

While there has been an increasing awareness of the need to develop a more energy efficient transportation system, there has also been an awareness that in order to maintain the economic and social viability of urban areas and of our nation, increased energy efficiency cannot compromise urban mobility.

Many urban areas in Texas are experiencing reduced urban and suburban mobility. In response, investments are being made for the construction of new transportation facilities and the reconstruction of existing transportation facilities. As urban population and travel demand increase, desirable mobility levels will become even more difficult to achieve. To further complicate matters, large activity centers are being developed in suburban and urban fringe areas. The changing character of trips to these activity centers is not being satisfactorily served by the existing transportation network. Transportation officials, especially at the state level, often find themselves in a reactive situation because of the decision-making process, which is affected by land development interests, intergovernmental and interagency relationships, and funding sources and mandates.

The research discussed in this document examined the relationship between various aspects of the roadway transportation system and energy consumption. The results of this research will provide energy savings to the citizens of Texas, because the results will provide transportation planners, decision makers, and policy makers an additional resource to consult when examining transportation alternatives and the resulting effect on energy consumption and urban mobility.

Land Use Patterns and Transportation Energy Use

Various land use, transportation and socioeconomic variables affecting transportation energy consumption were identified based on the analysis of data from 25 major international cities, it was found that 91 percent of the variability in the per capita energy consumption could be accounted for by seven independent variables: population density, employment density, concentration of employment, vehicle ownership, average income, percentage of mass transit ridership, and gasoline price. Although each variable had a meaningful impact on per capita energy consumption, no conclusions were drawn with respect to the relative importance of each independent variable.

Mobility Trends and Energy Use

The relationship between urban congestion and excess fuel consumption was examined. A methodology for estimating the excess fuel consumption of vehicles operating in congested travel conditions, using estimates of delay, average vehicle speed, and average fuel efficiency to calculate the gallons of excess fuel consumed in congestion in fifty urban areas in the United States was developed and demonstrated. In 1991, the amount of fuel wasted in congestion totaled more than 4.6 billion gallons. Wasted fuel correlated with congestion to some extent, six of the top ten most congested urban areas were also in the top ten with respect to the largest amount of wasted fuel. The most congested urban area, Los Angeles, was also the area had the largest amount of wasted fuel.

To further explore the relationship between excess fuel consumption and congestion level, the values of excess fuel consumption for each urban area were normalized by values of travel (VMT), population size, and vehicles for the respective urban area. The closest relationship ($r^2 = 0.58$) was demonstrated between congestion level and excess fuel consumption per 1,000 VMT. A model that estimated the gains in fuel efficiency for various levels of congestion indicated that in 1995, the Houston area could reduce wasted fuel by as much as 15 million gallons by reducing the congestion level.

Energy Efficiency of Local Bus Service

The energy efficiency of local bus service was examined. The results of this analysis indicate that socioeconomic factors usually associated with transit ridership are correlated with local bus transit energy efficiency. As might also be expected, the analysis indicated that peak-period operations are typically associated with higher transit energy efficiency than off-peak period operations. Furthermore, there appeared to be a general trend of increasing energy efficiency (measured in passenger-miles per gallon) with larger fleet sizes in the four Texas cities examined.

Energy Efficiency of Park-and-Ride Service

The relationship between socioeconomic characteristics of park-and-ride lot market areas and the fuel efficiency of the park-and-ride service provided was analyzed. The results of the regression analysis indicate little or no correlation between socioeconomic characteristics and energy efficiency in the three cities studied. The energy efficiency for park-and-ride lots varied from a high of 195 passenger-miles per gallon to a low of 21 passenger-miles per gallon. Despite this large range, the average fuel efficiencies for each city were relatively consistent, with 73 passenger-miles per gallon in Dallas and 63 passenger-miles per gallon in both Houston and San Antonio.

There was significant variance in the correlation of energy efficiency to socioeconomic factors in the three cities studied. This may have been partially due to the service differences between the cities, and due to the difference in the number of park-and-ride facilities operating in each city. Although the results of this analysis do not provide definitive conclusions to the issue of socioeconomic variables and energy efficiency, the analysis procedure developed in this research does provide an appropriate methodology for future research efforts.

Energy Efficiency and Vehicle Speed in an Urban Environment

Speed-fuel economy relationships for urban area driving conditions were derived for the year 1985 and 2010. These relationships illustrated the positive impact that higher fuel economy standards in future years will have on fuel consumption. The models indicate that optimal fuel economy can be expected in the range from 25 mph to 50 mph, with fuel economy decreasing at higher and lower speeds.

Fuel Savings under Alternative Transportation Scenarios

Fuel consumption, and delay were calculated for a number of alternative transportation scenarios in Houston, Texas. Although both the strategic arterial scenario, which consisted of improvements to key arterials, and the improved traffic management scenario, which consisted of the implementation of traffic management practices to result in a ten percent increase in capacity, resulted in significant reductions in delay, these scenarios did not result in large decreases in fuel consumption (decreases were all less than five percent).

The results of the freeway alternatives analysis indicate that, considering the alternatives studied, addition of an HOV lane is the best solution to reduce fuel consumption. The second best alternative to minimize fuel consumption was implementation of traffic management practices to increase the capacity of the freeway by ten percent. It is worth noting that while the HOV alternative reduces fuel consumption when compared to the basic freeway case, the implementation of any of the other alternatives results in an increase in fuel consumption over the basic freeway case.

Energy Savings

This research highlighted a number of findings that can have a significant impact on energy savings to the citizens of Texas. If the results of this research are utilized to develop policies that encourage energy efficient land development, and policies that encourage the placement of transit routes in corridors with favorable socioeconomic characteristics, increased energy efficiency may be expected to result. Similarly, if the findings of this research, which illustrate that fuel savings are associated with decreased congestion, provide the impetus for operational and other measures that reduce congestion to be implemented, then increased energy efficiency may be expected to result. Finally, if the methodology presented for the analysis of potential fuel savings is incorporated into procedures to analyze transportation alternatives, than significant energy savings may be expected to result.

Conclusion

The research described in this document provided insight regarding the relationship between energy efficiency and transportation. The relationships between energy efficiency and specific aspects of transportation, including urban congestion, local bus operations, park-and-ride services, vehicle speed in an urban environment, and various transportation scenarios in Houston, Texas, were documented in this report. The findings of this research highlight the fact that transportation has a significant impact on energy consumption, and that energy efficiency should be considered when implementing policies and programs related to our nation's transportation infrastructure.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (continued)

CHAPTER 1. INTRODUCTION

Background

Since the 1973 oil embargo crisis, considerable attention has been focused on the availability and rising cost of energy, specifically energy derived from crude oil sources. The oil crisis shattered previous misconceptions about the guaranteed availability of inexpensive energy and highlighted the precarious position of the nation's transportation system as being highly dependent on the import of foreign crude oil. More recent events in the Persian Gulf reinforce this view.

The crux of the nation's transportation energy problem has been cited as being the imbalance between petroleum supply and demand. The United States has no peer with respect to its energy appetite, consuming approximately 30 percent of the world's energy while comprising only six percent of the world population. Transportation energy consumption is estimated to account for as much as 25 percent of the total energy consumed, and more than half of the total oil consumed. Automobile fuel consumption accounts for half of the total United States transportation energy consumption and approximately 30 percent of all United States oil consumption (1). This scenario is exacerbated when the trend of oil consumption is considered, oil consumption has risen 75 percent over the last 20 years while the population has increased by only 22 percent.

Increased energy consumption has stimulated other, related concerns, including the negative environmental impacts of energy consumption, such as harm to plant and animal life due to unnaturally occurring amounts of pollutants which result from the burning of petroleum products as fuels. "The combustion of fossil fuel in transportation vehicles contributes significantly to air pollution. In 1992 the transportation sector was responsible for 79 percent of carbon monoxide (CO) emissions and over 30 percent of nitrogen oxide (NO_x), lead, and volatile organic compound (VOC) emissions. Highway vehicles, which are responsible for the majority of transportation CO emissions, have reduced their emissions by 32 percent from 1970 to 1992, despite a 102 percent increase in vehicle travel in that time period" (2).

Furthermore, the long term effects of the emission of greenhouse gases such as carbon dioxide, nitrous oxide, methane, and others has received considerable attention. Some scientists contend that increases in atmospheric greenhouse gas concentrations will result in a general global warming, significantly affecting the world's climate. Since 1860, atmospheric concentrations of carbon dioxide have increased approximately 25 percent, partly due to the combustion of fossil fuels and industrial and agricultural activities. Some scientists allege that energy production accounts for approximately 60 percent of the current global contribution to potential greenhouse warming. Transportation energy use accounts for about 20 percent of the possible total warming contribution, over 60 percent of which is attributable to automobiles (3).

In response to concerns over air pollution, a variety of Federal legislation has been promulgated, including the Clean Air Act Amendments of 1970, 1977, and 1990, the Energy Policy and Conservation Act of 1975, the Motor Vehicle Fuel Efficiency Act of 1990, and the 1991 Intermodal Surface Transportation Efficiency Act. Provisions of these laws have attempted to reduce levels of air pollution and energy consumption simultaneously. With regard to energy consumption, the major emphasis has been to improve the fuel economy standards of automobiles. It has been concluded that, despite an initial downward trend in fuel economy following the implementation of emission controls, significant improvements to meet both emission standards and fuel economy standards are possible through the implementation of current technologies (4).

While over the past decades there has been an increasing awareness of the need to develop a more energy efficient transportation system, there has also been an awareness that in order to maintain the economic and social viability of urban areas and of our nation, increased energy efficiency cannot compromise urban mobility.

Many urban areas in Texas are experiencing reduced urban and suburban mobility. In response, investments are being made for the construction of new transportation facilities and the reconstruction of existing transportation facilities. As urban population and travel demand increase, desirable mobility levels will become even more difficult to achieve. To further complicate matters, large activity centers are being developed in suburban and urban fringe areas. The changing character of trips to these activity centers is not being satisfactorily served by the existing transportation network. Transportation officials, especially at the state level, often find themselves in a reactive situation because of the decision-making process, which is affected by land development interests, intergovernmental and interagency relationships, and funding sources and mandates.

The research discussed in this document examined the relationship between various aspects of the roadway transportation system and energy consumption. The results of this research will provide energy savings to the citizens of Texas, because the results will provide transportation planners, decision makers, and policy makers an additional resource to consult when examining transportation alternatives and the resulting effect on energy consumption and urban mobility.

This research provides quantitative information related to the energy savings and transportation solutions that might be obtained by various transportation infrastructure and modal alternatives and land use patterns. This will enable local and state officials to evaluate transportation and land development possibilities in terms of their potential for public transportation and for contributing to a more energy efficient system. Debate concerning the type of transportation system that should be constructed in major Texas cities has included discussions related to the energy efficiency and mobility of the alternatives.

Organization

Following this introductory chapter, six major topics related to energy efficiency and transportation are discussed in Chapters 2 through 7.

Chapter 2, Land Use Patterns and Transportation Energy Use, identifies various land use, transportation and socioeconomic variables affecting transportation energy consumption. After presenting a summary of the relevant literature on this subject, this chapter provides the results of an analysis of data from 25 major international cities in which transportation energy consumption is related to various land use, transportation and socioeconomic variables.

Chapter 3, Mobility Trends and Energy Use, focuses on mobility and energy concerns for vehicles operating in urban areas in the United States. This chapter examines the mobility level in various urban areas, as well as the mobility trends in these urban areas. This chapter also explores the relationship between the congestion level in an urban area, and the amount of excess fuel consumed in the urban area.

Chapter 4, Energy Efficiency of Local Bus Transit Service in Texas, discusses the relationship between the energy efficiency of local bus operations and urban area socioeconomic characteristics. The procedures used to estimate the energy efficiency of local bus service are presented, as are the results of the application of these procedures to four transit agencies in Texas. The results of statistical analysis, which was performed to determine the relationship to socioeconomic characteristics, are also presented.

Chapter 5, Energy Efficiency of Park-and-Ride Service, examines the energy efficiency of park-and-ride bus service in large Texas cities. The energy efficiency of park-and-ride bus service was calculated for three large urban areas. The energy efficiency values were then compared to the socioeconomic characteristics of each route to evaluate the relationship.

Chapter 6, Speed-Fuel Economy Relationships for Urban Driving Conditions, estimates the relationship between vehicle speed and fuel economy in urban driving conditions. Existing speed-fuel economy relationships and vehicle test data were examined; these were used to develop equations to estimate the speed-fuel consumption relationship for the years 1985 and 2010.

Chapter 7, An Analysis of Potential Delay and Fuel Savings for Harris County, Texas, provides a comparison of four regional alternatives to improve urban mobility in Houston. After explaining each scenario, and the methodology, this chapter discusses the results of the comparison of the alternative scenarios. Comparisons focus on changes in vehicle delay, fuel savings, and vehicle emissions.

The final chapter, Chapter 8, discusses the implications of the research findings discussed in previous chapters, as well as the recommendations and conclusions of this research.

CHAPTER 2. LAND USE PATTERNS AND TRANSPORTATION ENERGY USE

Introduction

While great efforts have been directed toward addressing energy conservation and environmental concerns, and much attention has been focused on these efforts, insufficient attention has been paid to the transportation system as a whole, and more specifically towards the interaction between land use, the transportation system, and the associated energy consumption. The interaction and interdependence between land use and the transportation system cannot be denied, "the need for passenger transportation services is derived from people's needs to participate in activities of various types (work, shop, visit friends and relatives, etc.), located in a variety of places dispersed over the urban region. Similarly, freight transportation services are required to move goods from point to point within the urban region, as well as into and out of the region, so that economic activities can take place" (5). Furthermore, changes in either the land use or transportation system necessarily impact each other. Improvements in the transportation system result in increased accessibility to nearby land areas, enhancing development opportunities, resulting in changes in the nature of the land use activities. Similarly, changes in the land use cause changes in the derived travel demand, resulting in impacts on the transportation system.

Traditionally, different institutions and professions have been responsible for transportation planning and land use planning. "This institutional dichotomy encourages planners and analysts to think of 'transportation problems' or 'land use problems' as independent entities. Alternatives for addressing the issue of improving transportation energy efficiency typically involve encouraging the use of more energy-efficient [transportation] modes (transit or carpool) and improving the technical efficiency of the vehicles in operation (e.g., improved automobile fuel economy), but they rarely include specific policies for encouraging an urban land use structure which facilitates improved transportation energy efficiency (i.e., which facilitates shorter trip lengths, encourages the use of high-efficiency modes, reduces the need to travel, etc.)" (5).

The purpose of this chapter is to identify various land use, transportation, and socioeconomic variables affecting transportation energy consumption, enabling transportation planners to consider alternative policies conducive to reducing transportation energy consumption. The chapter has been divided into two main sections, first, a literature review summarizing research identifying various land use, transportation, and socioeconomic variables affecting transportation energy consumption, and second, an analysis of data from 25 major international cities in which transportation energy consumption is related to various land use, transportation and socioeconomic variables.

Literature Review

Two general approaches to examining the relationships between transportation energy consumption and various land use, transportation, and socioeconomic variables have been identified in the literature. The first approach uses computer simulation models, and the second uses empirical studies with some type of statistical analysis.

Computer Modelling Approaches

Schneider and Beck (6) developed a computer-directed search procedure to evaluate the efficiency of an urban structure with respect to the location of employment and residential populations. Four performance measures were used in the evaluation:

1) Total travel time.
2) Total weighted accessibility.
3) Average link load.
4) Maximum link load.

Judgement was used to determine the importance of each of the performance measures for each of the optimal solutions found.

Conclusions indicated that it is feasible to reduce travel requirements in an urban area by long-term restructuring of the city's spatial patterns. An important corollary arising from this research was the desirability of placing employment and residential activities as close to each other as possible. The paper indicates the potential for a similar computer algorithm in long-term planning to reduce the energy utilized in transportation, but stops short of defining an optimal urban structure to achieve the same ends.

Edwards and Schofer (7) conducted experiments utilizing data from an existing city along with mathematical models to simulate travel behavior in a series of 37 hypothetical cities. Different combinations of urban form and the transportation network were considered in order to identify structural characteristics contributing to increased energy consumption and activity accessibility.

Results indicated that urban form, transportation level of service, and the role of transit in the transportation system accounted for most of the variation in energy requirements and accessibility to population. Urban form was characterized by four contributing factors: shape, geographic extent, population concentration about the city center, and employment concentration about the city center.

The paper concluded by stating the desirability, from an energy conservation perspective, of controlling city spread by developing higher density, nucleated forms. New high-speed traffic facilities to reduce congestion and hence conserve energy may be self-defeating since they encourage urban sprawl. Increased transit use promises significant energy savings although different means to counteract the associated reduced accessibility should be investigated.

Peskin and Schofer (8) explored the relationships between land use, transportation system characteristics, travel behavior and transportation energy consumption in an attempt to identify some promising strategies suited to minimizing transportation energy consumption.

Three types of hypothetical city structures were considered, including a concentric-ring city, a one-sided or shoreline city, and a polynucleated city. Four measures were used to ascertain the effectiveness of the different policies in terms of the changes from the base conditions: total energy consumption, average work trip congestion index, total automobile vehicle-miles travelled, and average work trip opportunity cost. The concentric-ring type city was found to be the most energy intensive, consuming over twice the energy of the least energy intensive type, the polynucleated city. The energy consumption of the one-sided type was approximately midway between these two extreme values.

Initial tests examined the effect of eight types of parameter changes representative of typical actions that might be taken in the areas of: encouraging changes in travel behavior, transportation network improvements, transportation pricing, and land use controls. Results indicated that, in general, policy changes that affected congestion directly (increased vehicles occupancy and freeway construction) were more effective than transportation pricing actions (relatively small increases in parking costs, increased gasoline prices, and reduced transit fares) in reducing transportation energy consumption. Increased vehicle occupancy showed the most potential for reducing energy consumption. Increased fuel prices were only marginally effective, and even then only at very high prices; it appears that gasoline demand is highly price inelastic. Doubling the parking cost was generally found to be a more effective approach, especially in the concentric-ring city where congestion was significantly reduced.

Increased concentration of growth in the CBD showed potentially significant reductions in transportation energy, particularly for concentric-ring and one-sided city types. Conversely, increased peripheral growth led to increased transportation energy consumption for the same two city types. The polynucleated city exhibited insignificant changes in transportation energy consumption for both scenarios.

Eliminating transit facilities resulted in the biggest increase in energy consumption across all three city types. On the other hand, improved transit facilities (other than free transit) did little to reduce energy consumption. Tests on the effects of additional freeways showed that in the case of concentric-ring and one-sided cities, the provision of additional diagonal freeways to the rectangular arterial grid was the most effective highway improvement in terms of reducing energy consumption.

Investigations to confirm the preliminary findings that congestion is an important influence on transportation energy consumption indicated that, in effect, total fuel consumption is a function of congestion which is, in part, a function of work trip length. Work trip length, in turn, is a function of the land use patterns.

Subsequent experiments on urban growth policies in the concentric-ring type city indicated that substantial reductions in energy consumption can be achieved by encouraging concentrated growth points in those areas where improvements in the highway network are simultaneously undertaken.

Kim and Schneider (9) utilized the model developed by Peskin and Schofer, as well as a statistical package program specifically designed to calculate various urban form measures, to define some of the relationships between urban form and transportation energy consumption. The transportation energy consumption of the three basic types of urban growth patterns were compared with a hypothetical base city, representative of several US cities in terms of land use patterns. The three types of growth patterns considered were concentration, dispersion, and polynucleation.

Generally, the results indicated that the concentrated urban forms are the most energy efficient and the dispersed forms the least energy efficient, with polynucleated urban forms falling in between. Nevertheless, some polynucleated forms were found to be more energy efficient than some concentrated forms.

The paper provided valuable insight on the measures of urban form that are useful in determining the relative efficiency of urban structures with respect to transportation energy consumption. Although more dispersed and less accessible, the polynucleated form shows promise from a land use policy and energy consumption point of view.

Empirical Studies

Steward and Bennett (10) explored the effects of urban size and structure in determining per capita expenditures on auto transportation fuel. The study focused on 134 standard metropolitan statistical areas (SMSAs) with a 1970 population of 200,000 or greater. Population parameters were used as the primary measure of urban form. The main hypotheses tested were, first, that gasoline consumption per capita decreases with increasing population, and second, that gasoline consumption per capita decreases with increasing population density.

A range of parameters were used as independent variables in the regression analysis:

1) SMSA population.
2) Population dispersion (indicated by the proportion of the population in central city, and the population per square mile outside the central city).
3) Rate of growth of SMSA and a variable reflecting (to a certain extent) the age of the SMSA.
4) Median family income and proportion of the population below the poverty line.

5) Proportion of the population 16 and over, 65 and over, and percent non-whites.
6) Percentage of city workers utilizing urban transit for work trips.
7) Price of gasoline.
8) Variable classifying the census region as either West, Northeast, or North Central.

Additional variables were introduced for economic and geographic structure, for example, a variable was introduced to differentiate between port and other cities. Nearly all port cities exhibited particularly low energy consumption rates. In addition, cities were classified as either manufacturing or diversified manufacturing, according to the Rand-McNally city classification. Finally, to reflect the number of nonresidents purchasing gasoline (highest in state capitals, and in other cities with tourist attractions), the ratio of receipts from hotels and motels to the SMSA population was introduced as an independent variable.

The regression results were found to have a very significant predictive power with a coefficient of determination (R^2) of 0.596. SMSA population size, rate of population growth, percentage of workers utilizing public transit and the variable identifying SMSAs as port cities were all found to be statistically significant with negative regression coefficients, although the coefficient for SMSA population size was quite small. Other than the rate of population growth variable, the sign of the regression coefficient reflected the expected relationship with energy consumption.

The non-white proportion of the population and per capita receipts for hotels and motels were statistically significant and positively related to gasoline consumption. Cities classified as diversified manufacturing centers also had significantly higher gasoline sales.

The regional variables were strongly correlated with gasoline consumption. Gasoline consumption was highest in the West and North Central regions. Gasoline consumption was lowest in the Northeast region. The Southern region gasoline consumption was less than the North Central, but greater than the Northeast region.

All other variables were not found to have a statistically significant relationship with gasoline consumption. The aggregated nature of the population dispersion variables might have precluded the establishment of a statistically significant relationship. It was concluded that an evaluation of population densities on a more detailed scale might prove useful.

Soot and Sen (11) examined the relationship between energy consumption for journey-to-work trips and urban structure in an urban area. Population and geographic variables affecting energy use were identified. The study utilized data from the 1970 Urban Transportation Planning Package (UTPP) for the Chicago area.

A weighted least squares regression analysis was performed utilizing 25 variables selected from the 280 variables available in the UTPP data. Five variables, all significant at the 0.01 level, were found to account for over 50 percent of the variation in the per capita energy consumption. The variables were: percent households with two or more variables, percent households heads aged 25-34, percent construction workers, percent single family homes, and percent clerical workers. All regression coefficients were positive except for percent clerical workers.

Analysis of the residuals indicated that another variable, local employment, has a profound effect on work trip energy patterns. The distance to the CBD was also considered a major influence on transportation energy consumption, primarily because it affects the average work trip length.

In conclusion, it was noted that "the six variables largely verify the expectation that low-density automobile-oriented suburbs are energy consumptive and high-density transit-oriented inner-city locations are far less energy consumptive."

Cheslow and Neels (12) investigated travel patterns and energy use in urban areas as determined by various descriptors of urban form. The study was broken into two major sections, defining a relationship between energy consumption and travel characteristics, and defining relationships between various urban form measures and urban travel characteristics. The integration of these two sections provided the relationship between transportation energy consumption and urban form.

The study found that although travel behavior is determined by physical development characteristics at both the neighborhood and metropolitan scale, the impact of neighborhood development characteristics was found to be substantial, although household demographic characteristics and vehicle ownership rates are frequently more important. This has important implications for planners attempting to reduce transportation energy consumption in developments at the neighborhood level. High density core development, as opposed to low density fringe development, in metropolitan areas was found to result in a reduction in household transportation energy consumption of approximately 40 percent. The results concurred with previous studies that found that, on a metropolitan level, population size, central employment concentration and the distance between work location and residence have a profound effect on travel choice and transportation energy consumption.

Anjomani and Chineme (13) attempted to establish a relationship between transportation energy consumption and various urban form and socioeconomic variables. The principal hypothesis examined was that "the more dense an urban area in terms of population and employment distribution, the less the resources consumed in trip making." However, it is assumed that "this negative relationship between density and transportation costs is expected to exhibit a 'diminishing return' effect because after a certain density level, further increases in density would be accompanied by increasing congestion which has the opposite effect of increasing transportation costs."

It was assumed that the population distribution in an urban area follows a negative exponential function, decreasing from the center of the city. The rate of change at which density declines is termed the density gradient and can be said to indicate the "degree of compactness" of the city.

The research failed to define an adequate relationship between population density and distance from the CBD, based on the negative exponential model, in 20 of the 41 cities considered. This contradicted the findings of Muth (1969), who properly fitted the same model to the same cities previously. However, the central city employment density and the rate of change of the population were established as significant variables in explaining the variations in per capita gasoline consumption

Newman and Kenworthy (14) were primarily motivated by the worldwide increase in oil consumption to examine the factors contributing to increased transportation energy consumption. Maintaining that "transportation energy, and in particular gasoline use, is a powerful reflection of how much automobile dependence there is in a city," they studied the effects of transport patterns and land use on automobile dependence. Private per capita gasoline consumption was used as the surrogate measure for automobile dependence.

Data were collected from 32 major cities around the world for the years 1960, 1970, and 1980, focusing on those with well developed transport systems. The analysis of the data was confined specifically to 1980 values and was conducted in three parts:

1) General comparison of the data.
2) Correlation analysis.
3) Factor analysis, and cluster analysis.

The correlation analysis indicated that: the concentration of employment in the central and inner areas relative to the outer areas has a profound effect on gasoline use, a negative exponential rather than a linear relationship may be more plausible in defining the link between gasoline and urban density, the number of jobs in the central city and inner areas (concentration of jobs) is more critical than actual density of jobs, and higher average speeds promote car use and detract from public transit use.

The authors concluded the analysis by suggesting, "if a city were going to try and lower its gasoline and automobile consumption then it would need to consider:

1) Increasing its land use intensity.
2) Increasing the orientation of its transport infrastructure to non-automobile modes.
3) Increasing its level of restraint to high speed traffic flow.
4) Increasing its degree of centralization.
5) Increasing its public transport performance."

Other factors affecting gasoline and patterns of auto use were also examined. These were categorized into economic factors: demographic size of the city, vehicle ownership, income, gasoline price, vehicle fuel efficiency, and social/cultural factors including climate related lifestyle factors, spatial traditions, and politics.

Correlations between some of the quantifiable variables and gasoline consumption indicated the following results.

1) There is no correlation between city population and size and gasoline consumption.
2) Car ownership is strongly correlated with car use, as well as gasoline consumption.
3) Income per capita is strongly correlated with gasoline consumption per capita (0.7994) when viewed across the international spectrum. Within specific nations though, where income ranges are relatively small, no significant correlation was found.
4) Gasoline price is significantly correlated with gasoline consumption (-0.8500)
5) Vehicle fuel efficiency is highly correlated with gasoline consumption (+0.8500). When adjustments are made for average urban speeds, the correlation coefficient reduces to 0.5906.

Transit Fare and Service Charges

Various studies have investigated the fare elasticities of transit service. These values are summarized in Table 2-1. Similar coefficients of elasticity for bus transit service are given in Table 2-2. Inspection of these tables reveal the following:

- Transit use is inelastic with respect to all variables (i.e., the numerical values of all the coefficients is less than 1.00).
- Service elasticities tend to be higher than fare elasticities (i.e., given a choice to use an increase in subsidies for a fare decrease or an increase in bus service levels, the increase in service will be more effective in increasing ridership and decreasing energy use).
- The effect of a fare change decrease as city size increases. Thus a larger fare increase is needed in a large city to produce a given percentage increase in transit ridership. However, the large transit rider base in a large city will cause a sizable increase in transit patronage.
- Off-peak transit ridership is more sensitive to a fare change than peak period ridership. This is largely due to the tact that work trips are much more time constrained than trips for other purposes. This is supported by the fact that the fare elasticity of shopping trips (which can be made in off-peak periods) is over twice that of work trips. Thus, the fare structure can be used to shift transit riders from the peak periods (especially the p.m. peak) to other times of the day. This will result in more efficient use of transit equipment as well as labor. This will increase the energy efficiency of transit (an increase in passenger-miles per gallon of fuel) as well as lower the dollar cost per passenger-mile.
- Short trips (less than 1.3 miles) are more sensitive to fare changes than longer trips. This is due to people exercising the option to walk if the distance is short.

Thus, attracting very short trips to transit by low fares (or no fare) will not directly decrease transportation energy use. It may however, have indirect benefits such as encouraging a larger and denser CBD or suburban focal point which in turn results in a larger percentage of person trips being made by transit, and thereby reducing energy use.

- Non-CBD trips are more sensitive to a fare change than are CBD trips. This reflects the historical pattern of transit being focused on the CBD. It suggests that increasing transit service to large suburban focal points might result in increase transit use to and from these focal points. This would increase the energy efficiency of these transit routes and reduce the demand for auto use and thus private gasoline consumption.
- Increasing the frequency of bus service (decreasing the headway between busses along a route) and decreasing the bus travel time (decreasing in-vehicle time) may be effective in attracting off-peak riders and thus reducing the consumption of gasoline by private vehicles.

The transit fare and service elasticities together with the cross-elasticities between auto and transit and the income elasticities of auto use and transit, indicate that simple isolated changes in a urban transit system will not unilaterally increase transit use nor reduce transportation energy consumption. Rather a well designed and coordinated program involving the following must be pursued: transit service improvements, differential peak and off-peak fares. pricing of auto use, and modified land use patterns which cam be efficiently served by the transportation system.

Table 2-1: Average Transit Fare Elasticity

Factors Effecting Elasticity		Elasticity[1]
Aggregate:	Fare increase	-0.34 ± 0.11
	Fare decrease	-0.37 ± 0.11
City Size: (Poputation)	> one million	-0.24 ± 0.10
	500,000 to one million	-0.30 ± 0.12
	< 500,000	-0.35 ± 0.12
Disaggregate: Mode:	bus	-0.35 ± 0.14
	rapid rail	-0.17 ± 0.05
Time Period:		-0.17 ± 0.09
	off-peak	-0.40 ± 0.26
	24-hour	-0.29 ± 0.19
Trip length:	< 1.3 miles	-0.52 ± 0.11
	> 1.3 miles	-0.21 ± 0.15
Route:	CBD oriented	-0.40 ± 0.04
	Non-CBD	-0.62 ± 0.09

SOURCE: Adapted frome Reference (<u>15</u>) Table 5.36, p. 165 which is based on several other sources.

(1) average coefficient of elasticity ± one standard deviation example: A 10% reduction in fare is expected to increase ridership by 3.4%. It is likely that the increase will be between 3.3% and 3.5%.

Table 2-2: Service Elasticities for Bus Systems

Service Characteristic		Elasticity
Headway:	peak	-0.37 ± 0.19
	off-peak	-0.46 ± 0.26
In-Vehichle Travel		-0.03 ± 0.13
	off-peak	-0.92 ± 0.37

SOURCE: Adapted frome Reference (<u>15</u>) Table 5.36, p. 165 which is based on several other sources.

Discussion

A number of urban form, transportation, and socioeconomic variables have been identified in the literature as having a significant impact on transportation energy consumption. The impacts of most of these variables have been supported by a number of the studies. However, some of the studies offer conflicting evidence as to the effects of the variables. It is necessary therefore to determine the "true" effect of each variable on transportation energy consumption. In essence, the literature review has only provided us with an understanding of how the different variables affect transportation energy consumption. In order to gain the complete picture of the effect of each variable, it is necessary to address the additional question of why each variable affects transportation energy consumption in the described manner. This is critical from a statistical point of view.

In any regression analysis, it is necessary to have some a priori expectation of the effect of each variable on the dependent variable. A regression analysis does not provide a theory as to why the dependent variables affect the independent variable in the manner demonstrated by the model; rather, the model describes how the independent variables affect the dependent variable. Of prime importance are the signs of the regression coefficients.

Any a priori expectation of the manner in which each independent variable affects the dependent variable should be reflected in the sign of the regression coefficients. Confirmation of this a priori expectation gives the user of the regression model substantially more confidence that the model is a "true" representation of the relationship between the independent and dependent variables. The findings of this literature review, along with the causal explanations for the effects of each of the most widely used variables on transportation energy consumption are provided next.

Population Size

Population size was determined to be a significant factor in some of the studies (10,12) whereas other studies determined otherwise (13,14). All other things being equal, it is logical that larger populations would result in longer average trip lengths and hence increased per capita energy consumption. However, in an analysis of this type, it is impossible to fix all variables affecting trip characteristics to determine the effect of population size alone. In view of this, and the conflicting nature of the studies reviewed, it cannot be determined with any confidence what the a priori expectation of increased population size on transportation energy consumption would be.

Population Density

Population density was determined to be a significant factor affecting transportation energy use in a number of the studies reviewed (7,9,11,12,14). Despite the evidence that many city CBDs are losing their attractiveness as the prime retail and commercial area, the CBD still remains the single largest concentration of employment in most urban areas. For this reason, it is expected that a significant proportion of daily work trips in an urban area are concentrated toward the city center. It is not unreasonable to presume that if a large percentage of the population reside within the central city area, then the average trip lengths would be reduced. In addition, higher population densities both within and outside the central area lead to a more compact urban form, effectively reducing average trip lengths. Moreover, higher population densities are more conducive to supporting mass transit operations. Furthermore, increased densities have been found to result in decreased trip frequencies (12). All of these factors lead to a reduction in transportation fuel consumption.

However, it is maintained that beyond a certain threshold, increased densities can have the opposite effect on energy consumption (10,13). Where there are inadequate transportation facilities for automobiles, increased population densities with the associated increased trip generation rates per unit area can lead to severe congestion problems, resulting in increased transportation energy consumption.

It can be argued that increased population densities do not result in increased fuel consumption, but rather the inability to cater to automobile demand results in increased fuel consumption. It is quite conceivable that cities with low population densities but inadequate roadway facilities would experience similar per capita increases in fuel consumption due to congestion.

The causal relationship between higher population densities and reduced transportation energy consumption appears to be well grounded. Where the effects of congestion on per capita energy consumption might be substantial, it would be prudent to introduce a dependent variable such as length of roadway per capita (or per vehicle) to improve regression results.

Population and Employment Concentration

The degree of concentration of population and employment was found to be one of the most significant factors affecting transportation energy consumption (7,8,9,11,12,14). With an increased concentration of population and employment, trip length tend to be shorter and mass transit facilities, particularly rail, can be supported more readily. Increased concentration of population and employment is thus expected to decrease transportation energy consumption.

Transit Ridership

Higher per capita ridership on public transit was found to decrease per capita transportation energy consumption (7,8,10,12,14). The causal relationship here is intuitively obvious -- mass transit is between 5 and 25 times more energy efficient (per passenger-mile) than the automobile (11).

Vehicle Ownership

Rate of vehicle ownership was found to be positively related to transportation energy consumption (7,11,12,14). Generally, it has been found that higher car ownership rates per household result in increased trip frequencies (11,12). This, coupled with the high energy consumption rate of automobiles compared with other modes of transportation, results in increased per capita energy consumption with an increased rate of vehicle ownership.

Income

Income level was found to be significantly positively correlated with private gasoline consumption (14). That is, gasoline consumption, and auto use increases with increasing income. Moreover, the income elasticity of transit use is negative. Thus, transit use decreases as incomes increase. However, some studies found that income level was not statistically significant in explaining variations in transportation energy consumption (10,13).

Frequently, income level is used as a surrogate measure for vehicle ownership. "Higher per capita income can be expected to result in greater reliance on automobiles because of a higher rate of car ownership and the greater time-associated costs which automobile use can economize" (10). In view of the statistical insignificance of this variable in explaining differences in per capita transportation energy consumption, its use as a surrogate measure for vehicle ownership is ill-advised.

Despite this, income level becomes a critical factor when comparing per capita energy consumption across national boundaries. In this international realm, the median income ranges are significantly larger than within a particular country. To a degree, income level acts not only as a measure of the ability to afford a private motor vehicle, but also as an indicator of the economic level of activity in the nation. Developed countries tend to have higher income levels than less developed countries. Furthermore, highly developed countries tend to have more service-oriented and recreational activities. The cumulative effect of higher income levels and increased activity levels is to increase trip frequencies, and increase transportation energy consumption.

Gasoline Price

Gasoline price was found to be highly negatively correlated with transportation energy consumption (14). However, Peskin and Schofer (8) found that gasoline consumption is very insensitive to price increases, and Stewart and Bennett (10) found that gasoline price is not statistically significant in explaining variations in transportation energy consumption.

Newman and Kenworthy (14) offer a plausible explanation for the inelasticity of gasoline price, "if low gasoline prices in the past have contributed to very inefficient land use, then increases in fuel price may not in themselves lead to much saving if high car use is built-in to the structure of the city. People will just tend to put more of their income into fuel and less in other areas."

However, with the above explanation, the authors highlight a possible explanation for the major differences in urban form on an international scale. Assuming that the historical ranking of each city by gasoline price has remained more or less constant, then it might be that the relative efficiency/inefficiency of each city's urban form may have been dictated by its relative ranking with respect to gasoline price.

Trip Length

Longer average trip length was determined to be a significant factor in increasing transportation energy consumption (6,7,8,9,11,12,14). To a large extent other variables such as urban density and degree of concentration act as surrogate measures in determining average trip lengths. However, average trip length itself reflects the degree of mixed development land use. In this respect, average work trip length can provide significant information not reflected by other urban form variables. Logically, increased average work trip length is expected to result in higher per capita energy consumption.

Other than population size, some conclusion on the a priori expectation of how each variable affects transportation energy consumption has been reached in this discussion. To summarize:

(1) Increased population density, degree of concentration of population and employment, per capita ridership on public transit and gasoline price are all expected to decrease transportation energy consumption.
(2) Increased urban population, increased per capita rate of vehicle ownership, and longer average trip length are expected to increase transportation energy consumption.

Data Collection

All data for this study were obtained from the book Cities and Automobile Dependence by Newman and Kenworthy (14). The data in the appendices of this book provide a wealth of information on transportation, land use and socioeconomic variables in 32 major cities around the world.

Newman and Kenworthy's study considered correlations between private per capita energy consumption and the various transportation, land use and socioeconomic variables. The aim of this study is to examine the relationships between total transportation energy consumption and various transportation, land use, and socioeconomic variables. Accordingly, the dependent variable used in this study is *total per capita transportation energy consumption per annum* expressed in terms of equivalent gallons of gasoline.

Any regression analysis should restrict the number of independent variables used in the analysis in order to increase the significance of the regression results associated with higher degrees of freedom. Consequently, this study has examined a total of eight independent variables. The principal criteria governing the choice of these variables was the significance as reported in the literature (discussed previously) and availability of data from Newman and Kenworthy. Generally, the variables may be defined as follows (for more detailed explanations, consult reference (14)):

1) Population density (DENS) - the total population residing within a metropolitan area divided by the total metropolitan land area, expressed in persons per square mile.

2) Employment density (EMPLOY) - the total number of people working within a metropolitan area divided by the total metropolitan land area, expressed in persons per square mile.
3) Employment concentration (CONC) - the number of jobs within the inner area of a city (this includes the central business district and, generally, is taken as the pre-WWII city limits) divided by the total number of jobs in the whole metropolitan area, expressed as a percentage.
4) Vehicle ownership rate (VEH) - the total number of vehicles (including commercial) per 1,000 persons.
5) Transit ridership (TRANS) - the total number of passenger-miles on transit divided by the total number of person miles travelled, and expressed as a percentage.
6) Income (INC) - the per capita annual income in US dollars, adjusted for purchasing power.
7) Gasoline price (GAS) - the average price of gasoline, in US cents per liter.
8) Average work trip length (LENGTH) - the average work trip length in miles.

Results

Data for all of the variables discussed in the previous section, other than average work trip length, were available for 25 cities. Data on average trip work lengths were available for only 20 of these same 25 cities. Consequently, it was decided to analyze the data as two overlapping subsets, Data Set One with 25 observations and seven independent variables (average work trip length excluded), and Data Set Two with 25 observations and eight independent variables. Analysis of the data was performed using the Statistical Analysis System (SAS) software.

Figures 2-1 through 2-8, from the SAS output, show each of the independent variables plotted against the dependent variables. An initial examination of Figures 2-1 and 2-2 indicate that a negative exponential relationship between transportation energy consumption and population and employment densities might be appropriate. However, this relationship may be

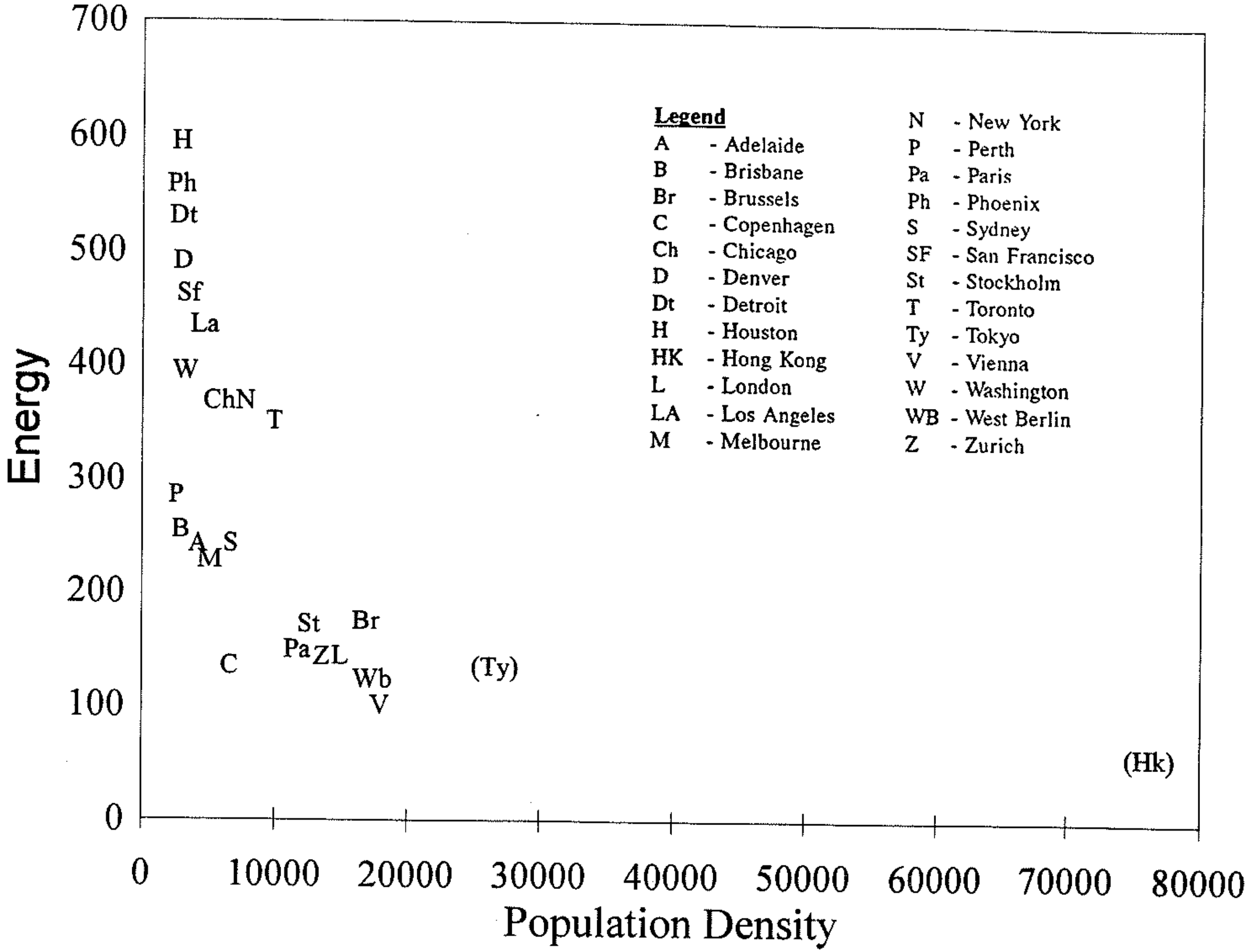


Figure 2-1. Transportation Energy Consumption vs. Population Density

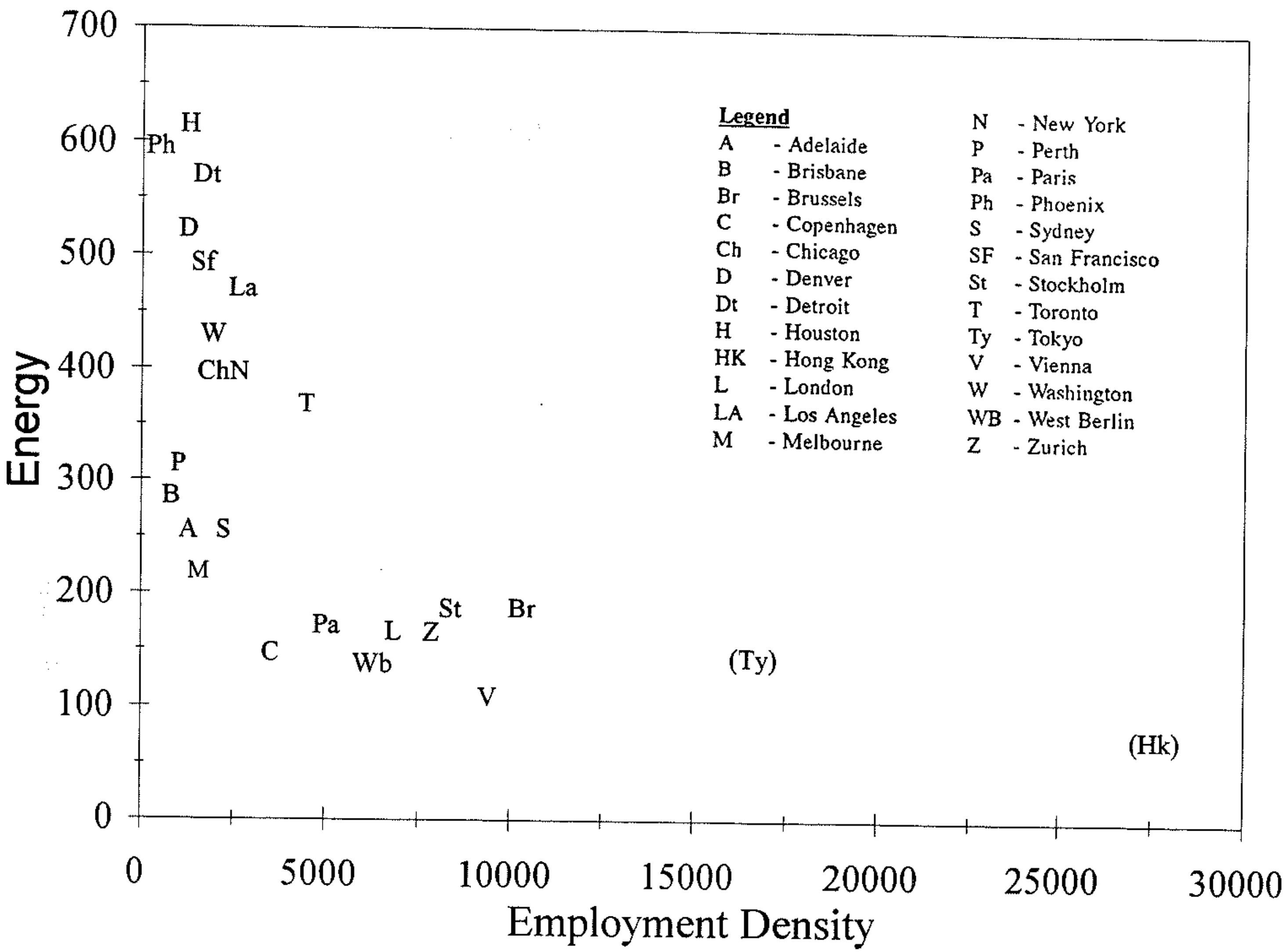


Figure 2-2. Transportation Energy Consumption vs. Employment Density

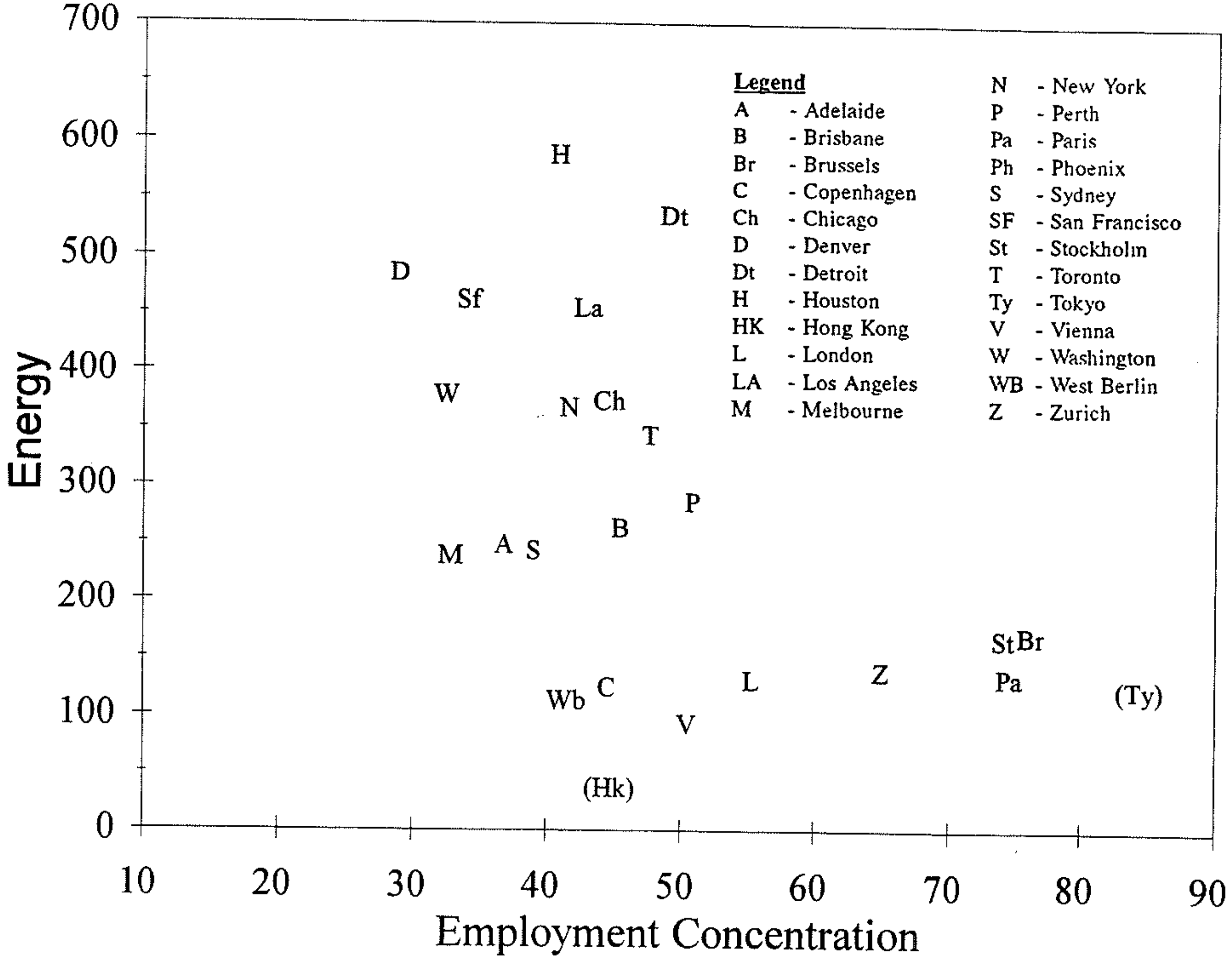


Figure 2-3. Transportation Energy Consumption vs. Employment Concentration Density

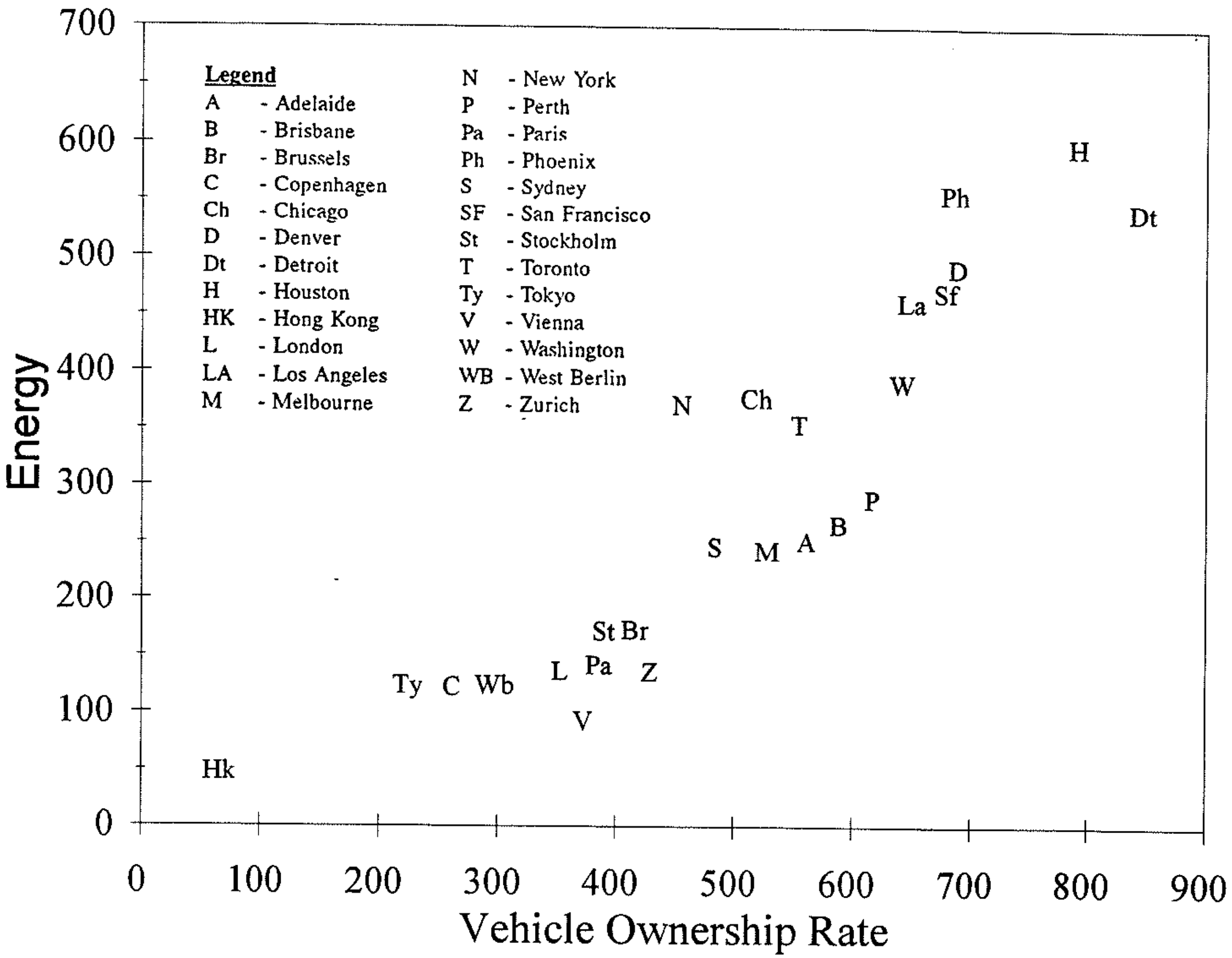


Figure 2-4. Transportation Energy Consumption vs. Vehicle Ownership Rate

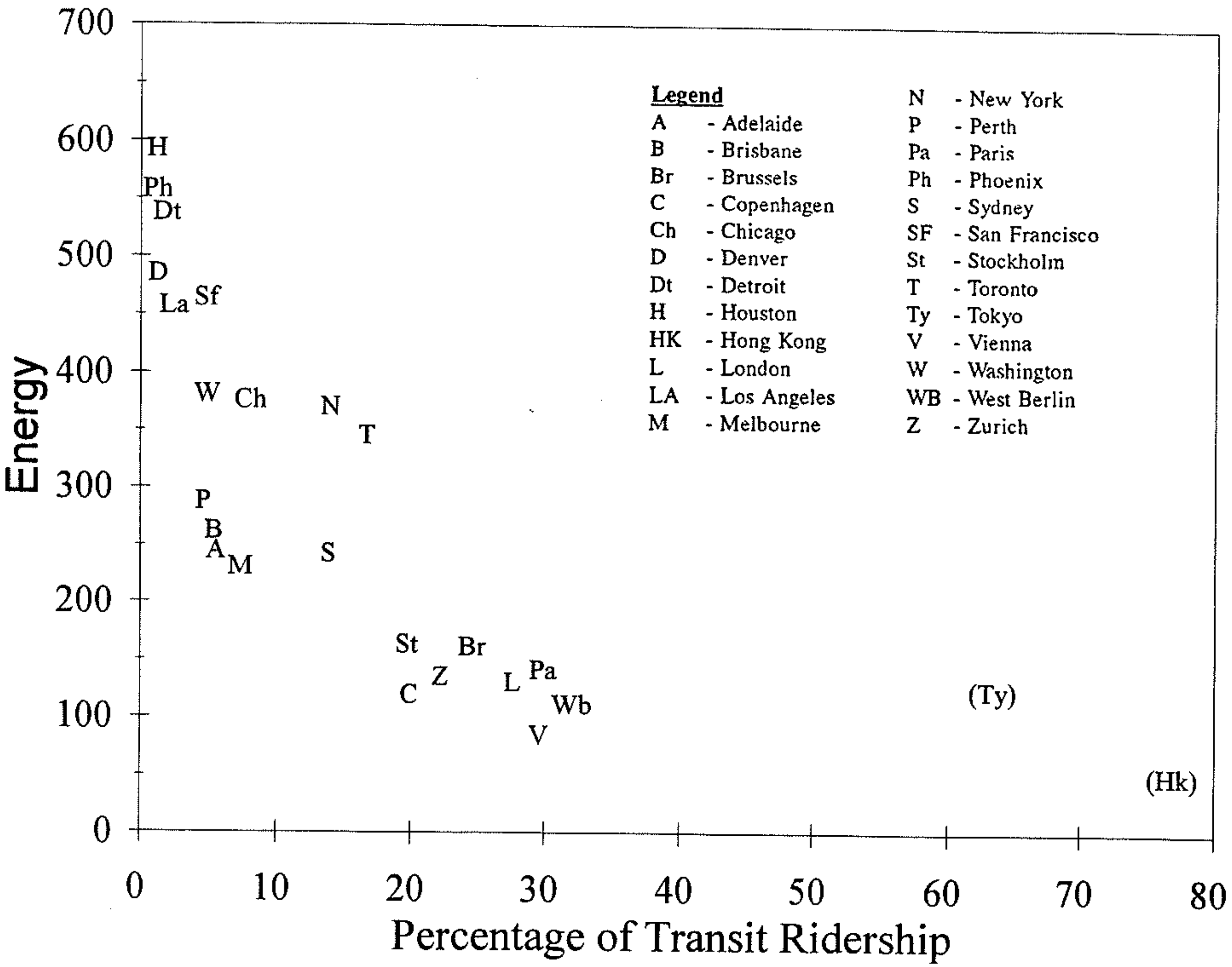


Figure 2-5. Transportation Energy Consumption vs. Transit Ridership

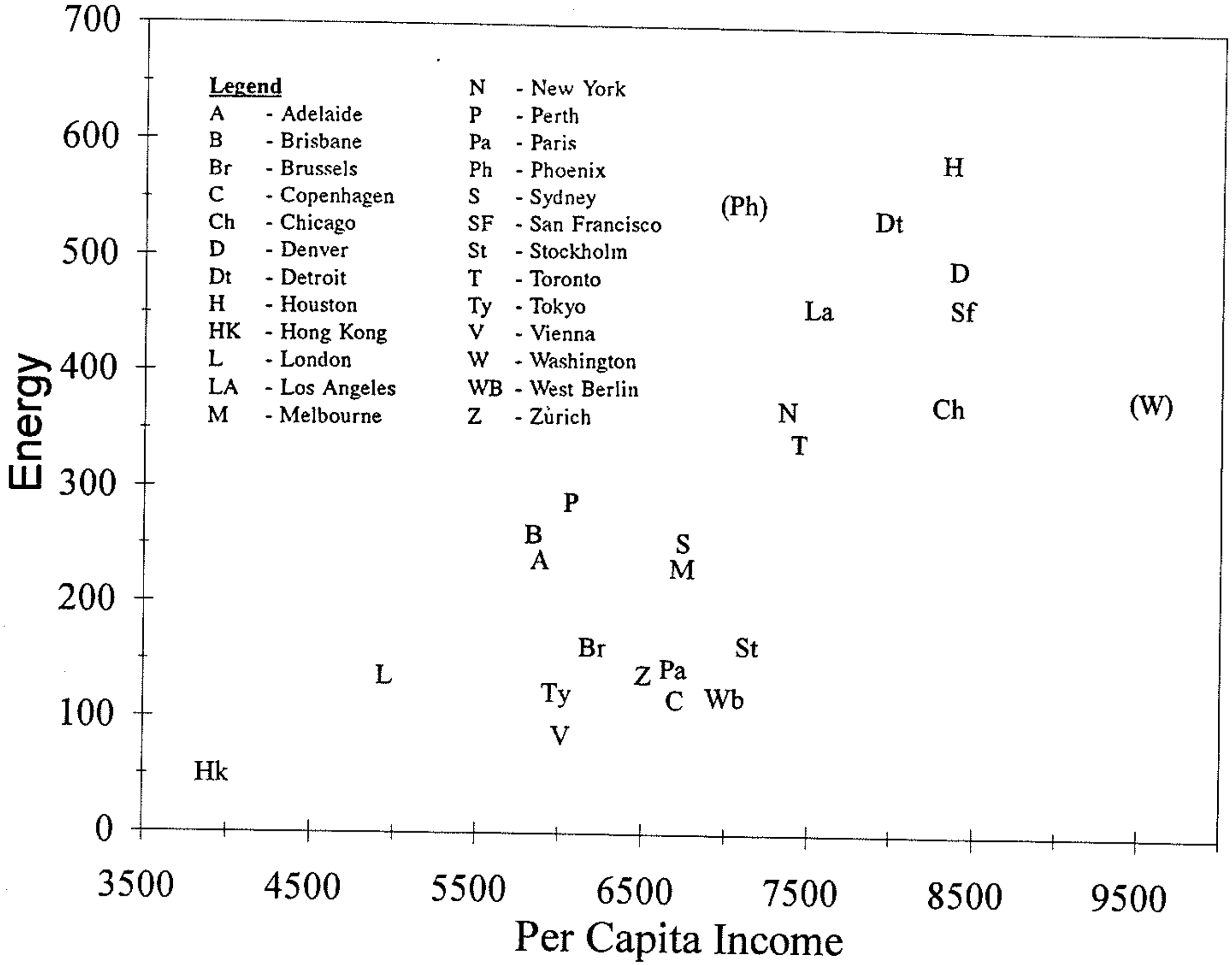


Figure 2-6. Transportation Energy Consumption vs. Income Per Capita

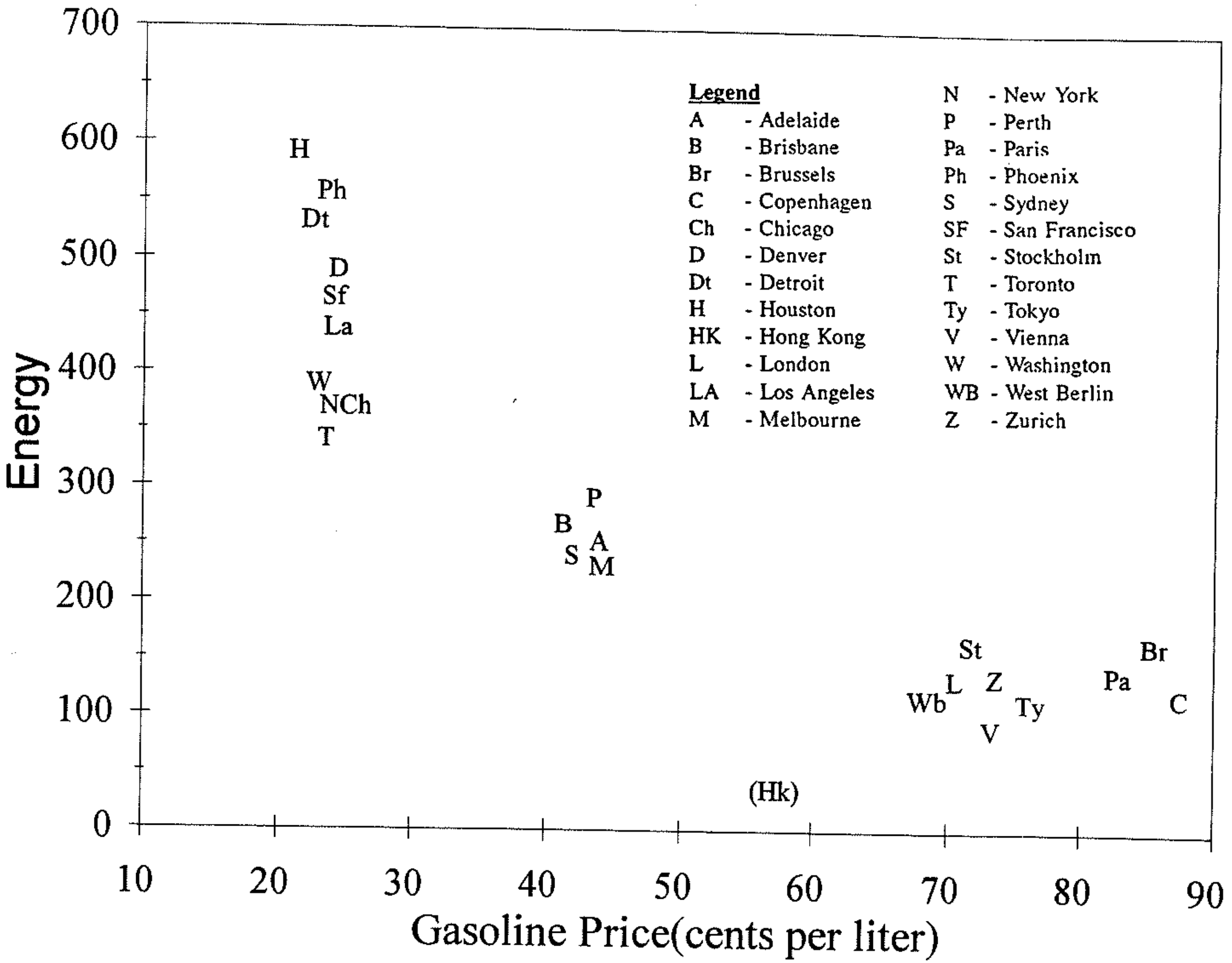


Figure 2-7. Transportation Energy Consumption vs. Gasoline Price

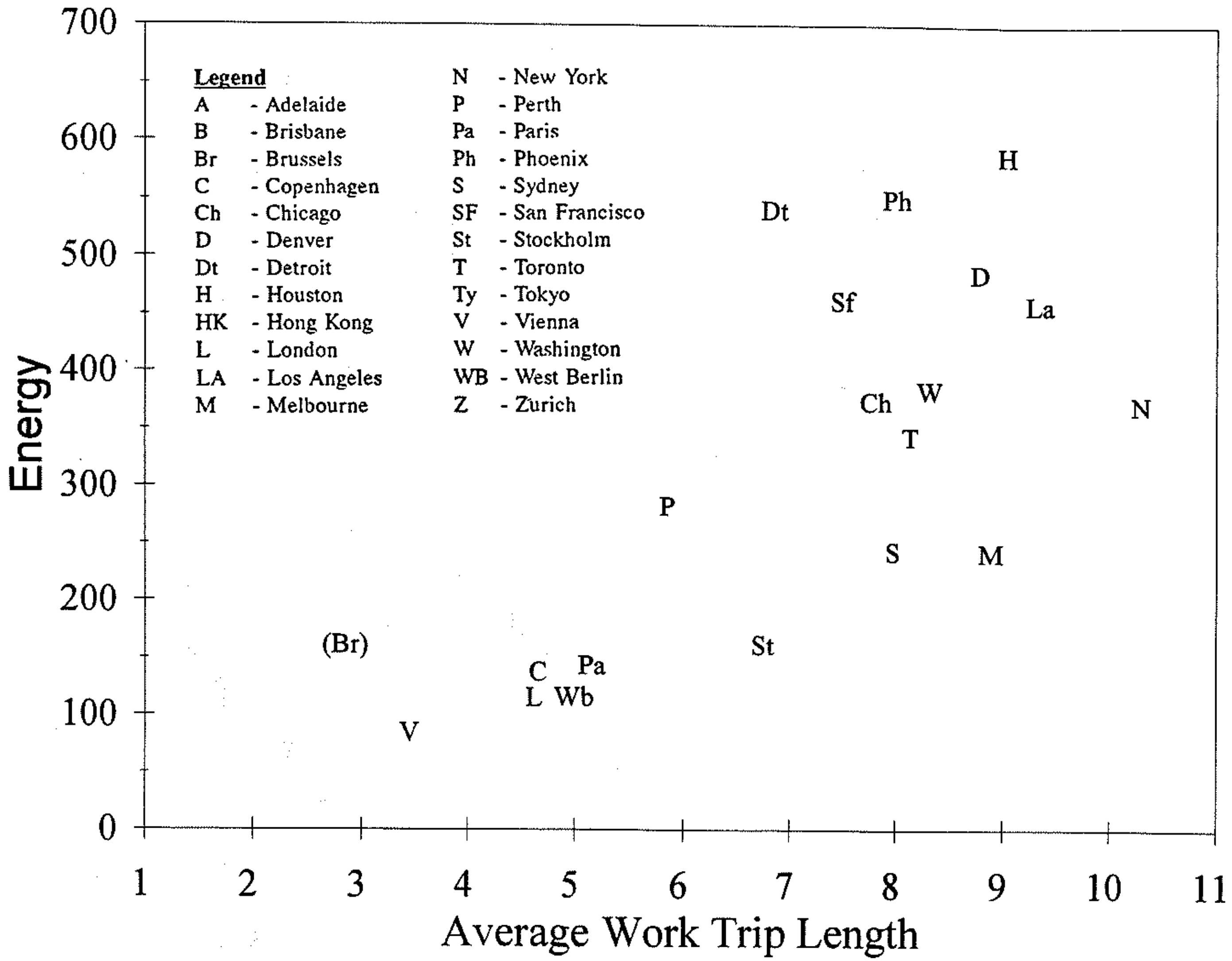


Figure 2-8. Transportation Energy Consumption vs. Average Work Trip Length

due to the influence of Hong Kong (HK), which has substantially higher population and employment densities than the other cities.

There appears to be a weak link between transportation energy consumption and the concentration of employment, although a negative linear relationship could be inferred, as shown in Figure 2-3. As can be seen in Figure 2-4, a strong positive linear relationship is indicated between energy consumption and vehicle ownership rate.

Figures 2-5 and 2-7 indicate a fairly strong negative exponential relationship between transportation energy consumption and transit ridership and gasoline price, respectively. Figures 2-6 and 2-8 indicate fairly strong positive linear relationships between transportation energy consumption and per capita income and average work trip length, respectively, although there is considerable scatter in the data.

All of the plots confirm the expectations previously discussed. Whether or not these expectations are statistically significant has not been determined. A number of data points (indicated in parenthesis in the figures) can be seen to be significantly outside of the range of the other points, and may be considered outliers. These points were examined statistically to determine whether or not they are likely to influence the regression results. Accordingly, the following methodology was adopted for the analysis of the two data sets.

1) The dependent variable was regressed against all the independent variables and the residuals were plotted against each independent variable as well as the dependent variable.
2) An analysis was conducted to identify analytically those observations that were outliers with respect to the independent and dependent variables.
3) The outlying observations were analyzed with respect to both axes to determine whether the observations were influential in affecting the regression analysis. A transformation to reduce the effects of the influential observations was then carried out and the regression analysis was re-run. Where some outlying observations were unaffected by the transformation, and a rational explanation could be made for the "non-conformance" of these observation points, the points were deleted and analysis continued with the reduced data set. In addition to reducing the effects of outlying observations, the transformation highlighted improved models for fitting in the detailed analysis.
4) The data were standardized through the use of the correlation transformation and the independent variables were resolved into their principal components through the use of eigen vectors to minimize the effects of multicollinearity between the independent variables. The resulting independent variables (called ZDENS, ZEMPLOY, ZCONC, etc.) are all linear combinations of the standardized original variables population density (DENS), empoyment density (EMPLOY), consentration of employment (CONC), etc (see pages 2-24 and 2-25 for a complete listing of variables). The resulting independent variables are all orthogonal to one another, and have no correlation with each other.

5) A regression analysis was run and the resulting orthogonal independent variables provided all possible model combinations. This enabled the best combination to be determined for any number of variables.

6) A detailed regression analysis was performed for each number of orthogonal variables, starting with the full complement of variables and reducing by one each time. The variable deleted was the one contributing least to the R^2 from the previous regression.

7) After each regression run, tests were performed on all the regression coefficients to determine their significance. The regression model giving the highest R^2 value, with all coefficients significant at the $\alpha = 0.05$ level, was chosen as the most suitable model.

Data Set One

The first data set consisted of 25 observation points and seven independent variables: population density, employment density, concentration of employment, vehicle ownership, transit ridership, average income, and gasoline price. From the plots of energy consumption vs. the independent variables (as well as plots of each independent variable against all others), the following observation points were identified as possible outliers: Hong Kong, Tokyo, Phoenix, and Washington DC. Further analysis to determine whether any of the outlying cities were influential in affecting the regression model indicated that Hong Kong was highly influential; all other cities were relatively influential.

Performing a natural logarithm transformation of the dependent variable merely compounded the problem with respect to influential observations. The analysis indicated both Hong Kong and Tokyo were highly influential in affecting the regression model. It was noted, however, that the R^2 value of the regression equation improved from 0.926 to 0.961. Both regression equations were statistically significant with a p-value less than 0.0001. Hong Kong was eliminated from the data set since the observation points were too influential on the regression mode. This can be ascribed to Hong Kong's very high residential and employment densities. In view of the fact that characteristics of this city are very different from the other cities, the deletion seemed reasonable.

A regression of all seven independent variables against energy consumption (with the remaining 24 observation points) yielded an R^2 value of 0.921 with a p-value less than 0.0001. A regression of the same variables against the natural logarithm of transportation energy consumption yielded an R^2 value of 0.949 with a p-value less than 0.0001. In both cases, no data points were determined to have an overly large influence on the regression model. Due to the consistency of the Log transformation on the dependent variable in giving a higher R^2 value, it was decided to maintain this transformation in the detailed analysis.

It was noted that serious multicollinearity effects existed between the independent variables. Table 2-3 gives the correlation coefficients between these variables, highlighting the multicollinearity effects. In view of the high multicollinearity between the independent variables, the variables were standardized using the correlation transformation described by Nether, Wasserman, and Kutner (16).

Table 2-3. Correlations between Independent Variables for Data Set One

	DENS	EMPLOY	CONC	VEH	TRANS	INC	GAS
DENS	1.000	0.980	0.748	-0.781	0.938	-0.479	0.761
EMPLOY		1.000	0.791	-0.722	0.910	-0.445	0.736
CONC			1.000	-0.573	0.724	-0.414	0.705
VEH				1.000	-0.841	0.586	-0.843
TRANS					1.000	-0.496	0.750
INC						1.000	-0.657
GAS							1.000

Detailed regression analysis was performed for all possible combinations of these standardized, orthogonal variables, checking in particular for significance of the regression coefficients and that the signs of the coefficients reflected the a priori expectations. All analysis determined the regression models to be highly significant with a p-value less than 0.0001. It must be noted, however, that in the cases where only one and two variables (ZDENS, ZDENS AND ZEMPLOY) were included in the model, Tokyo was observed to be very influential on the regression results. Accordingly, for these two cases, Tokyo was deleted. No problems with other overly influential observations were noted.

Three important general conclusions can be drawn from the regression analysis:

1) As the number of independent variables (standardized and transformed) changes, the signs of the regression coefficients vary. This can be ascribed to the high degree of multicollinearity between the dependent variables.
2) As the number of independent variables decreases, the number of regression coefficients with significant values increases.
3) As the number of independent variables decreases, the R^2 value of the regression decreases. Addition of variables will always improve the R^2. However, this is offset by the decreased significance associated with a loss in degrees of freedom.

The optimum model to choose is necessarily that one which yields the highest R^2 value in which the regression coefficients area all statistically significant. In view of the approximate nature of the values of the data, it was felt that an extremely high confidence level would be meaningless. Accordingly, an α value of 0.10 was chosen as acceptable. The optimum regression model is shown below with an R^2 value of 0.910 and a p-value for the regression equation of less than 0.0001.

$$\begin{aligned} Ln(ENERGY) = {} & 4.589 - 0.000012 * DENS - 0.000017 * EMPLOY \\ & - 0.00232 * CONC + 0.000768 * VEH - 0.00852 * TRANS \\ & + 0.000161 * INC - 0.00484 * GAS \end{aligned} \qquad \text{Eq. 7-1}$$

where:

ENERGY = Transportation energy per capita per year (gallon of gasoline equivalent).
DENS = Population density (persons per square mile).
EMPLOY = Employment density (persons per square mile).
CONC = Concentration of employment (percentage).
VEH = Vehicle ownership rate (vehicles per 1000 persons).
TRANS = Transit ridership (percentage).
INC = Per capita annual income (US dollars).
GAS = Gasoline price (US cents per liter).

All regression coefficients were statistically significant at an $\alpha = 0.05$ level. Furthermore, the signs on all the regression coefficients correctly reflect the a priori expectations previously discussed.

Data Set Two

The second data set consisted of 25 observation points and eight independent variables: population density, employment density, concentration of employment, vehicle ownership, transit ridership, average income, gasoline price, and average work trip length.

Initial regression analysis with all the independent variables against transportation energy consumption, and the natural logarithm of transportation energy consumption yielded R^2 values of 0.931 and 0.956, respectively. Both regression equations were statistically significant with a p-value less than 0.0001.

Phoenix, Brussels, and Vienna were identified as possible outlyers for the regression against the natural logarithm of transportation energy consumption. However, further analysis indicated that none of the outlying points were influencing the regression results unduly.

It was decided to maintain the log transformation on the dependent variable since the regression analysis returned a higher R^2 value. High variance inflation factors pointed to severe multicollinearity between the independent variables. This was expected since all the data points had been included in data set one. Table 2-4 provides the correlation coefficients between the independent variables.

To reduce the effects of multicollinearity, the same standardization and transformation procedure used for Data Set One was performed. A regression analysis was performed for all possible combinations of variables. The optimum model has been determined to be the one with ZONE only, returning an R^2 value of 0.869. The regression equation, shown in Equation 7-2, is highly significant with a p-value less than 0.0001.

Table 2-4. Correlations between Independent Variables for Data Set Two

	DENS	EMPLOY	CONC	VEH	TRANS	INC	GAS	LENGTH
DENS	1.000	0.968	0.648	-0.768	0.903	-0.591	0.792	-0.773
EMPLOY		1.000	0.716	-0.701	0.826	-0.554	0.784	-0.767
CONC			1.000	-0.484	0.615	-0.411	0.668	-0.581
VEH				1.000	-0.900	0.630	-0.832	0.604
TRANS					1.000	-0.615	0.835	-0.699
INC						1.000	-0.695	0.631
GAS							1.000	-0.849
LENGTH								1.000

$$\begin{aligned} Ln(ENERGY) = {} & 5.696 - 0.0000161 * DENS - 0.0000276 * EMPLOY \\ & - 0.004408 * CONC + 0.0005024 * VEH - 0.008027 * TRANS \\ & + 0.0000066 * INC - 0.00352 * GAS + 0.0384738 * LENGTH \end{aligned} \tag{Eq. 7-2}$$

where:

ENERGY = Transportation energy per capita per year (gallon of gasoline equivalent).
DENS = Population density (persons per square mile).
EMPLOY = Employment density (persons per square mile).
CONC = Concentration of employment (percentage).
VEH = Vehicle ownership rate (vehicles per 1000 persons).
TRANS = Transit ridership (percentage).
INC = Per capita annual income (US dollars).
GAS = Gasoline price (US cents per liter).
LENGTH = Average work trip length (miles).

All regression coefficients were statistically significant at an $\alpha = 0.05$ level or lower. Furthermore, the signs on all the regression coefficients correctly reflect the a priori expectations previously discussed.

Examination of the Residuals

No regression analysis is complete without an examination of the residuals to determine whether the assumptions that the residuals are normally distributed with constant variance holds true. In addition, an examination of the residuals often reveals inadequacies in the regression model that are not disclosed elsewhere.

Figures 2-9 and 2-10 give the residual plots against the predicted natural logarithm of per capita transportation energy consumption when only ZDENS is included in the model for Data Set One and Two, respectively. Examination of these plots shows that the residuals appear to be fairly normally distributed with a constant variance. No formal tests were performed to verify the latter observation. However, a regression of the ordered residuals for Data Set Two against their expected values under normality gave a coefficient of correlation of 0.975. The residuals can hence be said to be normally distributed at an $\alpha = 0.05$.

Figures 2-9 and 2-10 show that all the Australian cities analyzed have negative residuals implying that the regression model overestimates the per capita energy consumption in these cases. The reverse is true for all US cities analyzed (with the exception of Washington). The model both underestimates and overestimates the per capita energy consumption of the European cities. This would tend to suggest that some independent variable(s), not included in the model, may be responsible for the variability in the per capita energy consumption beyond that not explained by the R^2 value. These independent variables may be socioeconomic or cultural in nature. Further investigation of these variables is beyond the scope of this report due to the limited currently available data, however, it is recommended that a more detailed comparison between US and Australian cities be undertaken to clarify this issue.

Conclusion

Using data from 25 major international, first world cities, two regression models with the natural logarithm of transportation energy consumption as the dependent variable and various land use, transportation and socioeconomic variables as the independent variables were considered. The independent variables considered were: population density, employment density, concentration of employment, vehicle ownership, average income, percentage of mass transit ridership, and gasoline price in the first regression. These independent variables, as well as average work trip length, were used in the second regression analysis.

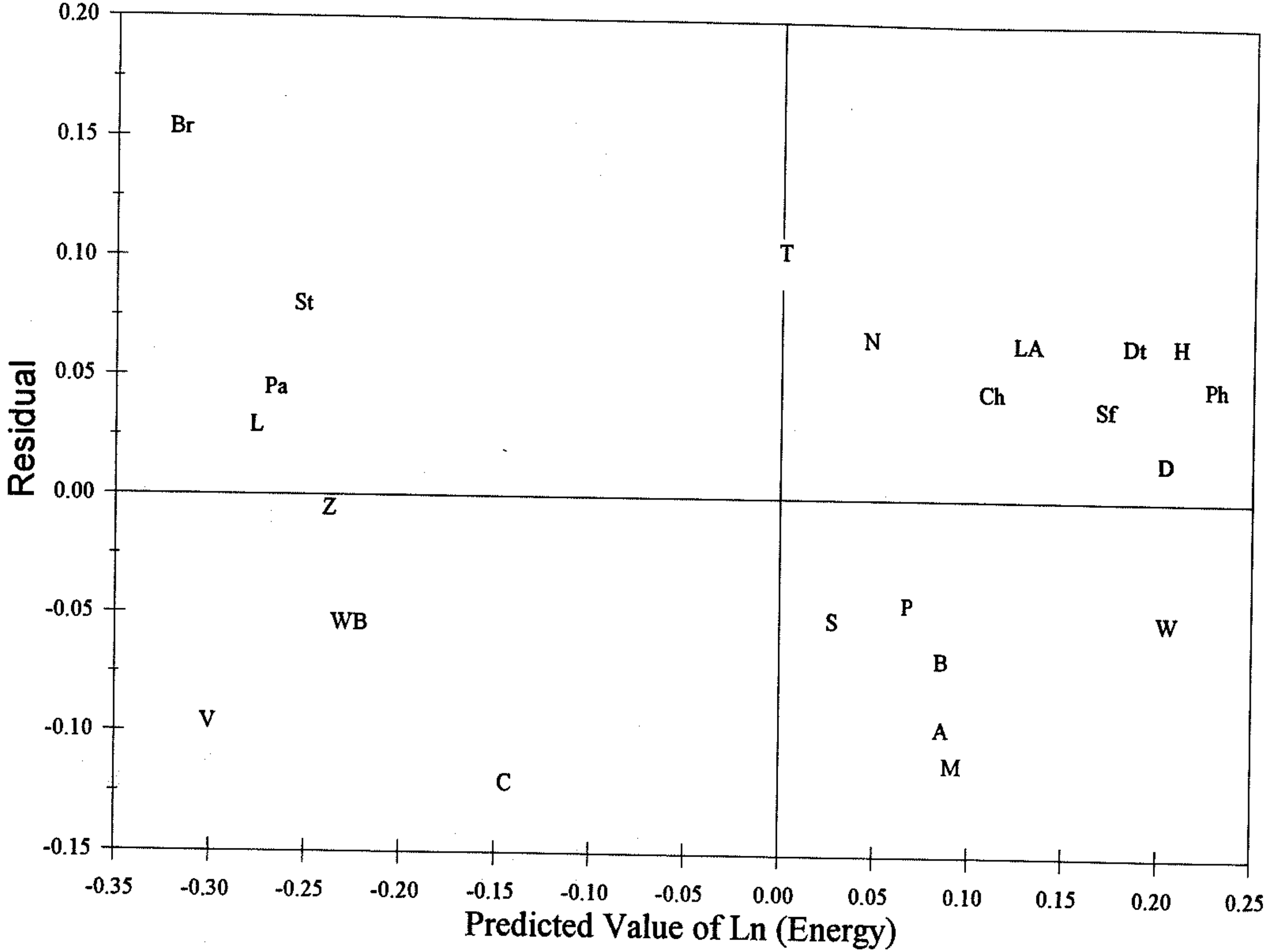


Figure 2-9. Residuals vs. Predicted Ln (Energy Consumption per Capita) for Data Set One

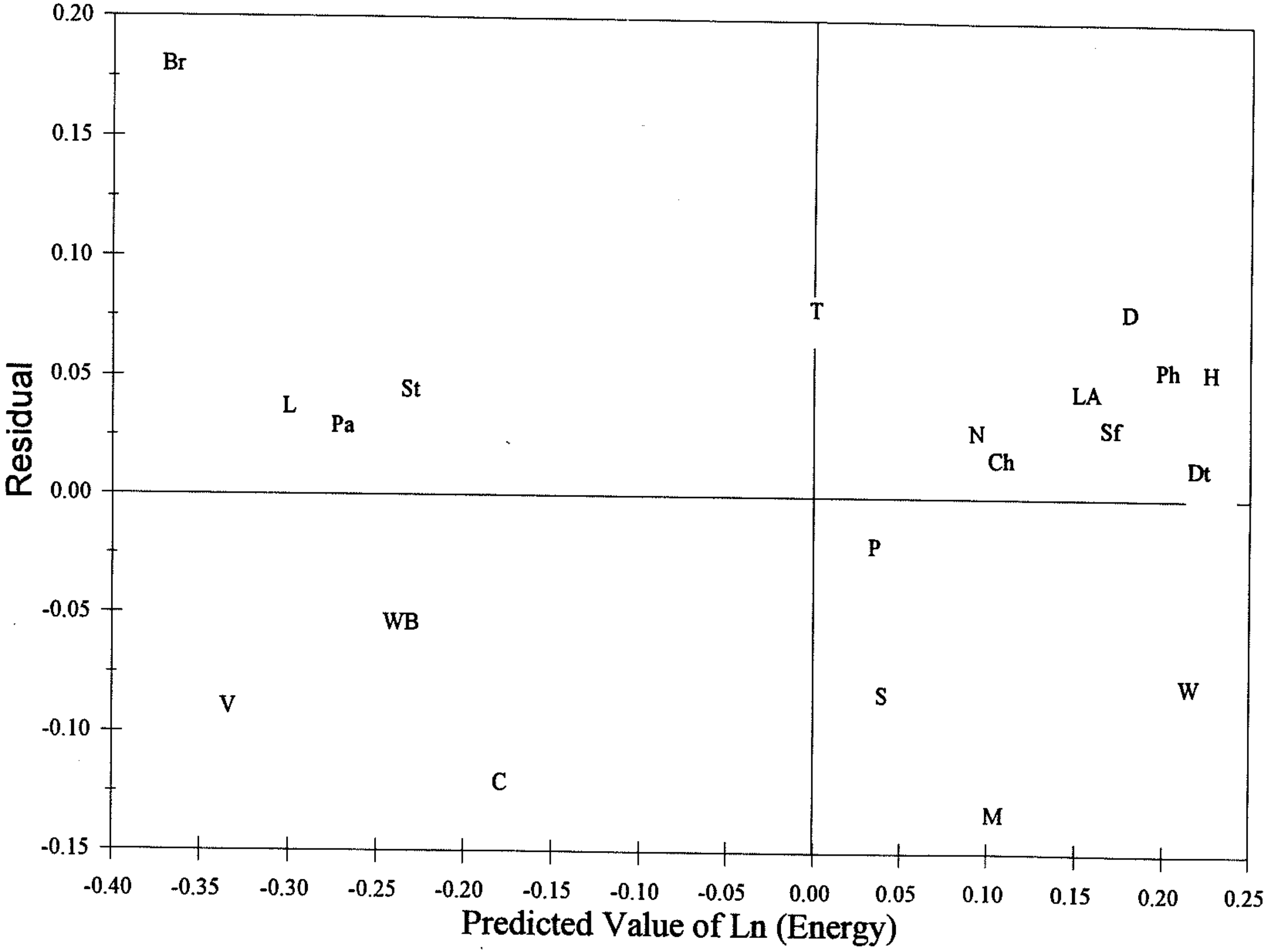


Figure 2-10. Residuals vs. Predicted Ln (Energy Consumption per Capita) for Data Set Two

The seven independent variables in the first analysis accounted for 91 percent of the variability in the natural logarithm of the per capita energy consumption. The eight independent variables in the second analysis accounted for 87 percent of the variability in the natural logarithm of the per capita energy consumption. The regression coefficients of all variables were found to reflect the a priori expectations of their influence on transportation energy consumption. All regression coefficients were found to be statistically significant at the $\alpha = 0.05$ level. Furthermore, the absolute values of all the standardized regression coefficients were found to be large enough to indicate that all independent variables have a meaningful impact on per capita transportation energy consumption. No conclusions could be drawn pertaining to the relative importance of each independent variable since the magnitudes of the standardized regression coefficients are highly dependent on the independent variables included in the model.

Severe multicollinearity effects between the independent variables precluded any meaningful inferences to be drawn from the regression equations. The notion of holding all variables but one constant to determine the effect of a unit increase/decrease in that variable on transportation energy consumption is simply not realistic. Nevertheless, the results have important implications. Despite the severe multicollinearity effects, the fact that the regression coefficients are all statistically significant indicates that planners and engineers can gain confidence by understanding the manner in which these variables are likely to affect transportation energy consumption.

One of the results of this analysis is that increasing gasoline price has a significant influence on decreasing transportation energy consumption. However, this result must not be misinterpreted. The data were obtained from cities worldwide and thus reflect a much greater range of values than would be expected to be seen within a single region or country. It is hypothesized that the influence of gasoline price on transportation energy consumption has developed over an extended period of time. Cities with higher gasoline prices over the years have developed more energy efficient urban structures and transportation systems. The extensive urban sprawl characteristic of many modern US cities may be the result of inexpensive, abundant gasoline. Moreover, autp use in the U.S. has been found to be very inelastic with respect to gasoline price (i.e., a large increase in price results in a small decrease in auto use). Further research on historical gasoline price trends and auto use are recommended to clarify this issue.

Income level has been presumed to be a surrogate measure for level of economic and social activity. High per capita transportation energy consumption in US cities can thus be partially attributed to the increased level of prosperity. Clearly, the only solution to address this "undesirable" consequence would be the development of more energy efficient urban structures and modes of transportation. Indeed, if the opportunity for increased travel within more prosperous societies is to be maintained, more efficient urban structures and modes of transportation might become a necessity.

Examination of the residuals indicated that the regression equations inadequately explain the differences in per capita energy consumption between US and Australian cities. It is apparent that some additional socioeconomic or cultural variables should be included in the model to explain these differences. Further investigation of this finding is recommended.

Generally, the results of this study have confirmed the findings in the literature. While no regression analysis explains why the independent variables affect the dependent variable in the manner shown, the analysis goes a long way in explaining how the independent variables affect the dependent variable. As a result of this, it is hoped that these results will be beneficial to urban and transportation planners in adopting policies and proposals consistent with a move towards a more energy efficient and integrated urban structure and transportation system.

CHAPTER 3. MOBILITY TRENDS AND ENERGY USE

Introduction

Traffic congestion in most urban and suburban areas in the United States has reached unprecedented levels recently. National and local media continue to focus their attention on the nation's transportation systems, while the legislature has demonstrated its interest in transportation through the promulgation of the Intermodal Surface Transportation Efficiency Act, and the transportation provisions in the 1990 Clean Air Act Amendments. Transportation professionals have devoted substantial time and resources to understand, quantify, alleviate, and manage congestion. Several efforts have attempted to quantify various aspects of congestion, and the resulting level of mobility on urban area basis.

This chapter discusses mobility and energy concerns for vehicles operating in urban areas in the United States. The objective of this analysis was an examination of the relationship between energy efficiency and congestion on an urban area basis. In order to accomplish this objective, a procedure for quantifying the average congestion level in urban areas is introduced, and calculations of energy use for vehicles operating in urban areas are discussed. This chapter also discusses the implications that increasing congestion and decreasing mobility levels have on energy efficiency.

Methodology

The methodology used to explore the relationship between congestion in an urban area and the energy efficiency of an area, as evidenced by the amount of fuel wasted, begins with the quantification of the congestion level in various urban areas throughout the United States. The Roadway Congestion Index (RCI), a method for quantifying the congestion level and resulting mobility level in an urban area, is discussed. The results of the application of this index to various urban areas, and resulting congestion trends, are presented.

The methodology also includes the development of a procedure for the calculation of the excess fuel consumption of vehicles in urban areas. The calculation of excess fuel consumption is based on an estimate of the fuel efficiency, which is determined based on the average delay, average speed, and average fuel mileage characteristics. The resulting excess fuel consumption value for each urban area is then compared to the congestion level of the urban area.

The excess fuel consumption value for each urban area is compared not only to the congestion level of the urban area, but also to the normalized congestion level of the urban area. Congestion levels are normalized based on the vehicle-miles traveled in the urban area, the number of vehicles in the urban area, and the population of the urban area. Statistical analysis, specifically regression analysis, is used to examine these relationships. Finally, the implications of reducing the congestion level in an urban area, in terms of its effect on the amount of excess fuel consumed, is discussed.

Mobility in Urban Areas

This section presents procedures for estimating the mobility level for vehicles operating in urban areas. The procedure was applied to fifty large and medium-sized urban areas in the United States, the resulting mobility levels are presented. The use of this procedure in examining mobility trends in urban areas in discussed, and several examples are given.

Roadway Congestion Index

Research at the Texas Transportation Institute (TTI) (17 to 22) resulted in the development of a methodology to quantify the congestion level for a particular urban area. The roadway congestion index (RCI) is an empirically derived formula that estimates the congestion level in an urban area based on the travel intensity, represented by daily vehicle-miles of travel (DVMT) per lane-mile, on freeways and principal arterial streets. Equation 3-1 shows the formula used to calculate the RCI. The RCI equation weights the travel intensity for the two functional classes of roadway by the number of vehicles miles that are served by each functional classification. The denominator of the RCI equation then normalizes the numerator by DVMT per lane-mile values representing the congestion threshold for freeways and principal arterial streets, 13,000 DVMT per lane-mile and 5,000 DVMT per lane-mile, respectively.

$$RCI = \frac{\left[\frac{Freeway}{DVMT/Ln.\text{-}Mi.} \times Freeway\ DVMT\right] + \left[\frac{Prin.\ Art.}{DVMT/Ln.\text{-}Mi.} \times Prin.\ Art.\ DVMT\right]}{[13{,}000 \times Freeway\ DVMT] + [5{,}000 \times Prin.\ Art.\ DVMT]} \qquad \text{Eq. 3-1}$$

where:

RCI = Roadway congestion index.
DVMT/Ln.-Mi. = Daily vehicle-miles of travel per lane-mile.

Once normalized, RCI values of 1.0 represent the beginning of undesirable mobility levels. Higher RCI levels indicate increasing levels of congestion, and decreasing levels of mobility within the urban area. For example, an urban area with an RCI value equal to 1.0 is just beginning to experience undesirable levels of congestion on an areawide basis; while an urban are with an RCI of 1.25 may be considered to have significant congestion and mobility limitations. The 1991 RCI values for fifty urban areas are shown in Table 3-1. The DVMT per lane-mile values for principal arterial and freeway facilities, used in the calculation of RCI values, are also shown for each urban area.

The RCI analysis was initially developed to study mobility trends in major Texas cities, but has been expanded to include fifty large and medium-sized urban areas throughout the United States. The principal source of data is the Highway Performance Monitoring System (HPMS) data base (23). Administered by the Federal Highway Administration (FHWA), this data base

Table 3-1. Summary of Roadway Congestion Index Values and Travel Statistics for U.S. Urban Areas, 1991

Urban Area	Freeway / Expressway		Principal Arterial Street		Roadway Congestion Index[3]	Rank
	DVMT[1] (1000)	DVMT/ Ln-Mile[2]	DVMT[1] (1000)	DVMT/ Ln-Mile[2]		
Los Angeles CA	110,280	21,110	81,710	6,590	1.56	1
Washington DC	25,760	16,830	19,650	8,470	1.39	2
San Fran-Oak CA	42,000	17,570	14,030	6,100	1.34	3
Miami FL	8,780	14,280	16,000	7,690	1.28	4
Chicago IL	38,980	16,010	30,540	7,180	1.28	4
San Diego CA	27,700	16,060	9,500	5,490	1.22	6
San Bernardino-Riv CA	14,970	16,540	10,650	4,660	1.20	7
Seattle-Everett WA	19,000	15,570	9,820	6,140	1.20	7
Atlanta GA	24,970	14,520	9,890	6,280	1.14	9
New York NY	83,010	14,020	53,020	6,960	1.14	9
Honolulu HI	4,700	13,820	1,620	8,100	1.13	11
New Orleans LA	5,040	13,810	4,140	6,620	1.12	12
Houston TX	29,500	14,640	10,900	5,010	1.11	13
Detroit MI	23,700	13,310	24,180	6,490	1.10	14
Portland OR	7,520	13,430	3,830	6,600	1.08	15
San Jose CA	16,520	14,060	6,730	4,800	1.07	16
Dallas TX	23,900	13,940	8,400	4,880	1.06	17
Boston MA	21,680	14,260	12,500	4,530	1.06	17
Philadelphia PA	18,400	12,150	21,620	6,630	1.06	17
Tampa FL	3,650	11,970	4,400	6,570	1.05	20
Sacramento CA	9,640	12,680	7,000	6,280	1.04	21
Phoenix AZ	8,160	12,750	18,020	5,590	1.04	21
Denver CO	11,430	12,770	10,800	5,840	1.03	23
Baltimore MD	16,040	12,830	9,880	5,910	1.02	24
Milwaukee WI	7,810	13,020	4,930	4,880	1.00	25
St. Louis MO	19,050	11,240	12,750	7,040	0.98	26
Norfolk VA	5,570	11,840	4,430	5,910	0.97	27
Cincinnati OH	11,600	12,750	3,800	4,610	0.97	27
Cleveland OH	13,970	12,250	5,850	5,200	0.96	29
Jacksonville FL	5,470	12,160	5,900	4,880	0.95	30
Ft. Lauderdale FL	7,130	11,880	6,000	5,330	0.95	30
Austin TX	5,500	12,090	2,150	4,940	0.94	32
Albuquerque NM	2,480	11,530	3,850	5,130	0.94	32
Minn-St. Paul MN	18,210	12,180	5,720	4,730	0.94	32
Memphis TN	4,400	11,280	4,200	5,220	0.92	35
Fort Worth TX	12,300	11,940	4,250	4,830	0.92	35
Nashville TN	5,210	10,320	5,460	5,750	0.90	37
Hartford CT	6,240	10,760	3,800	5,850	0.89	38
San Antonio TX	9,380	11,300	5,450	4,890	0.89	38
Louisville KY	6,250	10,590	3,120	6,000	0.88	40
Salt Lake City UT	5,480	10,650	2,080	5,860	0.86	41
Columbus OH	8,500	10,550	3,300	5,320	0.84	42
Indianapolis IN	8,150	10,650	3,960	4,500	0.83	43
Charlotte NC	2,490	8,300	3,190	5,910	0.82	44
Pittsburgh PA	8,250	8,130	11,080	5,970	0.82	44
Oklahoma City OK	7,030	9,690	3,770	5,460	0.80	46
El Paso TX	3,390	9,550	3,280	3,900	0.75	47
Kansas City MO	12,520	9,200	4,840	4,610	0.74	48
Corpus Christi TX	1,610	8,630	1,550	4,410	0.72	49
Orlando FL	6,050	10,080	3,980	2,520	0.72	49

1 Daily vehicle-miles of travel.
2 Daily vehicle-miles of travel per lane-mile.
3 See Equation 3-1.
Source: TTI Analysis.

contains basic travel data for several hundred urban areas. This data is supplemented with information collected by TTI from metropolitan planning organizations (MPOs), state departments of transportation (DOTs), cities, counties, and other local or regional agencies.

Congestion Trends

Recognizing the limitations of applying an average measure over an entire urban area, the RCI can be used to compare average congestion levels between urban areas, geographic regions, or population sizes. As seen in Table 3-2, the general trend in most urban areas between 1982 and 1991 has been one of increasing congestion level. Of the 50 urban areas in the RCI analysis, only three, Phoenix, Detroit, and Houston, have experienced a reduced congestion level over this time period. The average rate of increase of congestion level for all 50 urban areas was 18 percent. San Diego had the largest increase in congestion (56 percent), while Phoenix had the largest decline in congestion level (10 percent). The ten most congested urban areas in the 1991 analysis had an average RCI value of 1.28, with an average increase of approximately 27 percent between 1982 and 1991. Five of the ten most congested areas are in California, with each of the six remaining areas located in a different geographic regions of the United States.

Figure 3-1 illustrates the congestion trends for fifty urban areas by three population ranges: less than 750,000 persons, between 750,000 and 1,500,000 persons, and greater than 1,500,000 persons. Note that in the early 1980s, congestion in smaller urban areas increased faster than in the medium-sized urban areas; the congestion level in smaller urban areas is now similar to the congestion levels in medium-sized urban areas. It is also apparent that congestion is more severe in large urban areas, and has continued to increase.

Perhaps of greater significance is the use of the RCI to track trends in the congestion level for a particular urban area. The RCI is sensitive to changes in both travel (DVMT) and roadway supply (lane-miles). The proceedings from a recent congestion management systems workshop (24) considered the use of a performance measure or national congestion index (such as the RCI) to be integral in the framework of proposed congestion management systems. This "congestion index" would be useful for both national comparisons and for the evaluation of individual urban area conditions.

As an illustration of the use of the RCI for trend analysis, Figure 3-2 shows the trends in congestion level for four large urban areas in the United States. It can be seen that the congestion level over the past seven years has increased at a rapid rate (51 and 35 percent, respectively) in the San Diego and San Francisco-Oakland urban areas. On the other hand, the Detroit and Houston urban areas have experienced a slight decline in congestion (4 and 3 percent, respectively) over the same time period. This figure illustrates the usefulness of a congestion index for comparisons between urban areas and for individual urban area trend analysis.

Table 3-2. Roadway Congestion Index Values, 1982 to 1991

Urban Area	Year 1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	Percent Change 1982 to 1991
Phoenix AZ	1.15	1.16	1.10	1.13	1.20	1.18	1.00	1.03	1.03	1.04	-10
Houston TX	1.17	1.21	1.25	1.23	1.21	1.19	1.15	1.13	1.12	1.11	-5
Detroit MI	1.13	1.10	1.13	1.12	1.11	1.10	1.09	1.08	1.09	1.10	-3
Louisville KY	0.84	0.82	0.81	0.79	0.80	0.88	0.87	0.86	0.86	0.88	5
Pittsburgh PA	0.78	0.76	0.76	0.78	0.79	0.79	0.81	0.82	0.82	0.82	5
Philadelphia PA	1.00	1.03	1.04	0.90	1.06	1.06	1.07	1.05	1.05	1.06	6
Memphis TN	0.86	0.80	0.76	0.75	0.77	0.84	0.86	0.91	0.91	0.92	7
Corpus Christi TX	0.67	0.69	0.69	0.71	0.71	0.72	0.70	0.71	0.72	0.72	7
Orlando FL	0.66	0.68	0.67	0.71	0.71	0.72	0.74	0.72	0.72	0.72	9
San Bernardino-Riv CA	1.09	1.11	1.12	1.11	1.14	1.13	1.16	1.16	1.19	1.20	10
Ft. Lauderdale FL	0.86	0.85	0.84	0.84	0.84	0.90	0.90	0.92	0.94	0.95	10
Oklahoma City OK	0.72	0.72	0.75	0.74	0.71	0.76	0.78	0.78	0.79	0.80	11
Tampa FL	0.94	0.91	1.03	1.00	0.96	1.02	1.03	1.03	1.05	1.05	12
Jacksonville FL	0.85	0.92	0.98	0.98	0.95	0.94	0.95	0.93	0.93	0.95	12
Cincinnati OH	0.86	0.83	0.82	0.83	0.84	0.87	0.88	0.94	0.96	0.97	13
New York NY	1.01	1.02	0.99	1.00	1.06	1.06	1.10	1.12	1.14	1.14	13
New Orleans LA	0.98	1.00	1.05	1.09	1.11	1.14	1.13	1.13	1.12	1.12	14
San Antonio TX	0.77	0.79	0.82	0.87	0.90	0.85	0.86	0.87	0.88	0.89	16
Indianapolis IN	0.71	0.66	0.75	0.76	0.80	0.85	0.84	0.85	0.83	0.83	17
Hartford CT	0.76	0.79	0.86	0.85	0.85	0.87	0.91	0.89	0.89	0.89	17
Boston MA	0.90	0.93	0.95	0.98	1.04	1.04	1.12	1.09	1.06	1.06	18
St. Louis MO	0.83	0.87	0.88	0.89	0.93	0.96	0.98	0.96	0.99	0.98	18
El Paso TX	0.63	0.64	0.65	0.70	0.75	0.71	0.74	0.74	0.74	0.75	19
Kansas City MO	0.62	0.62	0.60	0.65	0.69	0.71	0.72	0.72	0.74	0.74	19
Cleveland OH	0.80	0.82	0.83	0.81	0.86	0.89	0.97	0.95	0.97	0.96	20
Milwaukee WI	0.83	0.84	0.87	0.88	0.90	0.95	0.94	0.97	0.99	1.00	20
Albuquerque NM	0.78	0.83	0.89	0.93	0.88	0.91	0.90	0.91	0.93	0.94	21
Fort Worth TX	0.76	0.79	0.80	0.82	0.87	0.87	0.87	0.87	0.90	0.92	21
Denver CO	0.85	0.88	0.93	0.96	0.97	0.95	0.99	1.01	1.03	1.03	21
Baltimore MD	0.84	0.84	0.85	0.84	0.88	0.90	0.92	0.99	1.01	1.02	21
Honolulu HI	0.93	0.95	0.97	0.97	1.05	1.07	1.10	1.09	1.11	1.13	22
Nashville TN	0.74	0.76	0.83	0.81	0.86	0.89	0.94	0.90	0.89	0.90	22
Miami FL	1.05	1.09	1.07	1.13	1.10	1.14	1.18	1.25	1.27	1.28	22
Austin TX	0.77	0.84	0.89	0.91	0.98	0.96	0.96	0.96	0.94	0.94	22
Charlotte NC	0.67	0.72	0.72	0.73	0.73	0.74	0.73	0.74	0.78	0.82	22
Norfolk VA	0.79	0.77	0.79	0.84	0.90	0.93	0.94	0.95	0.96	0.97	23
Columbus OH	0.68	0.71	0.71	0.71	0.75	0.78	0.79	0.82	0.83	0.84	24
Portland OR	0.87	0.86	0.88	0.93	0.97	1.00	1.05	1.07	1.07	1.08	24
Chicago IL	1.02	1.02	1.05	1.08	1.15	1.15	1.18	1.21	1.25	1.28	25
San Jose CA	0.85	0.87	0.90	0.94	0.96	0.98	0.99	1.02	1.04	1.07	26
Dallas TX	0.84	0.89	0.94	0.98	1.04	1.02	1.02	1.02	1.05	1.06	26
Seattle-Everett WA	0.95	0.99	1.02	1.05	1.09	1.14	1.17	1.21	1.20	1.20	26
Minn-St. Paul MN	0.74	0.79	0.81	0.83	0.87	0.87	0.88	0.90	0.93	0.94	27
Los Angeles CA	1.22	1.27	1.32	1.36	1.42	1.47	1.52	1.54	1.55	1.56	28
Atlanta GA	0.89	0.94	0.97	1.02	1.09	1.11	1.14	1.14	1.11	1.14	28
Washington DC	1.07	1.09	1.12	1.20	1.28	1.30	1.32	1.36	1.37	1.39	30
Sacramento CA	0.80	0.84	0.88	0.92	0.95	1.00	1.03	1.01	1.02	1.04	30
San Fran-Oak CA	1.01	1.05	1.12	1.17	1.24	1.31	1.33	1.36	1.35	1.34	33
Salt Lake City UT	0.63	0.63	0.65	0.68	0.68	0.70	0.72	0.81	0.85	0.86	37
San Diego CA	0.78	0.83	0.91	0.95	1.00	1.08	1.13	1.18	1.22	1.22	56
Northeastern Avg	0.91	0.92	0.94	0.94	0.99	1.00	1.04	1.05	1.05	1.05	
Midwestern Avg	0.82	0.82	0.83	0.84	0.87	0.90	0.91	0.92	0.94	0.94	
Southern Avg	0.84	0.86	0.88	0.90	0.91	0.94	0.96	0.97	0.97	0.98	
Southwestern Avg	0.82	0.85	0.87	0.90	0.93	0.91	0.90	0.91	0.93	0.93	
Western Avg	0.94	0.97	1.01	1.04	1.09	1.13	1.16	1.18	1.19	1.20	
Texas Avg	0.80	0.84	0.86	0.89	0.92	0.90	0.90	0.90	0.91	0.91	
Total Avg	0.86	0.88	0.90	0.92	0.95	0.97	0.98	0.99	1.00	1.01	
Maximum Value	1.22	1.27	1.32	1.36	1.42	1.47	1.52	1.54	1.55	1.56	
Minimum Value	0.62	0.62	0.60	0.65	0.68	0.70	0.70	0.71	0.72	0.72	

Source: TTI Analysis.

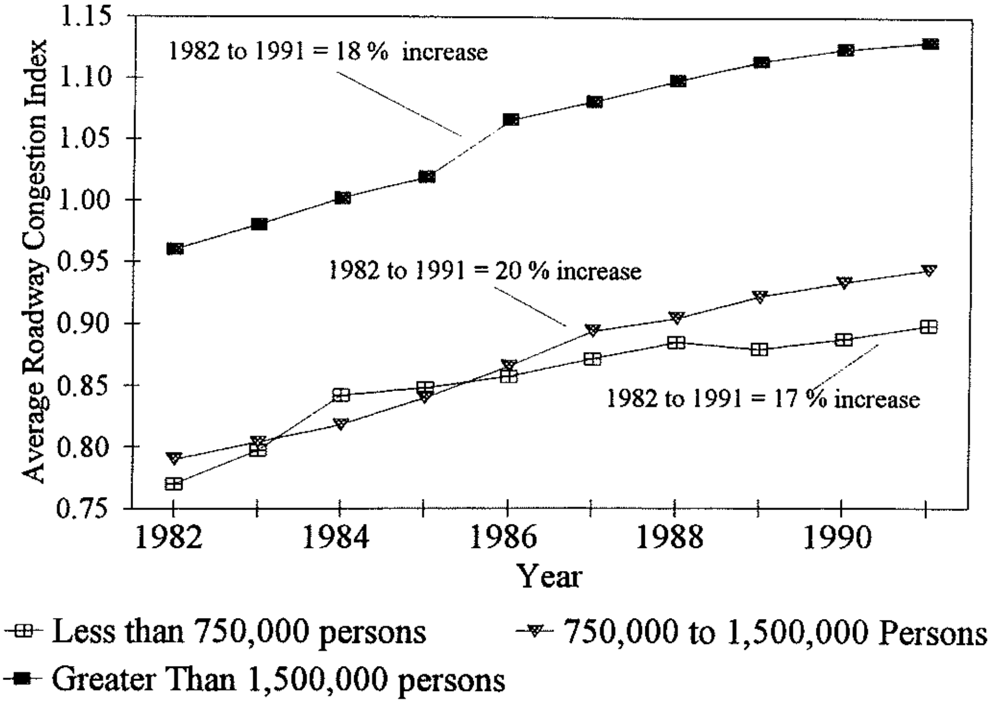


Figure 3-1. Congestion Trends by Population Range for U.S. Urban Areas, 1982 to 1991

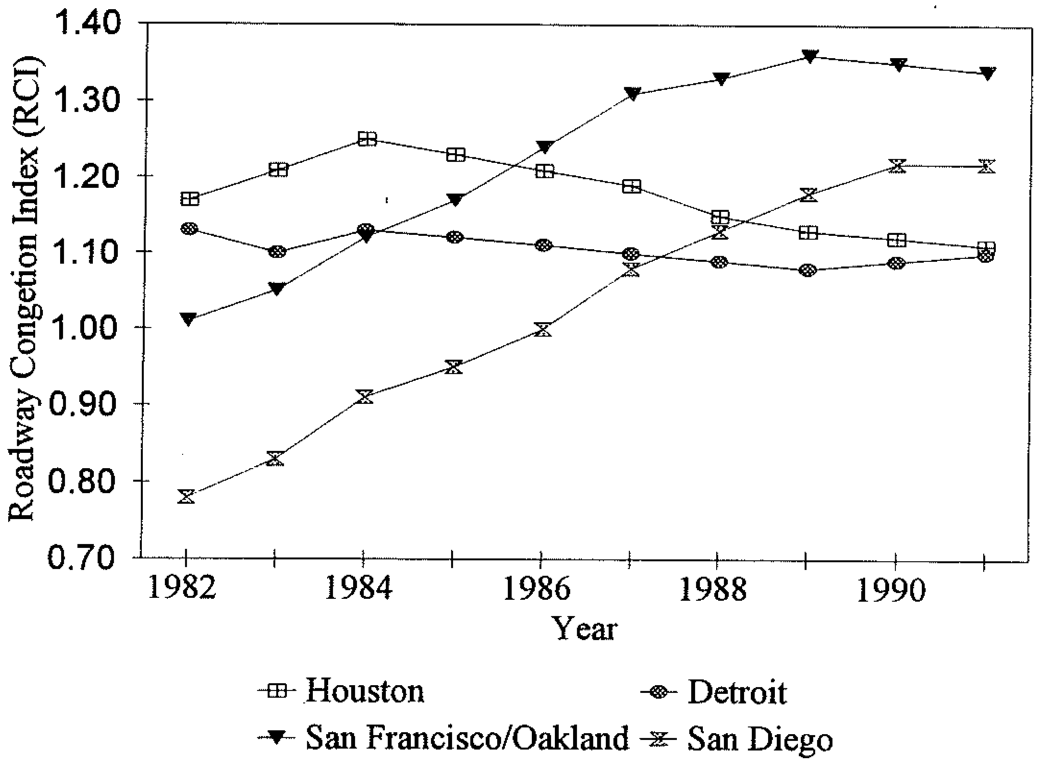


Figure 3-2. Congestion Trends for Four Large U.S. Urban Areas, 1982 to 1991

Calculation of Fuel Efficiency of Vehicles in Urban Areas

A methodology used to calculate the fuel efficiency of vehicles operating in congested travel conditions is introduced in this section. The procedure is applied to the same fifty urban areas for which congestion levels were calculated using the RCI analysis. Estimates of excess fuel consumption due to congestion are presented for each of these urban areas.

Excess Fuel Consumption in Congested Conditions

One of the more important economic and environmental consequences of congestion is decreased fuel efficiency. Decreased fuel efficiency is a result of the increased fuel consumption of vehicles experiencing delay in congested travel conditions.

A recent study by Fwa and Ang (25) reported on several fuel consumption models that have been developed to investigate the effects of average speed on fuel consumption. One of the models was modified for this study, then integrated with capacity and traffic calculations to determine excess fuel consumption due to congestion. This procedure is one that has been adopted in previous TTI congestion reports (20 to 22). The methodology, in general, uses estimated travel speed and delay (both recurring and incident) as the basis for the calculation of excess fuel consumption. The basic formula, shown in Equation 3-2, requires estimation of three variables: delay, average vehicular speed, and average fuel mileage. Each of these variables is discussed.

$$\underset{(gallons/year)}{Wasted\ Fuel} = \frac{\underset{(veh\,hrs/day)}{TotalDelay} \times \underset{Speed\ (mph)}{Average\ Vehicular} \times \underset{Days\ per\ Year}{250\ Working}}{Average\ Fuel\ Mileage\ (mpg)} \qquad \text{Eq. 3-2}$$

Delay

The estimation of delay was performed in several steps. First, the recurring delay was calculated based on the peak period congested DVMT, and on the average speeds in the peak and off peak periods. This recurring delay was then used in the calculation of incident delay.

Equation 3-3 was used for the calculation of the recurring delay. The peak period congested DVMT is the number of daily vehicles miles that are traveled while the facility is congested; the congestion level and the estimated speed are defined by the ADT/lane. The congestion level and estimated speed corresponding to the ADT/lane are shown in Table 3-3 for both freeways and principle arterial streets.

$$\underset{(veh\,hrs/day)}{Recurring\ Delay} = \frac{\overset{PeakPeriod}{Congested\ DVMT}}{Avg.\ PeakPeriod\ Speed} - \frac{\overset{PeakPeriod}{Congested\ DVMT}}{Avg.\ Off\text{-}Peak\ Speed} \qquad \text{Eq. 3-3}$$

Table 3-3. Assumed Speeds for Varying Severity of Congestion

Functional Classification	Parameters	Congestion Daily Vehicle-Miles of Travel[1,2]		
		Moderate	Heavy	Severe
Freeway	ADT/Lane	15,000-17,500	17,501-20,000	Over 20,000
	Speed (mph)[3]	38	33	30
Principal Arterial Streets	ADT/Lane	5,750-7,000	7,001-8,500	Over 8,500
	Speed (mph)[3]	28	25	23

[1] Assumes congested freeway operation when ADT/lane exceeds 15,000.
[2] Assumes congested principal arterial street operation when ADT/lane exceeds 5,750.
[3] Value represents a weighted average (23).
Source: TTI Analysis and Houston-Galveston Regional Transportation Study (26).

Equation 3-4 was used for the calculation of incident delay for both freeways and arterials, note that this equation utilizes the recurring delay calculated previously, and a ratio describing the relationship between incident and recurring delay. While Equation 3-4 was used for the calculation of incident delay for both freeways and arterials, the estimation of the incident-to-recurring delay ratio varied for freeways and arterials.

$$\underset{(veh\,hrs/day)}{\textit{Incident Delay}} = \underset{(veh\,hrs/day)}{\textit{Recurring Delay}} \times \underset{(for\ each\ functional\ class)}{\textit{Incident Delay/Recurring Delay Ratio}} \quad \text{Eq. 3-4}$$

For freeways, the methodology for the incident-to-recurring delay ratio was developed by TTI, using the results of an earlier study by Lindley (27). Lindley used a freeway incident database to calculate the frequency of incidents for various prevailing conditions. An incident-to-recurring delay ratio was calculated using data reported by Lindley for the freeway system in each urban area. These ratios have been used in this study to estimate freeway incident delay.

For the calculation of incident delay on principal arterial streets, a constant incident-to-recurring delay ratio of 1.1 was assumed. A single ratio for the incident to recurring delay ratio was considered valid because characteristics of incident and recurring delay on arterial street systems are relatively consistent among urban areas, and because incident response and incident removal are facilitated by more frequent access provided on arterials. The total delay is the sum of recurring and incident delay for both freeways and principal arterial streets.

Average Vehicular Speed

The average vehicular speed during peak-period congested conditions is calculated using Equation 3-5 for each urban area. This calculation uses an average of the speeds on freeways and principal arterial streets, weighted by peak-period VMT.

$$\underset{(mph)}{\textit{Average Speed}} = \left[\frac{\textit{Avg Freeway Speed}^{*} \times \textit{Peak Period Freeway VMT}}{\textit{Total Peak Period VMT}}\right] + \left[\frac{\textit{Avg Prin Art Speed}^{*} \times \textit{Peak Period Prin Art VMT}}{\textit{Total Peak Period VMT}}\right] \qquad \text{Eq. 3-5}$$

***** *The average speeds for freeways and principal arterial streets are weighted (by daily vehicle-miles of travel) averages of urban area speeds (Table 3-3).***

Average Fuel Mileage

Equation 3-6 was used to determine the average fuel mileage, which is calculated based on the average vehicular speed. This value was calculated for each urban area. This equation is based on a fuel consumption model developed by Raus (28), which determined average fuel consumption rates for U.S. cars for average speeds between 1 and 35 miles per hour. Since the Raus model was essentially linear for speeds between 20 and 35 miles per hour, Lindley (27) performed a linear regression analysis to generate a model for average speeds greater than 35 miles per hour. Lindley's model is reported in this study as Equation 3-6.

$$\begin{matrix}\textit{Average Fuel}\\ \textit{Mileage (mpg)}\end{matrix} = 8.8 + [\ 0.25 \times \textit{Average Vehicle Speed (mph)}\ ] \qquad \text{Eq. 3-6}$$

It should be noted that this equation assumes a linear relationship between average speed and fuel consumption. Although this is not accurate for individual vehicles, it is appropriate for the calculation of average speeds for urban area roadway systems. In fact, Equation 3-6 produces more reasonable results than individual vehicle curves for average speeds for urban area roadway systems. The precision of this relationship is thought to be consistent with the planning-level analysis being performed.

Results

The calculation of the fuel wasted in congestion relies on total delay, average vehicular speed, and average fuel mileage; the estimation of these values was discussed in the preceding section. For each urban area, the total delay, average speed, average fuel mileage, and the resulting wasted fuel are shown in Table 3-4. In most cases, the calculation of wasted fuel was based on average values for an entire urban area. For the planning and analysis purposes intended of this study, the estimates in Table 3-4 represent reasonable values for excess fuel consumption by vehicles operating in congested conditions.

The amount of wasted fuel for the fifty urban areas totals more than 4.6 billion gallons. On the average in these fifty areas, over 51 gallons per vehicle, or 35 gallons per person, was wasted in congestion in 1991. Six of the ten most congested urban areas were also among the ten areas with the largest amount of wasted fuel. The urban area with the highest congestion level, Los Angeles, was also the area with the largest amount of wasted fuel.

Congestion and Fuel Efficiency

This section considers the relationship between the congestion level in an urban area, and the amount of excess fuel consumed. A relationship between excess fuel consumption and congestion level is presented, and the implications of a reduction in congestion on fuel consumption in urban areas is discussed.

The aggregate fuel efficiency of vehicles operating in urban areas depends on several factors. The fuel efficiency of individual vehicles certainly plays a role in overall fuel efficiency. Legislation mandating a higher Corporate Average Fuel Economy (CAFE) has contributed to some significant overall improvements in fuel efficiency. Another important factor is the average travel speed of vehicles, which is largely influenced by the type of facility and the operating conditions. The effects that poor operating conditions, such as congestion, as evidenced by total delay, can have on fuel efficiency in urban areas was illustrated in Table 3-4. The relationship between congestion and wasted fuel is intuitive to most drivers. Congestion is synonymous with delay which, for most, means idling in stationary or stop-and-go traffic. The relationship between congestion and wasted fuel is less apparent when drivers are travelling at reduced speeds.

A cursory examination of Table 3-4 reveals that excess fuel consumption is much greater in some urban areas than others. It may be hypothesized that the level of excess fuel consumption varies depending on the amount of congestion experienced in that area. Under this premise, the excess fuel consumption in an urban area would increase as the congestion level increases. Figure 3-3 illustrates an examination of the relationship between the urban area congestion level, as indicated by the roadway congestion index (RCI), and the excess fuel consumption. The congestion level and wasted fuel are plotted for fifty urban areas in the United States.

Regression analysis was performed to further explore the relationship between the congestion level in an urban area and the amount of fuel that is wasted. A key indicator of significance in such an analysis is the level of the coefficient of determination, r^2. The r^2 value is a statistic that measures the percent of variability in one factor that is explained by the variability of the second factor. The closer the value of r^2 is to 1.0, the greater the likelihood that the variance in each of the variables is related. In other words, an r^2 value of 1.0 would

Table 3-4. Estimates of Excess Fuel Consumption and Variables Used in Calculation, 1991

Urban Area	Average Vehicular Speed (MPH)[1]	Average Fuel Mileage	Wasted Fuel (million gals)	Total Delay (1000 veh-hrs/day)
Albuquerque NM	28.1	15.8	9.0	20.3
Atlanta GA	29.1	16.1	106.7	235.6
Austin TX	31.8	16.8	22.6	47.6
Baltimore MD	28.6	16.1	57.5	128.3
Boston MA	29.7	16.2	157.9	345.2
Charlotte NC	28.8	16.0	16.7	37.1
Chicago IL	28.3	15.9	245.5	551.4
Cincinnati OH	33.3	17.1	21.0	43.2
Cleveland OH	32.3	16.9	23.4	49.0
Columbus OH	28.9	16.0	18.6	41.3
Corpus Christi TX	31.1	16.6	1.6	3.5
Dallas TX	31.4	16.6	124.3	263.6
Denver CO	28.8	16.0	65.4	145.2
Detroit MI	27.2	15.6	166.7	382.2
El Paso TX	33.4	17.2	4.6	9.4
Fort Worth TX	31.1	16.6	47.8	102.0
Ft. Lauderdale FL	27.9	15.8	31.8	72.1
Hartford CT	30.3	16.4	13.9	30.0
Honolulu HI	29.9	16.3	25.8	56.2
Houston TX	30.3	16.4	183.5	396.8
Indianapolis IN	31.6	16.7	8.0	17.0
Jacksonville FL	29.6	16.2	25.3	55.4
Kansas City MO	28.1	15.8	12.6	28.3
Los Angeles CA	28.6	16.0	805.2	1795.1
Louisville KY	26.5	15.4	9.5	22.1
Memphis TN	29.0	16.1	9.9	22.0
Miami FL	26.6	15.4	99.5	231.4
Milwaukee WI	29.9	16.3	21.8	47.5
Minn-St. Paul MN	29.7	16.2	47.8	104.5
Nashville TN	28.7	16.0	18.2	40.6
New Orleans LA	28.3	15.9	30.6	68.8
New York NY	29.7	16.2	693.7	1515.2
Norfolk VA	29.2	16.1	34.5	76.2
Oklahoma City OK	28.8	16.0	10.1	22.4
Orlando FL	28.7	16.0	33.4	74.4
Philadelphia PA	26.5	15.4	119.3	277.6
Phoenix AZ	27.4	15.6	80.8	184.6
Pittsburgh PA	26.3	15.4	50.1	117.1
Portland OR	30.4	16.4	39.5	85.4
Sacramento CA	30.1	16.3	37.8	82.0
Salt Lake City UT	30.8	16.5	8.3	17.8
San Antonio TX	30.9	16.5	28.5	60.9
San Bernardino-Riv CA	29.7	16.2	112.0	244.9
San Diego CA	31.5	16.7	73.1	154.8
San Fran-Oak CA	30.0	16.3	293.6	638.1
San Jose CA	29.7	16.2	105.8	231.1
Seattle-Everett WA	30.1	16.3	124.6	270.2
St. Louis MO	28.0	15.8	59.2	133.6
Tampa FL	28.6	16.0	22.4	50.0
Washington DC	28.0	15.8	251.3	567.7

[1] Average speed on freeways and principal arterial streets during peak-period congested conditions.

Source: TTI Analysis.

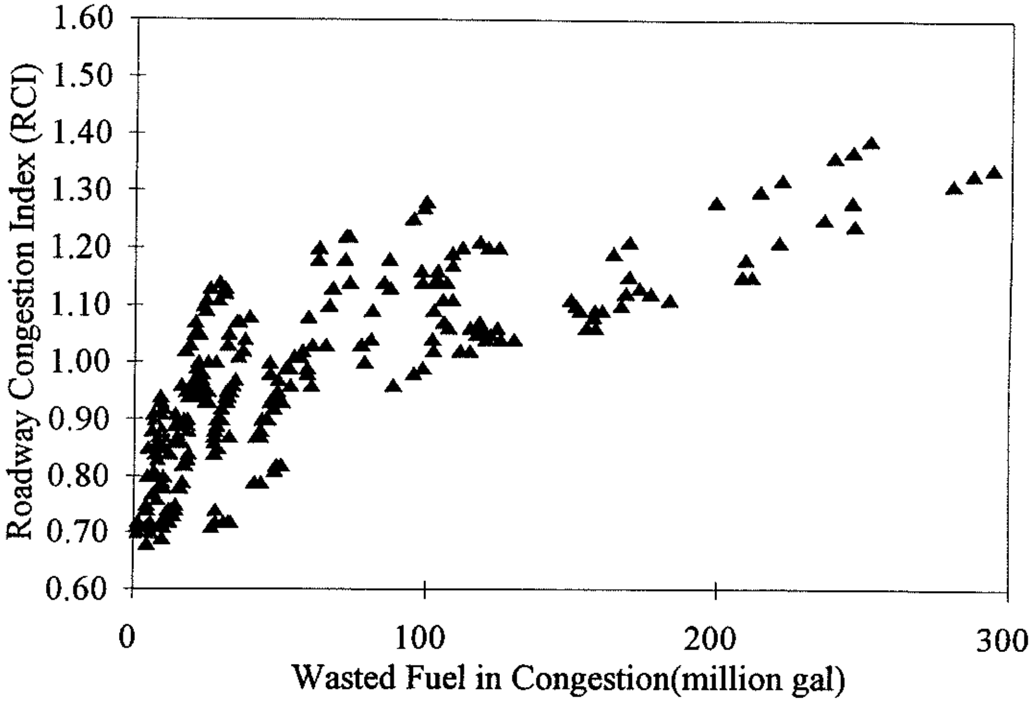


Figure 3-3. Excess Fuel Consumption Versus Congestion Level, 1986 to 1991

indicate that changes in the level of a dependent variable are directly affected by changes in the level of the independent variable. In this case, an r^2 value of 1.0 would indicate that changes in the level of wasted fuel are directly affected by changes in the level of congestion in an urban area. In general, an r^2 value of 0.5 or greater is considered indicative of a close relationship, and an r^2 value less than 0.5 indicates that the relationship between the variables is not considered significant.

Initially, the coefficient of determination (r^2) was calculated assuming that a linear relationship between congestion and excess fuel consumption. This analysis resulted in an r^2 value of 0.44, which implies that there is not a strong linear relationship between congestion and excess fuel consumption. The results of this analysis indicate that while congestion level is moderately related to excess fuel consumption, there are other factors specific to each urban area that also affect excess fuel consumption and should be considered.

Intuitively, there are a number of factors that might have an effect on the amount of excess fuel consumed in an urban area. The amount of travel, as evidenced by the VMT, in an urban area has an influence on fuel consumption, as does the number of vehicles operating in the urban area. The population size might also affect the fuel consumption in an urban area. To discount the effects that these variables have on fuel consumption in individual urban areas, the amount of excess fuel consumed was normalized by these variables; the results are shown in Table 3-5. A ranking of the urban areas by each normalizing factor is provided for comparison.

When the excess fuel values are normalized by the various factors, a comparison between urban areas can be made more readily. These normalizing factors diminish the effects that increased travel, more vehicles, or more people have on the amount of excess fuel consumed in each urban area. For this reason, it is worth investigating the relationship between the normalized values of excess fuel consumption and the urban area congestion level. The relationship between the congestion level and gallons of wasted fuel, normalized by VMT, is shown in Figure 3-4. The r^2 value calculated for this relationship was 0.66, thus the congestion level is more strongly correlated with the excess fuel consumption when it is normalized by VMT, than when it is not. By normalizing the excess fuel consumption by the amount of vehicle-miles traveled, a relationship with less variability between urban areas is developed.

The excess fuel consumption from Table 3-5, normalized with respect to the population and the number of registered vehicles, is shown versus the congestion level in Figures 3-5 and 3-6. Figure 3-5 illustrates wasted fuel per capita, which had an r^2 value of 0.61 for the years 1986 through 1991. Figure 3-6 illustrates wasted fuel per vehicle, which had an r^2 value of 0.59 for the same time period.

Implications of Congestion Reduction on Excess Fuel Consumption

In an effort to ascertain the possible implications of a reduction in congestion on excess fuel consumption, a model was developed to estimate the gains in fuel efficiency for incremental reductions in congestion. This model used the relationship between congestion level and excess fuel consumption per 1,000 VMT ($r^2 = 0.66$). A best-fit line developed using a linear regression of this relationship is shown in Figure 3-7.

From the regression line in Figure 3-7, inferences can be made about the excess consumption of fuel given various levels of congestion. For example, roadway congestion in the Houston urban area decreased 8% between the years of 1986 and 1991 (see Table 3-2); if the RCI value decreased at half of this rate (4%) over the next four years (1992 through 1995), the total congestion reduction would result in an RCI value of 1.07. Using the regression equation in Figure 3-7, it was calculated that wasted fuel per 1,000 VMT would decrease by 9%, or 0.9 gallons per 1,000 VMT. Assuming that growth in travel continued at the 1991 rate of 2% (15.6 billion VMT in 1995), this reduction in congestion accounts for a savings of approximately 15 million gallons in the Houston urban area in 1995 alone.

Table 3-5. Normalized Values of Excess Fuel Consumption, 1991

Urban Area	Gallons (millions)	Rank	Gallons per 1,000 VMT	Rank	Gallons per Vehicle	Rank	Gallons per Capita	Rank
Los Angeles CA	805.2	1	16.8	9	103.1	5	68.5	6
New York NY	693.7	2	20.4	3	114.4	3	41.2	16
San Fran-Oak CA	293.6	3	21.0	2	96.7	6	78.8	2
Washington DC	251.3	4	22.1	1	148.9	1	76.6	3
Chicago IL	245.5	5	14.1	13	60.7	14	32.7	24
Houston TX	183.5	6	18.2	6	81.8	10	63.3	7
Detroit MI	166.7	7	13.9	15	58.1	15	41.8	14
Boston MA	157.9	8	18.5	4	95.1	7	53.4	10
Seattle-Everett WA	124.6	9	17.3	8	93.6	8	69.1	5
Dallas TX	124.3	10	15.4	12	82.3	9	60.0	8
Philadelphia PA	119.3	11	11.9	21	42.8	26	28.2	30
San Bernardino-Riv CA	112.0	12	17.5	7	140.6	2	90.7	1
Atlanta GA	106.7	13	12.2	20	67.2	12	56.1	9
San Jose CA	105.8	14	18.2	5	103.6	4	70.5	4
Miami FL	99.5	15	16.1	11	69.5	11	52.9	11
Phoenix AZ	80.8	16	12.3	19	65.1	13	41.8	13
San Diego CA	73.1	17	7.9	33	52.0	19	31.1	28
Denver CO	65.4	18	11.8	23	47.0	22	41.4	15
St. Louis MO	59.2	19	7.5	35	58.1	16	30.4	29
Baltimore MD	57.5	20	8.9	31	54.6	18	28.1	31
Pittsburgh PA	50.1	21	10.4	27	40.5	29	26.9	33
Fort Worth TX	47.8	22	11.6	25	47.9	21	39.8	17
Minn-St. Paul MN	47.8	23	8.0	32	28.1	37	23.2	36
Portland OR	39.5	24	13.9	14	57.8	17	38.0	19
Sacramento CA	37.8	25	9.1	29	29.5	36	32.5	25
Norfolk VA	34.5	26	13.8	16	41.6	28	36.4	21
Orlando FL	33.4	27	13.3	18	44.9	23	38.0	20
Ft. Lauderdale FL	31.8	28	9.7	28	30.9	35	25.0	34
New Orleans LA	30.6	29	13.4	17	34.8	33	28.0	32
San Antonio TX	28.5	30	7.7	34	32.6	34	24.1	35
Honolulu HI	25.8	31	16.3	10	50.7	20	38.8	18
Jacksonville FL	25.3	32	8.9	30	41.8	27	33.7	23
Cleveland OH	23.4	33	4.7	42	15.7	46	13.1	43
Austin TX	22.6	34	11.8	22	44.3	24	43.0	12
Tampa FL	22.4	35	11.1	26	35.0	32	31.6	27
Milwaukee WI	21.8	36	6.8	36	40.4	30	17.8	39
Cincinnati OH	21.0	37	5.5	41	22.5	40	17.5	40
Columbus OH	18.6	38	6.3	38	24.8	39	20.7	38
Nashville TN	18.2	39	6.8	37	35.4	31	31.7	26
Charlotte NC	16.7	40	11.8	24	44.2	25	36.3	22
Hartford CT	13.9	41	5.5	40	26.4	38	22.7	37
Kansas City MO	12.6	42	2.9	47	16.8	44	10.8	46
Oklahoma City OK	10.1	43	3.7	46	20.5	43	13.6	42
Memphis TN	9.9	44	4.6	43	15.8	45	11.5	45
Louisville KY	9.5	45	4.1	45	20.6	42	11.8	44
Albuquerque NM	9.0	46	5.7	39	21.3	41	16.7	41
Salt Lake City UT	8.3	47	4.4	44	11.8	49	9.9	47
Indianapolis IN	8.0	48	2.7	49	13.8	47	8.5	48
El Paso TX	4.6	49	2.7	48	13.2	48	8.1	49
Corpus Christi TX	1.6	50	2.1	50	7.6	50	5.8	50

Source: TTI Analysis.

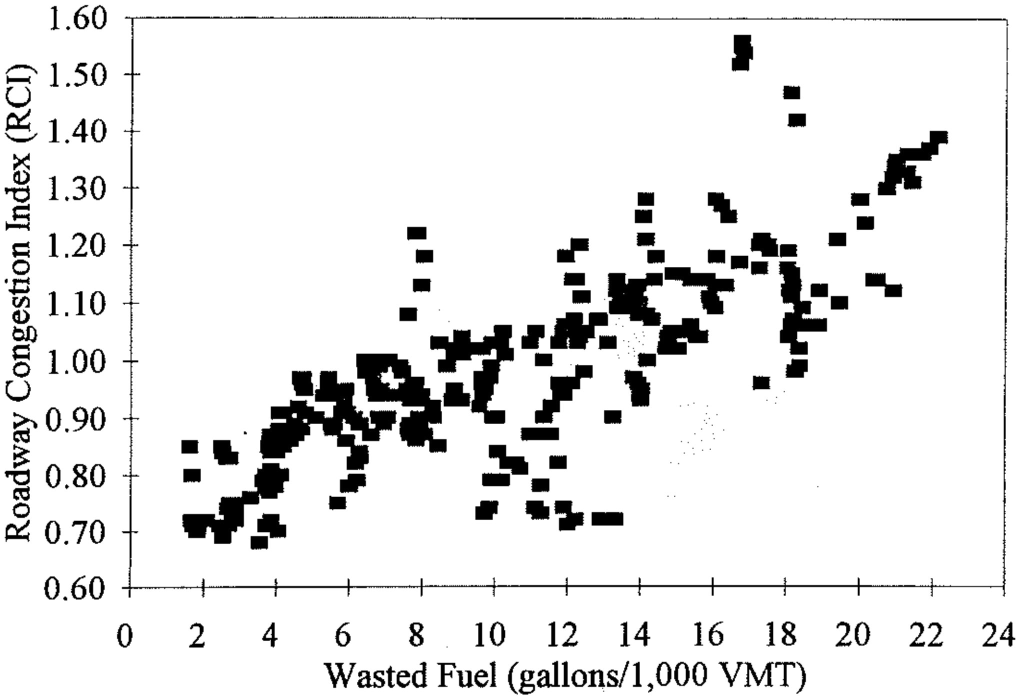


Figure 3-4. Excess Fuel Consumption (per 1,000 VMT) Versus Congestion Level

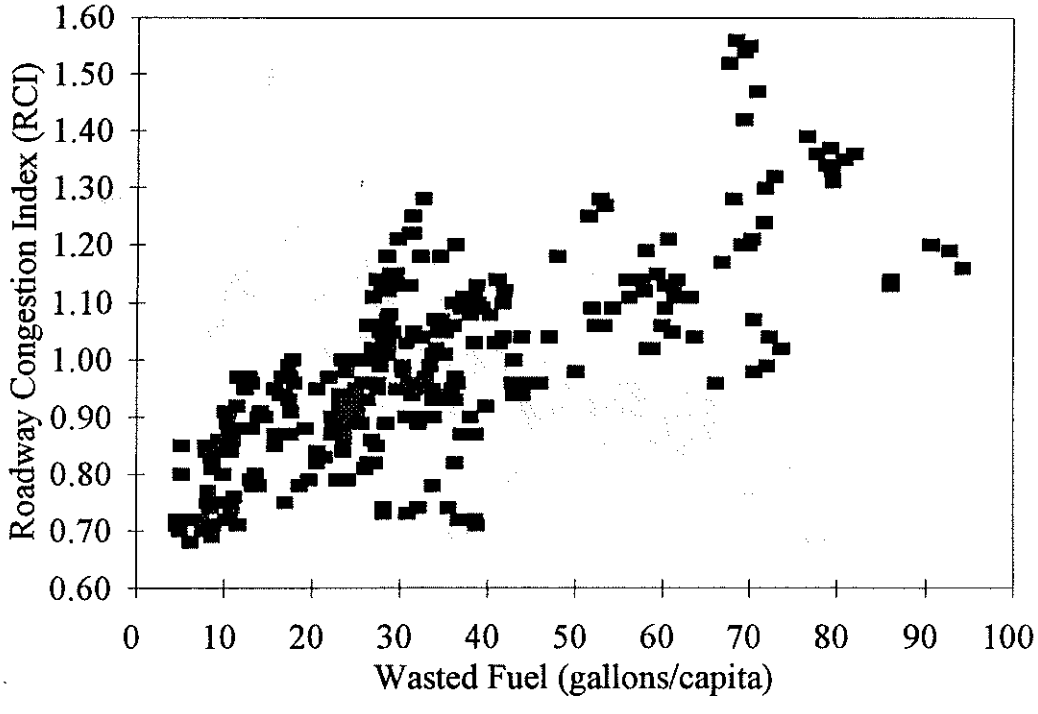


Figure 3-5. Excess Fuel Consumption (per capita) Versus Congestion Level, 1986 to 1991

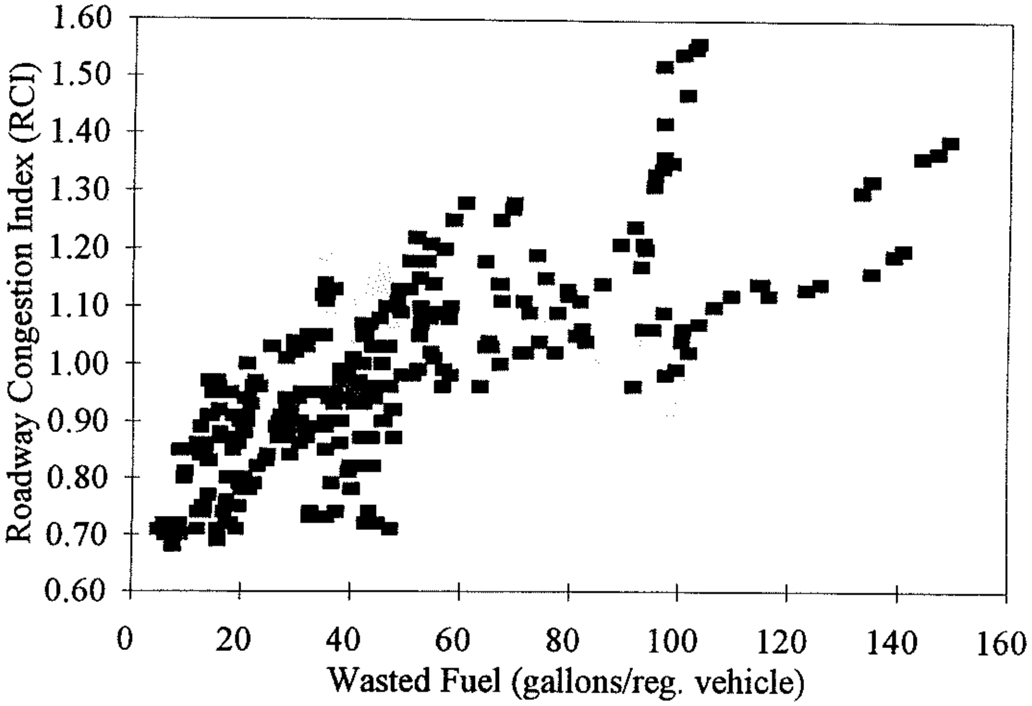


Figure 3-6. Excess Fuel Consumption (per vehicle) Versus Congestion Level, 1986 to 1991

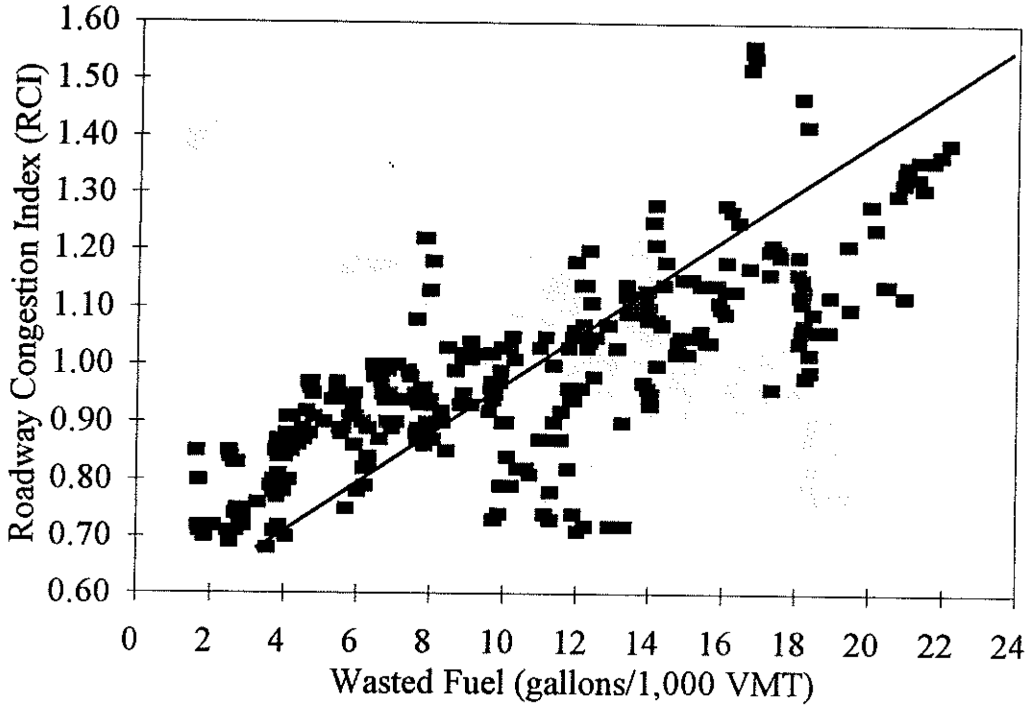


Figure 3-7. Best-Fit Line for the Relationship Between Wasted Fuel and Congestion Level

Conclusion

This chapter presented the roadway congestion index (RCI) as a measure of congestion level and, consequently, mobility level in urban areas. The usefulness of the RCI to track trends in mobility level and to make large-scale comparisons was illustrated. In general, the average mobility level is decreasing in urban areas, and decreasing more quickly in the largest urban areas (largest based on population). The average increase in congestion level for the fifty areas in this analysis was 17 percent between 1982 and 1991, while the increase for the ten most congested urban areas in 1991 had a range from 10 to 56 percent, and an average increase of 27 percent for the same time period. Three urban areas evaluated, Phoenix, Houston, and Detroit, all experienced a decrease in congestion over this time period.

This chapter also presented a methodology for estimating the excess fuel consumption of vehicles operating in congested travel conditions. The procedure used estimates of delay, average vehicle speed, and average fuel efficiency to calculate the gallons of wasted fuel in fifty urban areas in the United States. In 1991, the amount of fuel wasted in congestion totaled more than 4.6 billion gallons, equating to more than 51 gallons per vehicle, or 35 gallons per person. Wasted fuel correlated with congestion to some extent; five of the top ten most congested urban areas were also in the top ten with respect to the largest amount of wasted fuel. The most congested urban area, Los Angeles, was also the area had the largest amount of wasted fuel.

To further explore the relationship between excess fuel consumption and congestion level, the values of excess fuel consumption for each urban area were normalized by the amount of travel (VMT), the population size, and the number of vehicles in each urban area. The relationship between excess fuel consumption per 1,000 VMT and congestion level had the highest correlation ($r^2 = 0.58$), followed by excess fuel consumption per capita and congestion level ($r^2 = 0.55$), and excess fuel consumption per vehicle and congestion level ($r^2 = 0.51$).

A model was developed to estimate the gains in fuel efficiency for various levels of congestion. It was estimated that in 1995, the Houston urban area's potential savings, in terms of a reduction in wasted fuel due to reduced congestion, could be as high as 15 million gallons.

CHAPTER 4. ENERGY EFFICIENCY OF LOCAL BUS TRANSIT SERVICE IN TEXAS

Introduction

This chapter examines the relationship between the energy efficiency of local bus operations and urban area socioeconomic characteristics. A brief overview of the factors affecting the energy efficiency of local bus service is presented, and a detailed analysis of routes in four Texas cities is used to examine several possible predictors for local bus service energy efficiency. The analysis utilizes a sample of routes from each large transit system in Texas. The energy efficiency of various routes is determined and compared to various characteristics of the population along each route.

Energy Efficiency

Energy efficiency is an important consideration because the cost of energy is a fast-growing component of a transit agency's expenditures (29). Between 1960 and 1974, fuel consumption per bus hour and per bus mile increased as a result of three factors (30):

- Increased use of emissions control.
- Widespread use of air conditioning.
- Change from the use of six-cylinder bus engines to eight-cylinder bus engines.

The implementation of these changes has increased both patron comfort and the quality of bus emissions, but have increased fuel consumption. Although these changes decrease fuel economy, their use is common because of both the increased awareness of environmental concerns, and the need to make local bus service an attractive mode of travel.

With respect to the future of energy efficiency, it can be assumed that ongoing advances in engine and transmission design will be implemented to increase the fuel economy while achieving similar levels of power. While this will enhance transit fuel efficiency, the true key may lie in the hands of transit operators. Khan (31) defines efficiency as a relationship between resource input, such as fuel costs and labor, and the service output of the bus system. Energy efficiency, in the form of passengers carried per gallon of fuel, is a significant component of this, because it is an indicator of how well the system is being utilized. A large number of passengers carried per gallon of fuel would indicate an energy efficient system. He further states that there are many conservation measures which transit operators could implement to increase energy efficiency.

- Better matching of vehicle size with demand on a route-by-route basis.
- Improved routing and scheduling.
- Computerized scheduling techniques.
- Reduced deadhead miles.

- Improved vehicle maintenance.
- Reduced vehicle idling.
- Implementation of driver training programs.

The first three measures could reduce the in-vehicle travel time, an important factor to most travelers. A reduction in travel time could result in an increase in the number of passengers carried per gallon of fuel by attracting a larger number of home-based work trips during weekday peak periods. This assumes that people who normally drive an automobile to and from work would be diverted to transit. Boyle (32) agrees with this assumption, and adds that routing and scheduling improvements could result in a significant annual fuel savings.

Janarthanan, et al. (29) emphasize the importance of achieving energy efficiency criteria without sacrificing service quality. The authors state that some of the major obstacles to achieving higher energy efficiency are related to the existence of overlapping routes, routes which are too long, and a resultant excess of capacity. Solutions to these problems could include the evaluation of strategic transfer points, and the increase of maximum policy headways.

In a study by Stintz (33), the researcher determines that, on the basis of automobile occupancy of 1.6 passengers per vehicle, bus transit is only half as energy intensive (or twice as energy efficient) as automobile travel. However, the applicability of this finding is questionable, because the current automobile occupancy in Texas (and most other states) is about 1.2 passengers per vehicle. The author further states that any energy impacts caused by fare reductions and service improvements would be minimal for the following reasons:

- Transit accounts for only a small fraction of urban travel (2% according to the 1990 Nationwide Personal Transportation Study (34)).

- Any increase in ridership is not usually caused by a mode shift by automobile drivers, but rather a mode shift by automobile passengers and people who normally walk.

- Service expansion and lower headways only serve to decrease the number of passengers on the bus at any given time.

Other studies have suggested an optimum duty cycle for buses to reduce fuel requirements (35,36,37). One study determined that optimal bus stop spacings for urban/suburban service should be in the range of 500 to 1,000 feet. Another estimated a 23 percent increase in fuel efficiency as a result of a 50 percent reduction in stops. While this may be beneficial from a vehicle energy savings point of view, it is argued that these measures work against any measures intended to increase ridership.

Urban Transit Bus Operations Energy Efficiency

Statistics from the Federal Transit Administration were used to evaluate general levels of energy efficiency in bus operations in U.S. cities. The relationship illustrated in Figure 4-1 indicates that, on a daily passenger-mile per gallon basis, the largest systems are the most energy efficient, despite the fact that these systems have the lowest vehicle fuel efficiency in the range studied (Figure 4-2). This seems to indicate that there is some economy of scale related to larger systems, although the relationship could be due to demographic or other factors (such as population density) common to larger bus systems. Some of these factors are investigated in later sections of this chapter.

Local Bus Operations Data

This section discusses the data sources used in the analysis of local bus routes, summaries of the transit systems which the data represent, and a discussion of the limitations of the data used.

Data Sources

The seven transit systems in Texas urban areas with a population greater than 250,000 persons were initially selected for analysis. Because of limitations in the data collection practices of some agencies, sufficient data were available to analyze only four agencies.

- Fort Worth Transportation Authority, Fort Worth
- Capital Metropolitan Transit Authority, Austin
- VIA Metropolitan Transit Authority, San Antonio
- Metropolitan Transit Authority of Harris County, Houston

The data were supplied in the form of ride-checks. Ride-checks are a detailed list of the number of passengers boarding the bus and getting off the bus at all stops along a route. Normally these surveys are conducted on an annual basis. The ride-checks used for this report were collected in 1990. All socioeconomic and demographic information used in this report were obtained from the 1990 census tract data.

Transit System Information Summaries

A brief description of each of the four systems included in the analysis is presented in this section (38).

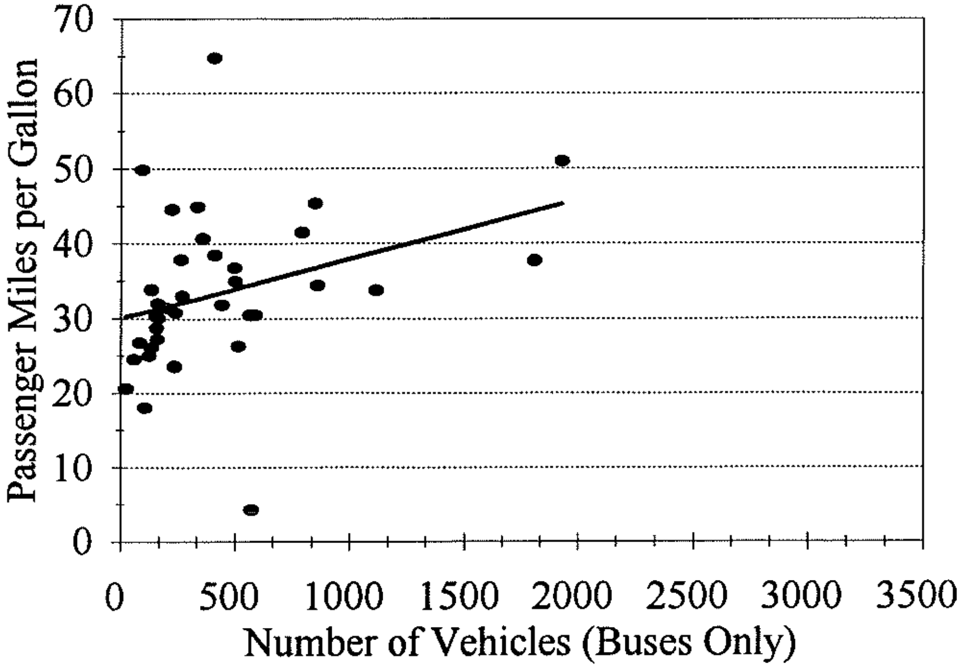


Figure 4-1. Energy Efficiency of Various Systems in the United States

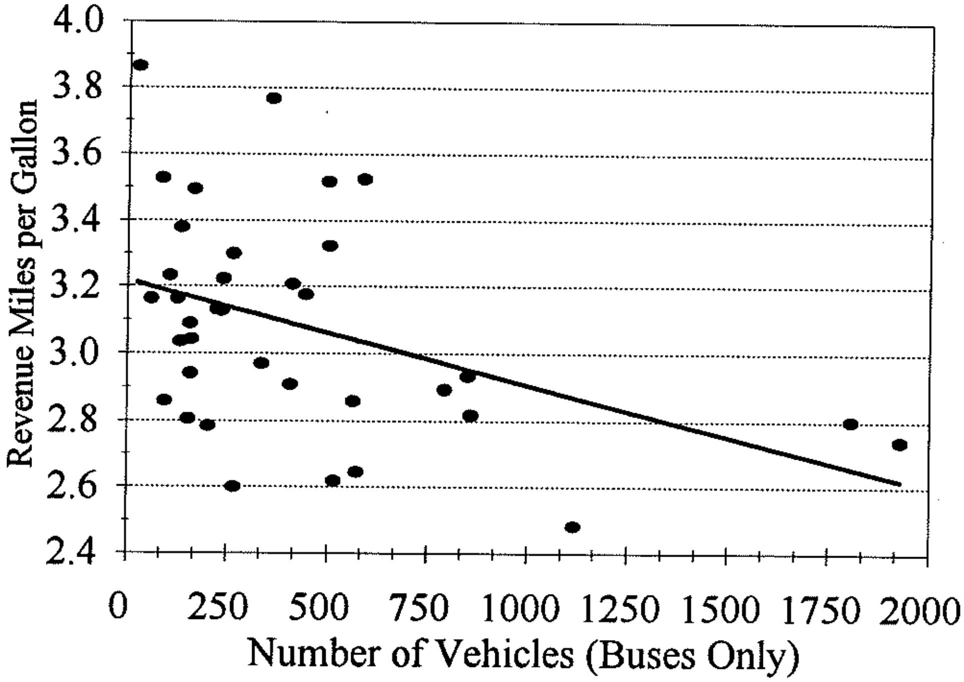


Figure 4-2. Average Energy Efficiency of Transit System Vehicles

Fort Worth

The Fort Worth Transportation Authority operates "The T." This is a relatively new system, formed in 1985 from the former Fort Worth city bus system. In the year beginning October 1990, this agency's total local service fleet consisted of almost 130 buses, and reported 5.6 million unlinked passenger trips.

Austin

The Capital Metropolitan Transit Authority, better known as "Capital Metro," was established in 1985 to serve Austin and seven of its suburbs. In 1989 and 1990, a free-fare experiment was conducted. To facilitate a more accurate comparison to the other systems, the data used in this report were collected after fares were reinstated. This system's fleet consists of over 325 active and purchased motor buses and served nearly 26.7 million unlinked passenger trips in the 1991 calendar year.

San Antonio

VIA Metropolitan Transit Authority or "VIA," is the regional transit authority for the Bexar County (San Antonio) area. Over 530 motor buses served 43.8 million unlinked passenger trips in the year beginning March 1990.

Houston

The Metropolitan Transit Authority of Harris County is better known to local residents as "Metro". The authority was established by referendum in 1978, when voters approved a one percent sales tax to assist in operating the agency. Local transit service is only one of Metro's responsibilities. Other activities Metro is involved in and has responsibility for include ridematching programs, park-and-ride lots and services, demand response services, and paratransit services. Approximately 900 40-foot buses are used to provide local service. In 1990, approximately 88 million unlinked passenger trips were served by Metro, making this agency the largest, with respect to passenger trips served, included in this analysis.

Problems with the Data

Ideally, this analysis would have included ride checks for each bus run throughout the day, for several days. The average for an entire day's worth of data could then be aggregated or analyzed by time of day. However, some agencies were only able to supply ride checks from a limited number of scheduled runs. In some cases, a time period was represented by only one run. Although not optimal, use of such limited data was acceptable under the assumption that the limited data does adequately represent the time period during which it occurred, to the extent that it provides a reasonable representation of the energy efficiency of all runs in that period.

Methodology

Energy efficiency, as it applies to any mode of transportation, is a measure of the mobility supplied by a specific amount of fuel. In English units, this mobility is expressed most effectively in passenger-miles. Passenger-miles are used to quantify the amount of person travel just as vehicle-miles traveled (VMT) quantify vehicle travel. For example, if eight persons in a single vehicle traveled a distance of two miles, 16 passenger-miles of travel were consumed.

The quantity of energy used to supply passenger-miles of travel may be expressed as either a measure of fuel volume or a unit of energy. The gallon has been used in this study. When expressed in terms of energy, the energy consumed is expressed in BTUs (British Thermal Units) in the English system. The measure of energy efficiency which is calculated from these units may be expressed in passenger-miles per gallon, or passenger-miles per BTU. In this study, energy efficiency is expressed in passenger-miles per gallon of diesel fuel, conversion factors may be used to transform this to express the energy content of other fuels, including alternative fuels such as liquid natural gas (LNG).

Local service bus routes were selected for analysis. The two quantities used to determine the energy efficiency for each route were the passenger-miles of travel, and the gallons of fuel which were consumed to supply this travel. While route-specific ridership data are generally available, and while many transit agencies maintain detailed records of some operating data, the quantity of fuel consumed was not available on a route-specific basis.

Because of the microscopic nature of this analysis, ridership information had to be as detailed as possible. Larger transit agencies collect ride-checks at least annually for some or all routes in their systems to analyze service. Agencies normally use this information to determine the effectiveness of different service elements, such as stop location, or even the route path. For this study, the ride checks were used to determine the number of passengers on board between the stops along the route.

Ride checks are normally collected on each scheduled run during the day. Since the number of runs made each day can range from five to seventy, analyzing each run separately would be tedious, time-consuming, and probably redundant. Instead, runs along the same route were compared and grouped by time period. The time periods chosen for analysis were morning peak, midday, afternoon peak, and off-peak, which includes all runs not made during the three "peak" periods. The groups were determined by combining consecutive runs which display similar ridership levels and headway spacings. Within these groups, the number of passengers on-board between stops are similar.

The number of passenger-miles of travel supplied along each route during each time period was calculated using the grouped ride checks. To accomplish this, the number of passengers on-board between stops was multiplied by the distance between the stops. Since these distances were measured from scaled maps, a block-by-block measurement would have been difficult. Instead, route segments in which the number of passengers did not deviate by more than three were considered homogeneous. These route segments were combined, the ridership was averaged, and the distance was measured from the first stop to the last stop in the group. The number of passenger-miles of travel was calculated as the product of the average number of passengers on the bus, according to the ride check, times the number of miles between the stops. After this was performed for the entire length of the route for each time period, the passenger-mile per bus mile statistic was calculated as the sum of the passenger-miles divided by the number of miles that the bus traveled while on the route. (The "bus mile" statistic does not include mileage accumulated while the bus is "deadheaded", that is, while not providing passenger service, such as when traveling to and from the bus garage during the day.)

To determine energy efficiency, the number of passenger-miles per bus-mile was multiplied by the fuel economy of the bus (in miles per gallon). The resulting value is expressed in passenger-miles per gallon. While most transit agencies maintain records of fuel economy for each specific type or brand of bus operated in the system, different combinations of these buses may be operated on a single route at different time periods. The type of bus to be used on a particular route, on a particular day, at a certain time of day, is determined by equipment schedulers on the basis of equipment availability, and average passenger load. It is not uncommon for the kind of bus on a particular route to vary from day to day or at different times of the day. However, if the fuel economy varies significantly between the buses used on a single route, the determination of one value for each route may not be possible. Therefore, a fleet average was used. The value in Texas is generally 3.5 miles-per-gallon for local bus routes, but varies slightly between systems for a number of reasons, including equipment manufacturer, equipment type, seating capacity, and the topography of the urban area.

To examine the relationship between the energy efficiency of local bus transit and ridership, trip length, and fuel consumption, ridership data were obtained for transit system routes and superimposed on areas of each city. Transit routes of both high and low ridership and routes through areas with different socioeconomic characteristics were analyzed to determine if any relationship exists between overall ridership levels and efficiency. The routes from each system chosen for analysis are listed in Table 4-1.

Analysis

The data provided by each agency were used to determine the number of passengers on board at each point along the route. Ultimately, a comparison of the energy efficiency in peak and off-peak periods was desired. However, each route's peak periods varied due to passenger characteristics and trip purpose. Upon examining the data, it was determined that no specific block of time could be designated as the peak period for all routes. However, general time-of-day variations in the ridership pattern of each route made it possible to distinguish peak and non-peak periods. Generally, the periods of time which exhibited the highest hourly ridership were designated as peak periods. These periods normally coincided with route headway reductions,which were employed by the agencies during the high-demand time periods. After

Table 4-1. Transit Routes Analyzed in Each Study City

System	Route Number and Name
The "T"	31 - Lancaster/Handley 33 - Polytechnic Heights/Edgewood 33 - Polytechnic Heights/Martin 36 - Evans/East Loop 36 - Evans/West Loop 59 - Wycliff 72 - Central/Samuels
Capital Metro	1 - Lamar 8 - Govalle 9 - Enfield 10 - South First 22 - Chicon
VIA	5 - McCullough 24 - East Houston 51 - Nogalitos 88 - Bandera
Houston Metro	2 - Bellaire-Dairy Ashford 2 - Bellaire-9400 Branch 2 - Bellaire-Fondren Southwest 35 - Leeland 65 - Bissonnet-Chimney Rock 65 - Bissonnet-Dairy Ashford

these periods were delineated, average stop-to-stop ridership was calculated for the morning peak, midday, evening peak, and off-peak periods.

The average fleet fuel consumption of the vehicles used in regular service was determined from fleet consumption information provided by the transit agencies. The values used in this report are shown in Table 4-2. The equipment used on each of these routes is the standard 40-foot transit bus.

The energy efficiency can be determined for a single time period on any route by incorporating the passenger and transit route data into Equation 4-1.

$$EE_{td} = \frac{\Sigma_i (P_s \ x \ L_s)_i}{L_r \ x \ (1/mpg)} \qquad \text{Eq. 4-1}$$

Table 4-2. Fuel Consumption Estimates

Transit Agency	Local Service Fleet Fuel Consumption (Miles per Gallon)
The Fort Worth "T"	3.63
Capital Metro	3.65
VIA	3.47
Harris County Metro	3.43

where:

EE_{td} = Energy efficiency for an individual time period.
P_s = Average number of passengers on board for the route segment.
L_r = Length of the route segment.
L_f = Total length of the route.
mpg = Bus fuel efficiency.
i = Number of segments on route.

The efficiency for the entire route, calculated based on Equation 4-2, was estimated with a weighted average of the individual time period efficiencies calculated in Equation 3-1.

$$EE_D = \frac{\Sigma_i (EE_{td} \ X \ B_p)_i}{B_t} \qquad \text{Eq. 4-2}$$

where:

EE_D = Daily energy efficiency.
EE_{td} = Energy efficiency by time-of-day calculated using Equation 3-1.
B_p = Number of bus runs which occurred during the time period.
B_t = Total number of bus runs on the route for the day.
i = Number of segments on route.

Results

The energy efficiency of the routes in each system are presented in Tables 4-3 through 4-6. The energy efficiencies are listed both for the four time periods, and as a daily average.

Data published by the Federal Transit Administration (FTA), includes the fleet energy efficiency for each of these systems. Capitol Metro has the lowest overall system wide average,

Table 4-3. Route Energy Efficiency for Selected Routes The T (Passenger-Miles per Gallon)

Route	Time Period				
	Morning Peak	Midday	Evening Peak	Off-Peak	Daily Average
Lancaster/Handley	37.6	27.5	43.0	29.3	34.0
Polytechnic/Edgewood	25.9	22.5	36.1	22.5	28.6
Polytechnic/Martin	28.2	12.3	26.2	12.3	19.6
Evans/East Loop	19.2	19.4	30.4	19.4	22.1
Evans/West Loop	24.5	14.3	13.7	14.3	16.0
Wycliff	35.3	11.6	15.9	10.6	19.1
Central/Samuels	12.6	12.4	19.9	12.3	13.4
AVERAGE	22.9	14.4	20.0	14.1	17.6

Table 4-4. Route Energy Efficiency for Selected Routes Capital Metro (Passenger-Miles per Gallon)

Route	Time Period				
	Morning Peak	Midday	Evening Peak	Off-Peak	Daily Average
Lamar	69.5	63.4	77.5	50.3	59.3
Govalle	61.4	56.5	75.5	39.3	45.2
Enfield	19.6	14.1	33.1	15.3	18.6
South First	34.6	41.6	45.5	28.6	33.8
Chicon	19.1	14.5	21.2	12.0	15.5
AVERAGE	33.7	31.7	43.8	23.8	28.3

with an energy efficiency of 18.9 passenger-miles per gallon, just below that of the "T", which is 19.0 passenger-miles/gallon. The average fleet energy efficiency for VIA is 30.4. Harris County Metro has the highest energy efficiency, 33.0 passenger-miles per gallon. The average overall values for the specific routes, shown in Tables 4-3 through 4-6, follow a similar order. The area wide averages tend to support these calculations, and the reliability of the samples used, by showing that the samples reflect the system wide patterns.

With the exception of VIA, each system's energy efficiency is higher in the morning and evening peak period than during non-peak periods. In VIA's case, the average efficiency is slightly higher in the midday period than in the morning peak period. The midday period displays a much higher level of efficiency than either the morning or evening peak periods.

Table 4-5. Route Energy Efficiency for Selected Routes
VIA (Passenger-Miles per Gallon)

Route	Time Period				
	Morning Peak	Midday	Evening Peak	Off-Peak	Daily Average
McCullough	32.3	32.6	52.4	30.5	35.8
East Houston	39.6	37.9	37.1	33.6	36.4
Nogalitos	37.1	59.5	38.4	46.8	47.8
Bandera	40.6	32.0	39.0	31.9	34.7
AVERAGE	37.4	40.5	41.7	35.7	38.7

Table 4-6. Route Energy Efficiency for Selected Routes
Houston Metro (Passenger-Miles per Gallon)

Route	Time Period				
	Morning Peak	Midday	Evening Peak	Off-Peak	Daily Average
Bissonnet/Chimney Rock	74.5	26.7	61.3	24.9	39.0
Bissonnet/Dairy Ashford	75.5	64.3	88.9	60.5	70.1
Leeland	68.9	17.3	38.1	18.0	28.4
Bellaire/Dairy Ashford	81.6	81.8	96.8	59.7	74.2
Bellaire/Fondren Southwest	77.6	75.8	100.3	66.4	73.5
Bellaire/9400 Branch	83.4	77.3	77.8	61.2	69.1
AVERAGE	74.1	46.0	72.1	42.5	52.8

Upon closer examination of Table 4-5, it appears that this may be due to the inclusion of the Nogalitos route. Results indicate that this route is utilized for more non-work trips or work trips occurring outside the traditional peak periods, than is the case for the other routes in this study.

Socioeconomic Analysis

There are a number of factors which may influence transit ridership. Perhaps the two most frequently cited are automobile ownership and population density. In addition, factors which are less quantitative in nature, such as public perception and service quality, may also have an effect. To determine if socioeconomic characteristics bear any relationship to energy efficiency levels, statistical analysis was performed considering a number of variables.

Data on each of the socioeconomic variables were obtained from the 1990 Census. Data were acquired at the tract level for all routes. Generally, it is assumed that the maximum distance a person is willing to walk to a bus stop is one-quarter of a mile. For this reason, each route was superimposed on a Census tract map, and all tracts falling within one-quarter mile of the route, on either side, were considered in the analysis of that route. The tract data were compiled for each route, and then averaged using population as a weighting factor. Regression analysis was performed as a means of relating overall route energy efficiency to the socioeconomic variables corresponding to the route. An explanation of the variable abbreviations is shown in Table 4-7.

A regression analysis was performed to investigate the level of significance each of these variables had on the daily energy efficiency of each route. A key indicator of significance in such an analysis is the value of the regression coefficient, R^2. The closer the value of R^2 is to 1.0, the higher the likelihood that the variance in each of the variables is related. In other words, an R^2 value of 1.0 would indicate that changes in the level of a dependent variable are directly affected by changes in the level of the independent variable. The values of R^2 are shown in Table 4-8. The F statistic, also shown in Table 4-8, is the ratio of explained variation to unexplained variation, divided by the respective degrees of freedom. Larger values of F provide evidence of a relationship between the variable and energy efficiency. All variables, except median income, exhibit a regression coefficient greater than 0.5, indicating a significant relationship.

The energy efficiency values determined in this study range from 12.0 passenger-miles per gallon during the off-peak period to 100 passenger-miles per gallon during the peak period. Currently, the average peak-period occupancy of an automobile is approximately 1.2 passengers per vehicle; if the average auto fuel efficiency in urban operation is 25 miles per gallon, the average peak-period energy efficiency of an automobile is 30 passenger-miles per gallon. This surpasses off-peak transit efficiency, but is much lower than the energy efficiency of buses during peak periods.

As shown in Tables 4-3 through 4-6, some routes fall below 30 passenger-miles per gallon, especially those in Fort Worth. However, the majority of routes do achieve greater efficiency, which seems to indicate that bus transit is relatively efficient, especially during peak-periods. Services other than traditional bus service might be more efficient during off-peak periods, when ridership levels are known to be low. Other forms of off-peak transit that could be provided include taxi or demand-responsive service. While these may be more energy efficient, it is beyond the scope of this report to determine the cost effectiveness of such alternatives. It also must be recognized that some transit service is provided for reasons other than fuel efficiency. Much of the local route transit service provides mobility for urban residents who do not have access to private transportation.

Table 4-7. Socioeconomic Variables

· Autozero, one, two, threeplus	The number of all households having zero, one, two, or three or more automobiles available.
· Density	The weighted population density along the route. This was determined by dividing population of the tract areas.
· Income	The median family income, averaged using population as a weighting factor.
· PCTCBD	The number of workers who work in the central business district. Since all but one route analyzed was radial to the CBD, this could be an indicator of the efficiency attained from work trips.
· Travtime	Travel time to work, as reported in the journey to work data.

Table 4-8. R^2 and F- Values for Comparisons with Energy Efficiency

Variable	R^2	F-Value
Autozero	0.62	30.48
Autoone	0.68	40.92
Autotwo	0.67	38.26
Autothreeplus	0.68	38.11
Density	0.62	31.60
Income	0.02	0.32
PCTCBD	0.69	42.82
Travtime	0.53	21.55

Conclusion

This analysis of the energy efficiency of local bus service indicated that socioeconomic characteristics do correlate with local bus energy efficiency. The analysis also indicated that peak-period operations are typically associated with higher transit energy efficiency than off-peak period operations.

There also appeared to be a general trend of increasing passenger travel energy efficiency with larger fleet sizes in the four Texas cities examined. This may be due to the fact that urban areas that have greater demand for transit are more likely to have larger fleets, and are more likely to have higher energy efficiency due to the increased corridor demand.

The number of autos in the household, the population density, the number of workers in the central business district, and the travel time to work all correlated with the energy efficiency of local bus service. Income was the only factor studied that did not correlate with energy efficiency. Having stated these findings, it is important to note that the results of the statistical analysis should be cautiously considered due to the limited data upon which it was based.

CHAPTER 5. ENERGY EFFICIENCY OF PARK-AND-RIDE SERVICE

Introduction

Various local, county, and state government agencies have encouraged park-and-ride transit service in an effort to reduce traffic congestion, reduce the demand for parking in downtown areas and major activity centers, conserve energy, and improve mobility. Park-and-ride service uses existing parking lots at schools, churches, and shopping centers, as well as lots built specifically for park-and-ride, to serve as places for express bus patrons to board buses. The lots provide a more concentrated point of demand for transit service, than does the low density residential areas that usually surround them.

Park-and-ride services were implemented in many areas, including Texas, in response to higher fuel prices and limited availability of fuel supplies in the 1970s. Park-and-ride service continues to play an important role in the transit systems of the larger Texas cities. This chapter includes an overview of park-and-ride, its usefulness, energy efficiency, and use in conjunction with high-occupancy vehicle (HOV) lanes.

The objectives of this analysis were to calculate the energy efficiency of park-and-ride bus service in large Texas cities, and compare these energy efficiency values to the socioeconomic characteristics associated with each route to determine possible correlation between demographics and energy efficiency. In addition to these two objectives, other elements of park-and-ride service are addressed, with special attention to their use as support facilities for the HOV lanes in Houston.

The average energy efficiency of the average automobile on the freeway is about 30 passenger- miles per gallon. This is based on an economy rating of 25 miles per gallon and an occupancy rate of 1.2 persons per automobile. A park-and-ride bus that carries 20 passengers will achieve an energy efficiency of about 80 passenger-miles per gallon using the observed express bus fuel economy value of 4 miles per gallon, which approximates the average for Texas park-and-ride service. These energy efficiency values demonstrate the potential benefits of park-and-ride as a means of moving persons to work.

This chapter describes an investigation into the relationship between the socioeconomic characteristics of park-and-ride lots and the ridership levels and energy efficiency of park-and-ride routes. For example, park-and-ride lots located in market areas with higher population density may be expected to have increased ridership because there is an increased opportunity to entice riders onto express bus service, because there are more persons living within a reasonable driving/walking distance of the lot. People who work in the central business district (CBD) may be more likely to use park-and-ride lots because the predominant service is radial routes to the CBD, and because parking costs are often higher in the CBD. The longer the travel time to work, and the higher cost to use the private auto, the more likely commuters will use a park-and-ride express bus.

Description of Park-and-Ride Lot Development

Several factors must be reviewed to understand the use and purpose of park-and-ride service. The primary goal of park-and-ride lots is to entice automobile commuters to use express buses, which will reduce roadway travel and traffic congestion, as well as the need for parking at the downtown activity center. Energy conservation became an additional objective during the oil embargo and energy crisis in the mid- and late-1970s, as did the reduction of vehicle emissions following the promulgation of the 1990 Clean Air Act Amendments.

Parking in the CBD is often limited, expensive, and difficult to find, due to the high density development and consequent high cost of land. Thus, a goal of many park-and-ride lots is to reduce the need for the construction of additional parking facilities in the CBD and other high density areas, allowing land in the CBD to be used for uses other than parking.

Park-and-ride lots also reduce the need for the construction of transportation improvements which would otherwise be needed due to an increase in demand. Commuters who leave their autos at outlying park-and-ride lots do not need to be accommodated on freeways and arterial streets near activity centers.

Park-and-Ride Lot Location

The placement of park-and-ride lots depends on several factors. First, the lots should be located to allow commuters to arrive by car, by bike or by foot, park or be dropped off, and change modes. In addition, the site should be placed along a corridor so that it intercepts the traffic before roadway congestion begins. The park-and-ride lot should be situated at the narrow end of a parabolic-shaped market area along the corridor, as shown in Figure 5-1.

Finding a parcel of affordable land near areas of high population is another key factor affecting the location of the lots. Because land costs usually decrease with increasing distance from the CBD, the location of the lot is usually along a freeway corridor between a suburban area and the CBD.

Park-and-ride lots are generally classified into three categories, each providing a different service:

- **Park-and-ride** services utilize express buses from the park-and-ride lot to the activity center. Park-and-ride can use existing parking lots in shopping centers, schools, and churches, as well as lots constructed specifically for park-and-ride. These lots sometimes serve as meeting places for carpoolers in addition to serving as boarding areas for express buses to the CBD or other activity center.

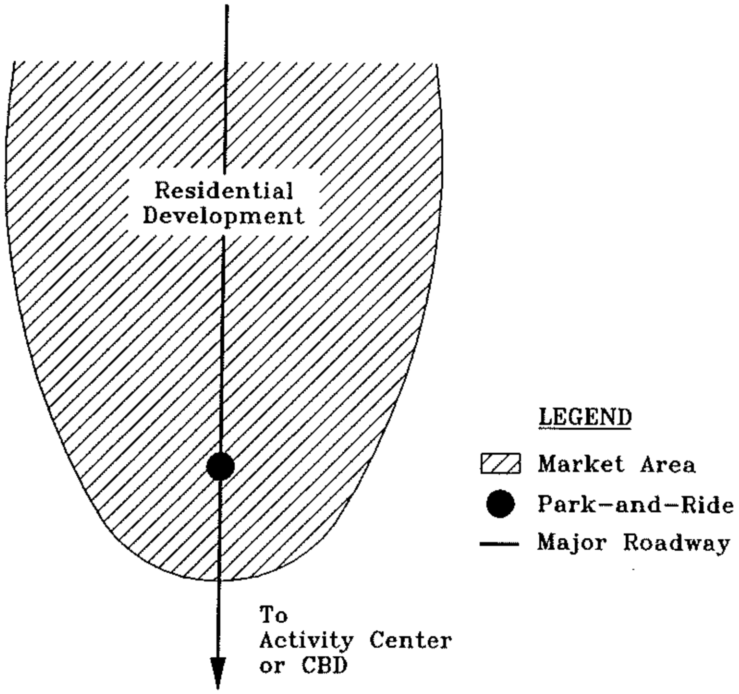


Figure 5-1. Market Area of Park-and-Ride Lot

- **Park-and-go** lots are additional stops along local bus routes. The parking facilities used to support park-and-go lots are relatively small compared to park-and-ride lots, and are often located on private property furnished by neighborhood churches, shopping centers, or other businesses.

- **Park-and-pool** lots provide a location for carpoolers to meet; no transit service is provided to these lots. These lots are used when some interest in ridesharing exists in an area but there is not sufficient justification to provide park-and-ride or park and go service to the area. Park-and-pool lots may also be provided within a corridor that has park-and-ride transit service.

Incentives For Park-and-Ride Use

Surveys of park-and-ride lot users indicate that commuters perceive park-and-ride service as an economic benefit and a convenient method of transportation. More than 80 percent of park-and-ride users have access to a private vehicle for the trip, indicating a predominance of choice riders (39). These park-and-ride users benefit from cost savings through reduced parking costs, reduced vehicle wear, and time savings when park-and-ride is associated with HOV lanes. One other major benefit is the reduced stress that results from relinquishing the driving responsibilities, the park-and-ride user can relax going to and from work.

With respect to time savings, on average, park-and-ride users experience a travel time savings of approximately 5 to 10 minutes during each peak period commute when the trip involves a high-occupancy vehicle lane (39). However, some of this time savings may be lost in getting to the park-and-ride lot, waiting for the bus to depart, or waiting for the appropriate stop in the CBD. But obviously, the overall benefits, including the time savings, the monetary benefits (due to fuel savings, parking costs, automobile wear) and the intangible benefits related to not driving a personal vehicle in congested traffic must offset any inconveniences for commuters who use park-and-ride.

By increasing the travel time savings, HOV can significantly increase bus ridership. Approximately 37 percent of park-and-ride bus patrons in Houston in 1990 reported driving alone before the opening of the HOV lane, while 9 percent had used carpools or vanpools. Almost 40 percent of the park-and-ride bus riders reported that they would not have begun using the park-and-ride service without the HOV lane and 93 percent stated that the HOV lane was at least somewhat important in their decision to use the park-and-ride service (39).

Methodology

One of the objectives of this study was to determine the energy efficiency of park-and-ride facilities in Dallas, Houston, and San Antonio. A procedure which incorporated factors such as ridership, route distance, scheduled bus trips and miles per gallon was developed to calculate the average efficiency. Once this was completed the efficiencies were compared to socioeconomic characteristics to determine if there was a relationship between demographics and energy efficiency.

Energy Efficiency

The energy efficiency of park-and-ride buses was calculated for Dallas, Houston, and San Antonio. An average energy efficiency was computed for the park-and-ride operations in each city. The averages for each city are not comparable, however, since the park-and-ride service of each system is unique. For example, in Dallas, express service is combined with local service on some routes. These routes use arterial streets for collection and distribution before stopping at park-and-ride lots on their way to the downtown area. While in Houston, some of the park-and-ride service utilizes the high-occupancy vehicle lanes on the freeways to reduce travel times. In San Antonio, the service from park-and-ride lots consists of buses that utilize the freeway mainlanes. Summarizing the findings or directly comparing the results across all three cities would not be appropriate due to these service differences.

The calculation shown in Equation 5-1 was used to calculated the energy efficiency. This calculation was based on morning ridership data provided by Dallas Area Rapid Transit (DART), Houston Metro, and VIA Metropolitan Transit in San Antonio. The route miles were computed using transit maps from the three cities. In Houston and San Antonio, this estimate was based on the distance from the park-and-ride lot to downtown via the arterial streets and freeways. In Dallas, the estimate was based on the distance from the beginning of the local service route, through the park-and-ride lot, to downtown. The local transit agencies provided transit schedules on which to base the number of bus trips, and the fuel consumption rate of their buses.

$$\begin{array}{c} \textit{Energy Efficiency} \\ (\textit{Passenger miles} \\ \textit{per gallon}) \end{array} = \frac{\textit{Passenger miles traveled}}{\textit{Gallons consumed}} = \frac{(\textit{passengers} \,/\, 2) \times (\textit{route miles to CBD})}{(\textit{route miles} \times 2) \times (\textit{bus trips}) / (\textit{bus miles per gallon})} \qquad \text{Eq. 5-1}$$

Two variables must be calculated to determine the bus service energy efficiency indicator (per gallon):

- **Passenger-miles traveled** - The average weekday ridership was divided in half to give the morning peak-period ridership. This number was multiplied by the route miles to the CBD to obtain a value for traveled in one peak period.

- **Gallons Consumed** - The number of route-miles was multiplied by two to obtain an estimate of the round trip mileage. While every bus may not make a round trip to the park-and-ride lot, this procedure approximates the fuel consumption of the park-and-ride bus fleet. The bus service miles were multiplied by the number of bus trips to obtain the total mileage driven. Other "deadhead" mileage, which might include the travel between the garage and the park-and-ride lot, is not specifically included for the purposes of this calculation although some of this distance is included as a result of the round trip mileage. The total mileage driven was divided by the bus fuel efficiency, which yielded the number of gallons consumed.

Census Data

The census data for each park-and-ride lot market area in Dallas, Houston, and San Antonio is displayed in Tables 5-1 through 5-3. These tables include all socioeconomic values extracted from the 1990 Census data. The socioeconomic values shown in Tables 5-1 through 5-3 have not been adjusted to conform to the parabolic shape of each market area, as discussed in the previous section. The data presented here contain the values for each Census tract within he market area, regardless of how much of the tract was inside the parabolic area. Because these are unadjusted values, they exceed the values used in the regression analysis.

Table 5-1. Houston Socioeconomic Characteristics by Park-and-Ride Route Market Area

Route Number	Population	Population >16 yrs	Education Level High Sch	Education Level College	Travel Time	Place of Work In CBD	Place of Work Out of CBD
201	19978	13272	3023	931	30.96	2849	3669
202	30976	22709	5144	5109	31.26	1849	8600
204	54611	36864	9642	8896	32.36	2748	13011
205	35840	24175	5775	5475	36.31	1585	6691
206	30978	21869	6223	3655	30.17	911	6809
210	96454	71931	11618	25528	28.73	5166	36201
212	65863	44307	9165	15101	35.58	3302	14692
214	22486	15074	4175	3366	34.06	683	6377
216	24813	17099	4239	4654	32.23	822	8191
218	67810	50808	10492	7340	26.82	2695	26294
221	25594	11872	3953	4730	31.82	857	6410
228	31619	20714	5027	6172	35.60	1171	9787
236	45592	32581	9272	2506	24.34	1149	12473
245	110605	76518	18184	13101	27.96	6068	31911
246	34228	25414	4924	8222	23.08	460	8897
259	85660	69766	13323	16313	24.80	3547	39295
261	55396	42773	8477	12591	26.17	2903	22390
262	95504	71507	14048	19292	27.54	3503	34603
263	55229	41070	8806	9804	27.56	2355	22858
270	52468	34213	7385	9501	30.60	1380	15691

Route Number	Autos per Household 0	1	2	3+	Drive Alone	Carpool
201	567	1315	1821	992	5861	2032
202	216	4079	4514	2479	11978	3738
204	269	3471	8344	4856	19212	6023
205	183	2213	5197	3236	10556	4034
206	252	2637	3669	2208	11046	3749
210	475	10421	15669	6382	35473	9078
212	155	3516	11067	5131	21746	7158
214	56	1090	3328	2330	8149	2740
216	99	1581	4261	2011	9594	2485
218	419	7364	8653	4686	24449	6566
221	54	1410	4392	2042	8927	2942
228	54	1541	5698	2458	11302	4048
236	609	4613	4901	3347	16627	5520
245	360	5373	11084	6992	35584	11099
246	187	4974	5629	2409	13719	4503
259	1666	17437	12250	4800	35787	10125
261	762	7456	8973	4009	25756	7042
262	417	7254	9732	3998	38930	11589
263	326	10522	8786	3274	23764	7591
270	211	1128	2363	1190	18360	6401

Table 5-1. Houston Socioeconomic Characteristics (Continued)

Route Number	Public Transp.	Square Mileage	Population Density	Population Dens 16+ yrs	Median Income	Ridership
201	266	4.74	4214.77	2800.00	17692.52	1074
202	380	44.31	699.07	512.50	27221.48	3301
204	538	79.48	687.10	463.81	30511.67	1606
205	426	104.22	343.89	231.96	30608.48	1491
206	305	89.85	344.77	243.39	24181.02	880
210	697	37.53	2570.05	1916.63	33244.06	370
212	846	51.20	1286.39	865.37	34939.63	1706
214	42	98.82	227.55	152.54	30439.73	1506
216	26	47.28	524.81	361.65	29761.20	266
218	217	21.28	3186.56	2387.59	25123.72	309
221	55	184.66	138.60	64.29	28641.16	657
228	78	116.82	270.66	177.32	30497.46	2283
236	172	17.10	2666.20	1921.11	23615.64	254
245	322	82.17	1346.05	931.22	33591.73	1365
246	43	21.53	1589.78	1180.40	25841.32	1324
259	1560	12.25	6992.65	5695.18	22038.07	259
261	836	14.70	3768.44	2909.73	26514.87	879
262	1013	108.80	877.79	657.23	25560.52	1244
263	895	12.53	4407.74	3277.73	21625.80	706
270	116	55.17	951.02	620.14	29323.38	537

Table 5-2. Dallas Socioeconomic Characteristics by Park-and-Ride Route Market Area

Route Number	Population	Population >16 yrs	Education Level		Travel Time	Place of Work	
			High Sch	College		In CBD	Out of CBD
73	88058	64407	10896	23632	23.14	3451	24363
77	129597	104915	19331	33683	21.82	7667	45410
78	63840	45660	13653	8589	23.37	3336	21115
80	53699	38220	10140	1145	48.15	2075	14636
81	116938	81772	22377	12976	24.18	3161	21210
82	129982	101898	18847	29818	22.15	7869	41782
83	59312	48454	8148	17433	20.98	2989	20205
85	53376	40210	10383	6304	19.28	1087	14142
200	73742	48449	9609	16903	27.42	1692	12345
201	55707	38747	7871	12821	24.19	1684	10665
202	36910	26906	8173	5848	21.30	1160	8263
203	85087	63325	17869	7494	19.59	1773	18705
204	89493	65074	17047	12493	21.12	1927	19354
205	62848	51888	10023	15650	19.68	2853	23483
206	29334	21265	5844	2185	26.78	1171	5284
207	17046	11597	3332	2069	26.75	647	3437
208	6194	4610	1166	754	23.42	139	1107

Table 5-2. Dallas Socioeconomic Characteristics (Continued)

Route Number	Autos per Household				Drive Alone	Carpool
	0	1	2	3+		
73	519	8006	14247	7634	36678	6373
77	1448	27084	22589	9838	64541	11683
78	564	6216	10151	6713	26972	8051
80	1114	5898	6329	5216	16646	6746
81	872	9956	16853	10774	44211	12637
82	1185	23577	22229	9607	60549	12215
83	552	10837	11281	4924	29759	4725
85	469	6393	7873	4852	23295	4924
200	141	3758	12223	5350	27806	6274
201	326	3644	9038	4758	21599	4469
202	290	4217	6445	4407	18221	4550
203	982	10781	12645	7991	36417	8779
204	474	7781	13824	8702	37741	8595
205	767	11646	10964	5601	32054	5565
206	339	2008	7119	3403	9685	3351
207	31	1088	2467	1846	6584	1819
208	45	448	962	750	2501	656

Route Number	Public Transp.	Square Mileage	Population Density	Population Dens 16+ yrs	Median Income	Ridership
73	930	35.89	2453.55	1794.57	33170.31	1355
77	2780	37.08	3495.06	2829.42	23228.31	1011
78	938	58.00	1100.69	787.24	23630.48	1227
80	747	39.07	1374.43	978.24	16373.47	229
81	952	80.60	1450.84	1014.54	22788.79	2250
82	3047	35.48	3663.53	2871.98	22420.24	2199
83	507	47.13	1258.48	1028.09	32549.74	2044
85	226	42.95	1242.75	936.20	22707.42	1346
200	242	72.06	1023.34	672.34	31234.24	1708
201	412	25.62	2174.36	1512.37	29770.69	982
202	59	119.37	309.21	225.40	23712.09	1135
203	137	33.09	2571.38	1913.72	19855.60	757
204	160	114.64	780.64	567.64	25376.71	1485
205	463	35.77	1757.00	1450.60	28212.78	579
206	78	271.48	108.05	78.33	21538.16	337
207	106	37.00	460.70	313.43	24747.29	213
208	7	75.93	81.58	60.71	36073.70	121

Table 5-3. San Antonio Socioeconomic Characteristics by Park-and-Ride Route Market Area

Route Number	Population	Population >16 yrs	Education Level High Sch	Education Level College	Travel Time	Place of Work In CBD	Place of Work Out of CBD
17	146589	103931	29172	18152	19.2	3814	39935
38	43746	31723	8265	1412	20.3	1843	12652
48	27442	16960	3644	358	23.7	889	6514
64	79699	57139	13295	3920	18.6	1502	27791
93	96049	73863	16062	20230	19.4	3963	35863

Route Number	Autos per Household 0	1	2	3+	Drive Alone	Carpool
17	917	14084	23894	11928	49789	13434
38	1287	5417	4888	2851	12208	3731
48	373	2304	2560	1648	6329	2304
64	763	6887	7289	4549	21133	6885
93	877	12458	15402	7923	36920	8161

Route Number	Public Transp.	Square Mileage	Population Density	Population Dens 16+ yrs	Median Income	Ridership
17	937	121.72	1204.31	853.85	21222.64	831
38	735	52.98	825.71	598.77	13652.18	259
48	299	56.92	482.12	297.96	13737.77	259
64	904	172.24	462.72	331.74	15562.96	836
93	795	164.60	583.53	448.74	23006.41	1266

Ridership and Socioeconomic Data

Several different data sources were used to compile the socioeconomic data for the regression analysis with energy efficiency. Census tract maps, Census data, and transit maps were used to obtain the necessary socioeconomic information for each park-and-ride lot market area. Several steps were used to identify the market area for the individual park-and-ride lots.

- **The park-and-ride routes were drawn on Census tract maps.** The routes taken by the express buses and the location of their corresponding park-and-ride lots were overlaid on Census tract maps to develop a definition of the market areas. The lots in Houston and San Antonio are typically located at the outer end of the bus route. As mentioned previously, many of the park-and-ride routes in Dallas have some local service included on the route. The local service stops by the lot on its way to the CBD. With this mixed service, the park-and-ride lot is usually not located at the outer end of the route.

- **A parabola, as shown in Figure 5-1, was placed along the routes which defined the market areas.** The "commutershed," or market area, of a park-and-ride lot is generally parabolic in shape. The end of the parabola was placed so that the lot was less than a mile from the edge of the parabola. Very few commuters will backtrack to utilize a park-and-ride lot (40). This suggests that the lot must be between residential development and an activity center to intercept inbound traffic.

  The shape of the market area of the Dallas lots depended on the route driven by the buses in their local service. The shape of the market area was generally a corridor with approximately 5 miles on each side of the route. The ridership information obtained from the transit service did not specify whether a rider was a local or express patron. Since no distinction could be made, the entire route ridership was considered to be park-and-ride.

- **The Census data for the park-and-ride lot market areas were compiled.** Socioeconomic data from the 1990 Census (shown in Tables 5-1 through 5-3) were used because they provided the most complete and recent detailed Census information. These data included population, education level, travel time to work, place of business, mode of transportation to work, and average income. The data in Tables 5-1 through 5-3 display the actual census data values for each market area. These data were grouped with park-and-ride lot ridership information. Regression analysis was performed on the data to determine if any correlation existed between the socioeconomic variables, energy efficiency, and park-and-ride lot use.

Results

The variety of operating conditions in the three areas made it difficult to develop consistent comparisons between cities. The energy efficiency also varied significantly between bus routes within each city.

The energy efficiency values were calculated using the number of park-and-ride buses operating on each route before 9:30 a.m. The buses operating after 9:30 a.m. were ignored because the midday service was provided for only a few trips from most of the larger park-and-ride lots in each of the cities and because ridership on these buses was very low, never more than a few persons. Furthermore, provision of these buses is not typically consistent with energy efficiency concerns. These routes are operated to provide midday access to the park-and-ride lot and are, therefore, meeting the social service objectives of public transportation rather than the mass transportation or energy efficiency-related objectives of transit.

The average energy efficiency of the park-and-ride buses in the three cities varied a great deal. The calculation of average energy efficiency involved the use of bus-miles as a weighting factor since mileage along the route determined how much fuel was consumed. The variance between cities could be explained by different factors affecting the service in each city.

The Dallas energy efficiency was based on a fuel consumption rate of 4.2 miles per gallon reported by DART for buses providing park-and-ride service (DART). Two types of buses are used to serve Houston park-and-ride lots; the intercity-type bus achieved 4.5 miles per gallon, and a few articulated buses used on one route achieved 3.2 miles per gallon (METRO). The park-and-ride system average fuel mileage was 4.3 miles per gallon. The San Antonio energy efficiency value was based on a fuel mileage rate of 4.2 miles per gallon (VIA). The Houston buses, which use the HOV facilities, may achieve a higher fuel mileage due to the non-stop, relatively constant high-speed trips. San Antonio buses, however, use the freeway mainlanes and are subject to the congested traffic flow which reduces the bus fuel mileage.

Dallas Park-and-Ride Route Energy Efficiency

The energy efficiency of the Dallas park-and-ride routes encompassed a wide range of values, as shown in Table 5-4. The lowest efficiency in the system occurred on the Pleasant Grove Express route with an efficiency of 27 passenger-miles per gallon. This low value was attributable to very low ridership on the route. The highest efficiency occurred on the Prestonwood Express route with an efficiency of 195 passenger-miles per gallon. The weighted average efficiency of the three true park-and-ride routes was 76 passenger-miles per gallon, whereas the 14 express routes with local service averaged 72 passenger-miles per gallon. The overall Dallas system average was 73 passenger-miles per gallon. The small number of true park-and-ride lots make it difficult to draw any conclusions regarding this difference.

Houston Park-and-Ride Energy Efficiency

The range of the energy efficiencies for the Houston park-and-ride routes, shown in Table 5-5, indicates a much more uniform distribution than the Dallas data. The lowest efficiency in the system occurred on the West Little York route with an efficiency of 43 passenger-miles per gallon. The highest efficiency occurred on the Addicks route with an efficiency of 71 passenger-miles per gallon. The average efficiency for routes which utilized the HOV lanes was 65 passenger-miles per gallon, while those which did not use HOV lanes averaged 58 passenger-miles per gallon. The average for all of the Houston park-and-ride routes was 63 passenger-miles per gallon.

Some of the difference between HOV and non-HOV efficiency may be explained by the fact that most of the suburban routes with high riderships use the HOV lanes while some of the routes closer to downtown do not use the HOV lanes. Most of the lots closer to downtown also

Table 5-4. Dallas Park-and-Ride Energy Efficiency

Route	Route #	Miles[1]	Trips[2]	Ridership[3]	Rank[4]	Psgr-Mi/Gal[5]	Rank[6]
Prestonwood Exp	83	29	11	2,044	3	195	1
Shady Trail Exp	85	47	7	912	11	137	2
Plano Exp*	200	40	15	1,708	4	120	3
Richland Exp	82	24	24	2,199	2	96	4
Spring Creek Exp	73	31	15	1,355	6	95	5
N. Central Exp	77	29	12	1,011	9	89	6
N. Irving Exp	202	42	16	1,135	8	75	7
Glenn Heights Exp	206	38	5	337	14	71	8
Add-Farm Branch Exp	205	34	10	579	13	61	9
Red Bird Exp	78	35	22	1,227	7	59	10
Garland Exp	81	34	44	2,250	1	54	11
S. Irving Exp*	203	22	15	757	12	53	12
Richardson Exp*	201	28	22	982	10	47	13
Carroll-Farm Branch Exp	204	36	34	1,485	5	46	14
Rowlett Exp	207	21	5	213	16	45	15
Valley Ranch Exp	208	36	4	121	17	32	16
Pleasant Grove Exp	80	19	9	229	15	27	17
Average[7]	NA[8]	32	16	1,091	NA	73	NA

* Denotes route with no local service

[1] One-way route-miles

[2] Morning peak period (6:00-9:30 a.m.) bus trips

[3] Daily passengers carried

[4] Rank of daily passengers carried

[5] Passenger-miles per gallon is indicator of energy efficiency

[6] Rank of passenger-miles per gallon

[7] Weighted by bus-miles

[8] NA = not applicable

had a less direct route to a freeway than some of the outer routes, which begin at or very near the freeway.

San Antonio Park-and-Ride Energy Efficiency

The energy efficiency of the San Antonio park-and-ride routes, shown in Table 5-6, is similar to that of the Houston system. The lowest efficiency occurred on the South Park Express

Table 5-5. Houston Park-and-Ride Energy Efficiency

Route	Corridor	Route #	Miles[1]	Trips[2]	Ridership[3]	Rank[4]	Psgr-Mi/Gal[5]	Rank[6]
Addicks*	I-10W	228	19	36	2,283	2	71	1
Seton Lake*	I-45N	212	17	28	1,706	3	69	2
Kuykendahl*	I-45N	202	16	39	3,301	1	68	3
Edgebrook*	I-45S	245	12	23	1,365	7	67	4
Spring*	I-45N	204	20	28	1,606	4	65	5
NW Station*	US 290	214	20	26	1,506	5	65	6
Bay Area*	I-45S	246	23	24	1,324	8	62	7
Eastex	I-59N	206	14	16	880	11	62	7
Alief	I-59S	263	16	13	706	13	61	9
Kingwood	I-59N	205	27	29	1,491	6	58	10
N. Shepherd*	I-45N	201	9	21	1,074	10	58	10
West Loop	I-610/59	261	10	17	879	12	58	10
Westwood	I-59S	262	14	24	1,244	9	58	10
Kingsland*	I-10W	221	29	13	657	14	57	14
Maxey Road	I-10E	236	11	5	254	20	57	14
Missouri City	I-59S	270	14	11	537	15	55	16
West Belt	I-10W	210	14	8	370	16	52	17
Pinemont*	I-290N	218	11	7	309	17	50	18
Southwest Freeway	I-59S	259	11	6	259	19	49	19
W. Little York*	I-290N	216	16	7	266	18	43	20
Average[7]	NA[8]	NA	16	19	1,101	NA	63	NA

* Denotes routes which use an HOV lane
[1] One-way route-miles
[2] Morning peak period (6:00-9:30 a.m.) bus trips
[3] Daily passengers carried
[4] Rank of daily passengers carried
[5] Passenger-miles per gallon is indicator of energy efficiency
[6] Rank of passenger-miles per gallon
[7] Weighted by bus-miles
[8] NA = Not Applicable

and McCreless Express routes, with 21 passenger miles per gallon. This low efficiency was due to very low ridership from each of these park-and-ride lots. The highest efficiency occurred on the Crossroads/UTSA route with an efficiency of 83 passenger-miles per gallon. The weighted average efficiency of the three highest routes was 72 passenger-miles per gallon; the average of

Table 5-6. San Antonio Park-and-Ride Energy Efficiency

Route	Route #	Miles[1]	Trips[2]	Ridership[3]	Rank[4]	Psgr-Mi/Gal[5]	Rank[6]
Crossroads/UTSA	93	10	16	1,266	1	83	1
Kelly-Lackland Exp	64	14	12	837	2	73	2
Windsor/410 Exp	17	15	14	831	3	62	3
McCreless Exp	38	9	8	159	4	21	4
South Park Exp	48	10	5	100	5	21	4
Average[7]	NA	12	11	639	NA	63 (72[9])	NA

[1] One-way route-miles
[2] Morning peak period (6:00-9:30 a.m.) bus trips
[3] Daily passengers carried
[4] Rank of daily passengers carried
[5] Passenger-miles per gallon is indicator of energy efficiency
[6] Rank of passenger-miles per gallon
[7] Weighted by bus-miles
[8] NA = Not Applicable
[9] Average of three most efficient routes

all of the routes in the park-and-ride system was 63 passenger-miles per gallon. The 72 passenger-miles per gallon may be more representative system average, because the ridership on the McCreless and South Park routes is extremely low, and greatly lowers the efficiency of the system.

Socioeconomic Characteristics

Each of the socioeconomic variables extracted from the Census data within the park-and-ride market area was averaged to determine an aggregate value for the market area of the lot. A regression analysis was performed to determine possible correlation between the socioeconomic values and the energy efficiency of each individual route. The coefficient of determination (R^2) value represents the percentage of variance in a dependent variable, in this case the energy efficiency, that is explained by variance in the independent variable.

The results of the regression analyses are displayed in Table 5-7. The regression analysis resulted in a wide range of R^2 values, with many variables having different effects on the energy efficiency in the study cities. A possible reason for the variation between the cities could be the size of the data sets. San Antonio had only five data points; this low number may not be sufficient to provide a valid correlation analysis. Dallas and Houston had more appropriately sized data sets, with 17 and 20 routes, respectively.

The regression analysis resulted in individual R^2 values between 0.00 and 0.94. Values of R^2 below 0.50 indicate little correlation between the comparison variables. For example, the

Table 5-7. Regression Analysis of Potential Energy Efficiency Predictor Variables

Independent Variable	R^2 Value for Energy Efficiency		
	Dallas n=17*	Houston n=20	San Antonio n=5
AUTO OWNERSHIP			
0	0.00	0.03	0.76
1	0.14	0.01	0.27
2	0.12	0.01	0.68
3+	0.07	0.03	0.19
PLACE OF WORK			
In CBD	0.08	0.23	0.18
MEANS OF TRANSPORTATION			
Public Transportation	0.02	0.02	0.93
Drive Alone	0.14	0.01	0.50
Carpool	0.07	0.00	0.07
EDUCATION LEVEL			
High School	0.13	0.01	0.21
College	0.19	0.00	0.60
POPULATION DENSITY	0.11	0.13	0.00
TRAVEL TIME TO WORK	0.00	0.00	0.59
MEDIAN INCOME	0.12	0.02	0.47
ROUTE MILES	0.09	0.05	0.27
RIDERSHIP	0.34	0.64	0.94

* n= number of park-and-ride routes

Dallas R^2 value of 0.34 indicates that only 34 percent of the variance in fuel efficiency can be explained by the variance of ridership in all market areas. Due to the large discrepancy between the factors in the three cities, it is very difficult to draw any conclusions from the data. However, it does appear that some variables, such as carpooling to work, do show a higher correlation to energy efficiency than other variables such, as population density.

Correlation between automobile ownership and park-and-ride efficiency in San Antonio was similar to what would be expected for park-and-ride service. The zero auto data showed a good R^2 value since people with no means of transportation are prime candidates for transit service in general. A typical park-and-ride patron, however, has more than one auto and works at a white collar job in the CBD (41), which is reflected by the Dallas and Houston data, where auto ownership is relatively independent of the propensity to use park-and-ride service.

The level of transit ridership in the areas served by park-and-ride lots should show a relationship with energy efficiency. The results of the regression analysis between the use of public transportation and energy efficiency showed less correlation than expected in Houston, and especially in Dallas. However, the R^2 value for San Antonio was much higher (0.94), indicating a definite correlation, however, it is important to note that this finding was based on a limited number of park-and-ride lots.

The downtowns of the three study cities contain many white collar jobs, which are generally performed by the college educated. Thus, a correlation between college education and energy efficiency would have been expected, in fact, the regression analysis does indicate a stronger correlation between energy efficiency and college education than between energy efficiency and high school education. The San Antonio R^2 values, and to a lesser extent Dallas, reflect this pattern.

While it might be expected that travel time to work would correlate with park-and-ride ridership, and thus, with energy efficiency, the results of this study do not indicate any such correlation. It may be that the range of distances studied was not large enough to illustrate this phenomena.

Conclusion

The regression analysis resulted in many R^2 values in the 0.00 to 0.50 range, which are of little use in determining the indicators of fuel efficient performance. These results would indicate that there is little or no data to substantiate a correlation between socioeconomic characteristics and energy efficiency.

There was a significant variance between the three cities with respect to the relationship of energy efficiency and the socioeconomic characteristics. This was probably partially due to the service differences between the cities, and the difference in the number of operating park-and-ride facilities. The inclusion of more park-and-ride lots in the analysis may improve the consistency of the results.

More research may be needed to determine if there are data to support the intuitive belief that a relationship exists between energy efficiency and socioeconomic characteristics. As expected, there is a relatively high correlation between ridership and energy efficiency.

CHAPTER 6. SPEED-FUEL ECONOMY RELATIONSHIPS FOR URBAN DRIVING CONDITIONS

Introduction

This chapter estimates the relationship between vehicle speed and fuel economy for the U.S. light duty vehicle fleet under urban driving conditions for the years 1985 and 2010. Examination of this relationship provides insight into the effect of speed variations on fuel economy. This relationship provides a framework for policy decisions that affect vehicle speed, such as setting speed limits, and operational decisions that have an impact on vehicle speed, including the implementation of traffic management and incident management programs. The chapter includes an examination of speed-fuel economy models, and the development of coefficients for the calibration of these models.

The information discussed in this chapter can be used for estimates of energy consumption by vehicles in roadway systems if relatively detailed information about vehicle speed is available. The application for these models appears to be primarily in computerized roadway simulation models or sophisticated land use-transportation models which provide reliable estimates of speed. The relationships discussed in this chapter are developed from two models developed by General Motors and independent data obtained from a study by Zaniewski et al (42).

Methodology

The methodology used to develop the speed-fuel economy relationship consisted of a number of steps. First, existing models were considered. These models, which were developed based on data collected in the 1970s, were then modified based on current conditions, with adjustments to account for model year, overall fleet economy, and changes in fleet composition. Model parameters were estimated for the year 1985, and the year 2010. The results of the model calibrated for the years 1985 and 2010 were then compared with more recent, independently collected data. Finally, equations based on both the model and the data were derived for the years 1985 and 2010.

Existing Speed-Fuel Economy Models

A large number of fuel consumption models, ranging from instantaneous models (relating fuel consumption to instantaneous speed variations) to average speed models (relating fuel consumption to average speed over a route), have been developed (43). The Organization for Economic Cooperation and Development (OECD) has identified two forms of these models, drive-mode elemental models and average speed models, as the most commonly used in practice.

Drive-mode Elemental Model

The drive-mode elemental models are defined by the OECD as (43),

> ...made up of the elements which contribute to fuel consumption while driving, i.e., fuel used in cruising, idling, and accelerating. The basic assumptions in an elemental model are that the elements are independent and that their sum equals the total fuel consumed.

The simplest form of the drive-mode elemental model is given by:

$$G = f_1 L + f_2 D + f_3 S \qquad \text{Eq. 6-1}$$

where:

G = fuel consumed per vehicle over a measured distance.
L = total distance traveled.
D = stopped delay per vehicle.
S = number of stops.
f_1 = fuel consumption rate per unit distance while cruising.
f_2 = fuel consumption rate per unit time while idling.
f_3 = excess fuel used in decelerating to a stop and accelerating back to cruise speed.

While the drive-mode elemental model produces satisfactory results, it does require specific data, including the number of stops, stopped delay per vehicle, and the excess fuel used in deceleration and acceleration, which may vary significantly with differing conditions and may be difficult to estimate.

Average Speed Model

The average speed model is based on the assumption that the average speed of an individual vehicle is directly related to the fuel consumption per unit distance. The basic form of the average speed model is given by:

$$\begin{aligned} F &= k_1 + k_2 T \\ &= k_1 + \frac{k_2}{\bar{V}} \end{aligned} \qquad \text{Eq. 6-2}$$

where:

F = Fuel consumption per vehicle per unit distance.
T = Travel time per unit distance, including stops and speed changes.
$\bar{V}$ = Average speed measured over a distance, including stops and speed changes.

k_1 = Constant associated with fuel consumed to overcome rolling resistance, approximately proportional to the vehicle's weight.
k_2 = Constant associated with fuel consumed while idling.

Note that the data required for this model is much more simplified than for the drive-mode elemental model. Whereas the drive-mode elemental model requires data such as the number of stops, stopped delay per vehicle, excess fuel used in deceleration and acceleration, total distance traveled, fuel consumption while traveling, and fuel consumption while idling; the average speed model incorporates stopped delay, acceleration and deceleration into an average travel time and average speed, which simplifies the collection of data.

This average speed model has been found to account for 70 percent of the variance in fuel consumption. However, due to the increased effects of air resistance at higher speeds, this model is only valid for speeds less than 35 mph. To account for the added discrepancies at higher speeds (up to 55 mph) a third term, $k_3\bar{V}^2$, was added to Equation 6-2, as shown in Equation 6-3.

$$F = k_1 + \frac{k_2}{\bar{V}} + k_3\bar{V}^2 \qquad \text{Eq. 6-3}$$

where:
F = Fuel consumption per vehicle per unit distance.
T = Travel time per unit distance, including stops and speed changes.
$\bar{V}$ = Average speed measured over a distance, including stops and speed changes.
k_1 = Constant associated with fuel consumed to overcome rolling resistance, approximately proportional to the vehicle's weight.
k_2 = Constant associated with fuel consumed while idling.
k_3 = Constant associated with fuel consumed to overcome air resistance at higher speeds.

Development of Coefficients for Average Speed Model

Raus (44) concludes that the basic form of the average speed models, as developed by the General Motors Research Laboratories, is the best relationship based on available information. The use of the basic form of the average speed model (Equation 6-2) has natural appeal over the drive-elemental models since the data requirements to the user are either readily available or obtainable with minimal collection effort.

Although the modified average speed model (Equation 6-3) has been found to account for 83 percent of the variance in fuel consumption, as opposed to 70 percent for the basic average speed model, the development of values for the "k" parameters in Equation 6-3 appears to be confined to a single study. On the other hand, the values for k_1 and k_2, in Equation 6-2 as determined by General Motors, have been corroborated by results obtained by the EPA. The values for k_1 and k_2 in the basic average speed model, therefore, appear to be well founded. Consequently, it was decided that this form of the model, with the parameter values as determined in the General Motors study, should also be considered in the determination of a general speed-fuel economy model applicable to the years 1985 and 2010. The model, which will be referred to as GM1 (General Motors Model 1) with the respective parameter values for k_1 and k_2 substituted in Equation 6-2, is shown in Equations 6-4 and 6-5.

$$F = 0.0362 + \frac{0.764}{\bar{V}} \qquad \text{Eq. 6-4}$$

$$E = \frac{1}{0.0362 + \frac{0.746}{\bar{V}}} \qquad \text{Eq. 6-5}$$

where:

E = Fuel economy in miles per gallon (E = 1/F).
F = Fuel consumption rate in gallons per mile (F = 1/E).
$\bar{V}$ = Average velocity in miles per hour.

Equations 6-4 and 6-5 were derived from a mixture of 1973 through 1976 passenger car models of various sizes, under urban driving conditions. Basing a speed-fuel economy relationship for the years 1985 and 2010 on the above relationship alone was not considered entirely satisfactory since, despite its corroboration with the EPA study, a bias could still exist due to the limited amount of and the age of the data available. The literature was reviewed to identify more recent data and to determine whether any subsequent speed-fuel economy relationships are compatible with the General Motors study (44).

Wagner (45) presents a model based on a later General Motors study. The model, which will be referred to as GM2 (General Motors Model 2), relates total fuel consumption, distance traveled, and total travel time, as shown in Equation 6-6.

$$F = 0.0425 * VMT + 0.60 * VHT \qquad \text{Eq. 6-6}$$

where:

F = Total fuel consumed in gallons.
VMT = Total vehicle-miles traveled.
VHT = Total vehicle-hours of travel.

For a single vehicle, equation 6-6 can be equivalently defined by Equation 6-7.

$$E = \frac{1}{0.0425 + \frac{0.60}{\bar{V}}} \qquad \text{Eq. 6-7}$$

where:

E = Fuel economy (miles per gallon).

$\bar{V}$ = Average speed (miles per hour).

The forms of the models presented by Raus and Wagner are essentially the same. The difference in the values of the parameters k_1 and k_2 arise from the former model being calibrated with tests using a vehicle mix of 1973 to 1976 new passenger cars, and the latter model with tests using a sample of 1976 cars.

Modification of Existing Speed-Fuel Economy Models

In order to ascertain the compatibility of the two models, the two equations (6-5 and 6-7) were adjusted to a common base year of 1985 by applying factors representing:

(1) the improved fuel economy of new model vehicles.
(2) the difference in fuel economy between new passenger car models and the overall fleet.
(3) the difference in the overall average fleet fuel economy brought about by a change in fleet composition, specifically, the increased percentage of pickup trucks in the light duty fleet.

Since the speed-fuel economy relationships for these two models are not strictly valid for speeds greater than 35 mph, additional data from an independent source (46) was utilized in an attempt to confirm the relationship given by the two models. In addition, predicted relationships for the year 2010, based primarily on proposed CAFE standards, were developed for the two models, as well as the independent data.

Results

This section presents the results of the adjustment of the GM1 and GM2 average speed fuel economy models (Equations 6-5 and 6-7) to common base years of 1985 and 2010. This section also presents the data from an independent source, which was adjusted for comparison with the results of the modified GM1 and GM2 equations. Finally, this chapter presents the speed-fuel economy equation that was determined based on the analysis of the GM1 and GM2 equations, and the independent data.

Adjustment to Common Base Year for GM Model 1

Equations 6-5 and 6-7 were adjusted to a common base year of 1985 by applying factors representing the differences in fuel economies between subsequent model years, the difference in fuel economies between new passenger car models and the overall fleet, and the difference in overall average fleet fuel economies brought about by the change in fleet composition, particularly the increased percentage of pickup trucks in the light duty fleet.

Difference in Fuel Economy between Model Years

Table 6-1 shows the average fuel economy for new passenger cars in model years 1968 through 1976. Based on the information in this table, the average fuel economy for new passenger cars in model years 1973 through 1976 can be calculated, as shown.

$$\begin{aligned} E &= \frac{(14.2 + 14.2 + 15.9 + 17.6)}{4} \\ &= 15.475 \end{aligned}$$

where:

E = Fuel economy (mpg).

The GM1 model was calibrated based on this average fuel efficiency, since it was developed using 1973 through 1976 model year vehicles. The appropriate equation for the fuel economy of new passenger cars under urban driving conditions in subsequent model years is given by combining this average fuel efficiency (calculated previously) with equation 6-5, and simplifying.

$$\begin{aligned} E &= \frac{MYV}{15.475} \times \frac{1}{0.0362 + \frac{0.746}{\bar{V}}} \\ &= \frac{0.60646 MYV}{0.0362 + \frac{0.746}{\bar{V}}} \end{aligned} \qquad \text{Eq. 6-8}$$

where:

E = Fuel economy (miles per gallon).

MYV = Average Model Year value (mpg), from Table 6-1.

$\bar{V}$ = Average speed (mph).

Difference in Fleet Fuel Economy Due to Inclusion of Newer Vehicles

Equation 6-8 represents the new passenger car fuel economy under urban driving conditions for model years subsequent to 1976. In order to obtain the overall passenger car fleet economy in subsequent years, an adjustment factor was applied to represent the difference

Table 6-1. Average Passenger Car Fuel Efficiency

Year	Average New Passenger Car Fuel Economies (miles per gallon)					
	Source 1	Source 2	Source 3	Source 4	Source 5	Average
1968	-	14.7	-	-	-	14.7
1969	-	14.7	-	-	-	14.7
1970	-	14.8	-	-	-	14.8
1971	-	14.4	-	-	-	14.4
1972	-	14.5	-	-	-	14.5
1973	14.2	14.2	-	14.2	-	14.2
1974	-	14.2	-	14.3	14.2	14.2
1975	-	15.8	-	15.9	15.9	15.9
1976	-	17.5	-	17.5	17.7	17.6
1977	-	18.3	-	18.1	18.4	18.3
1978	19.9	19.9	19.9	19.8	19.9	19.9
1979	20.3	20.3	20.3	20.4	20.4	20.3
1980	23.5	23.5	24.3	23.6	24.4	23.9
1981	-	25.2	25.9	25.2	26.1	25.6
1982	26.4	26.1	26.6	26.1	26.7	26.4
1983	26.1	26.0	26.4	26.0	26.5	26.2
1984	26.4	26.6	26.9	26.3	27.1	26.7
1985	27.0	-	27.6	27.0	27.6	27.3
1986	-	-	28.0	27.9	28.3	28.1
1987	-	-	28.2	28.2	28.3	28.2
1988	-	-	28.7	28.4	28.7	28.6
1989	-	-	28.3	28.0	-	28.2
1990	26.7	-	-	-	-	26.7

Source 1:	Reference (42).
Source 2:	Reference (47).
Source 3:	Howard Smolkin.
Source 4:	John R. Berg.
Source 5.	Reference (48).

between the new passenger car economy and the overall passenger vehicle fleet economy. The average fuel economies of vehicles on the road is shown in Table 6-2 for every year from 1967 to 1986. As shown in Equation 6-9, the fleet fuel economy is adjusted by the ratio of the overall passenger fleet economy of the vehicles on the road (from Table 6-2), divided by the fuel economy of the average model year vehicle (from Table 6-1). Equation 6-8 is adjusted and simplified, as shown in Equation 6-9.

$$\begin{aligned} E &= \frac{FYV}{MYV} \times \frac{0.0646\ MYV}{0.0362 + \frac{0.746}{\bar{V}}} \\ &= \frac{0.0646\ FYV}{0.0362 + \frac{0.746}{\bar{V}}} \end{aligned} \qquad \text{Eq. 6-9}$$

where:

E = Adjusted passenger fleet fuel economy (mpg).

FYV = Overall passenger fleet economy for years after 1976 (mpg), from Table 6-2.

MYV = Average Model Year fuel economy (mpg), from Table 6-1.

$\bar{V}$ = Average speed (mph).

Difference in Fuel Economy Due to Changes in Vehicle Composition

The sales of light trucks as a percentage of overall light duty fleet sales has increased, as shown in Figure 6-1. Note that since the early 1970s, the percentage of trucks has increased significantly, and it is expected to continue to increase in the future. It is estimated that by the year 2000, approximately one third of all light duty fleet sales will consist of light duty trucks (49). Since light trucks are less fuel efficient that passenger cars, the percentage increase in light duty truck sales and the resulting increase in the number of light trucks in the light duty fleet could have a significant effect on the overall light duty fleet fuel economy in the future.

While the average 1987 nominal fleet fuel economy for new automobiles was about 28 mpg, the fleet average for new light trucks was closer to 21 mpg. This indicates that light trucks have approximately 75 percent the efficiency of passenger vehicles. Examination of proposed CAFE standards for future years indicates that an overall efficiency of approximately 73 percent of the new passenger car fuel economy for light duty trucks is considered reasonable. For the purposes of this analysis, it was assumed that light duty trucks have approximately 73 percent the economy of passenger vehicles.

The range and distribution of model year vehicles within the vehicle fleet for any given year is at best an estimate. This analysis assumed that in any given year the average age of the vehicles on the road was five years old. For the purposes of estimating the percentage of light duty trucks in a given year, it was assumed that the percentage of light trucks is approximately

Table 6-2. Average Fuel Economies of Vehicles On-the-Road

Year	Fuel Economies of Vehicles On-the-Road (miles per gallon)		
	Source 1	Source 2	Average
1967	14.0	-	14.0
1968	13.8	-	13.8
1969	13.5	-	13.5
1970	13.4	-	13.4
1971	13.4	-	13.4
1972	13.4	-	13.4
1973	13.2	-	13.2
1974	13.4	13.4	13.4
1975	13.5	13.5	13.5
1976	13.5	13.5	13.5
1977	13.7	14.0	13.85
1978	14.0	14.0	14.0
1979	14.4	14.4	14.4
1980	15.5	15.5	15.5
1981	16.0	16.0	16.0
1982	16.6	16.6	16.6
1983	17.1	17.1	17.1
1984	17.8	17.9	17.85
1985	18.2	18.3	18.25
1986	18.3	18.3	18.3

Source 1: A. Henry Schilling, Environmental Protection Agency.
Source 2: (48).

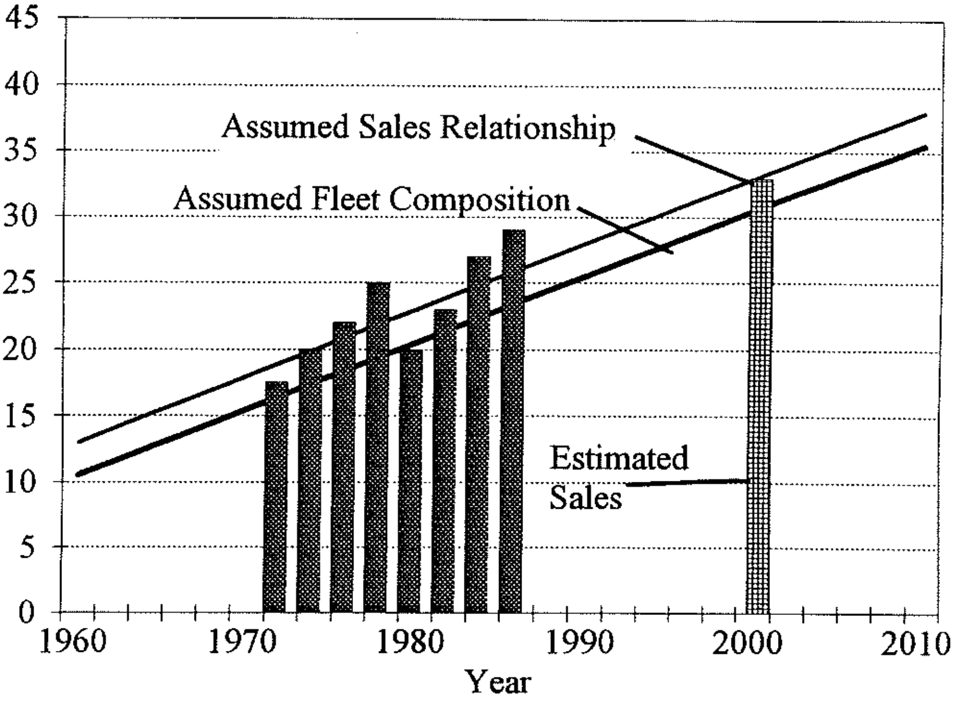


Figure 6-1. Sales of Light Trucks as a Percentage of Light Duty Fleet Sales

the percentage of the light duty truck sales five years previous. It was also assumed that the percentage of light duty truck sales in the year 2000 will be 33 percent, increasing linearly from the 1974 percentage of 20 percent. This assumption is indicated graphically in Figure 6-1.

The fleet composition adjustment factor is defined as the ratio of the whole light duty fleet economy to the passenger car fleet economy, as shown in Equation 6-10. The term 1-0.01***P*** adjusts for the percentage of the fleet that is light trucks; the 0.0073***P*** term adjusts for the fact that light duty trucks have a fuel efficiency that is approximately 73 percent of the fuel economy of autos.

$$\begin{aligned} FCAF &= \frac{FYV(1-0.01P+0.0073P)}{FYV} \\ &= (1-0.0027P) \end{aligned} \qquad \text{Eq. 6-10}$$

where:

FCAF = Fleet composition adjustment factor.

FYV = Overall passenger fleet economy for years after 1976 (mpg), from Table 6-2.

P = Estimated percentage of light trucks in fleet, from Figure 6-1.

The appropriate equation for the fuel economy of the entire light duty fleet in any year subsequent to 1976, adjusted for urban driving conditions and fleet composition, is given by Equation 6-11.

$$E = (1 - 0.0027P) \times \frac{(0.0646\,FYV)}{\left[0.0362 + \dfrac{0.746}{\bar{V}}\right]} \qquad \text{Eq 6-11}$$

where:

E = Passenger fleet fuel economy (mpg).
P = Estimated percentage of light trucks in fleet, from Figure 6-1.
FYV = Overall passenger fleet economy for years after 1976 (mpg), from Table 6-2.
$\bar{V}$ = Average velocity (mph).

Substituting the appropriate values of ***P*** and ***FYV*** for the year 1985 from Figure 6-1 and Table 6-2 into Equation 6-11 yields the relationship between average speed and fuel economy for the 1985 fleet of light duty vehicles operating under urban conditions. Note that 23 has been substituted for ***P***, the percentage of light trucks in the fleet composition, and that 18.25 has been substituted for ***FYV***, the overall passenger fleet economy for 1985.

$$E_{1985} = (1 - 0.0027 \times 23) \times \frac{0.0646 \times 18.25}{\left[0.0362 + \dfrac{0.746}{\bar{V}}\right]}$$

$$= \frac{1.106}{\left[0.0362 + \dfrac{0.746}{\bar{V}}\right]} \qquad \text{Eq. 6-12}$$

where:

E_{1985} = Passenger fleet fuel economy for the year 1985.
$\bar{V}$ = Average velocity (mph).

Similarly, the equation for the year 2010 is calculated by applying Equation 6-1 for the year 2010, using the proposed Corporate Average Fuel Economy (CAFE) standards for the year 2000 given in Table 6-3 as the estimated light duty fleet fuel economy (***FYV*** = 40), and the estimated percentage of pickup trucks from Figure 6-1 (***P*** = 35.5).

Table 6-3. Corporate Average Fuel Economy (CAFE) Standards

Model Year	Miles per Gallon
1978	18.0
1979	19.0
1980	20.0
1981	22.0
1982	24.0
1983	26.0
1984	27.0
1985	27.5
1986	26.0
1987	26.0
1988	26.0
1989	26.5
1990-1994	27.5
1995-2000	1.2 times the 1988 average fuel economy but greater than 27.5 and less than 40.0
2001-	1.4 times the 1988 average fuel economy but greater than 33.0 and less than 45.0

Sources: Motor Vehicle Fuel Efficiency Act of 1990, report of the Senate Committee on Commerce, Science, and Transportation on S. 1224, together with minority views. Washington, U.S. G.P.O., 1990. (42).

$$E_{2010} = (1 - 0.0027 \times 35.5) \times \frac{0.0646 \times 40}{\left[0.0362 + \frac{0.746}{\bar{V}}\right]} = \frac{2.336}{\left[0.0362 + \frac{0.746}{\bar{V}}\right]} \qquad \text{Eq. 6-13}$$

where:

E_{2010} = Passenger fleet fuel economy for the year 2010.

$\bar{V}$ = Average velocity.

Adjustment to Common Base Year for GM Model 2

The GM Model 2, as shown in Equation 6-7, was adjusted to the common base years of 1985 and 2010 by applying factors representing the improved fuel economies of later year vehicles, and the difference in overall average fleet fuel economies brought about by the change in fleet composition, particularly the increased percentage of pickup trucks in the light duty fleet. Note that the procedure used to adjust the GM Model 2 is identical to the procedure used to adjust the GM Model 1.

Difference in Fleet Fuel Economy Due to Inclusion of Newer Vehicles

As shown in Table 6-2, the average fuel economy for the passenger car fleet in 1976 is 13.5 mpg; the GM model 2 was developed using 1976 model year vehicles. Equation 6-14 represents the fuel economy under urban driving conditions for the on-the-road automobile fleet in years subsequent to 1976. As was the case for the GM1, in order to obtain the overall passenger car fleet economy in subsequent years, an adjustment factor was applied to represent the difference between the new passenger car economy and the overall passenger fleet economy. In this case, the appropriate adjustment factor is ***FYV/13.5***, where ***FYV*** represents the overall passenger fleet economy in subsequent years as given in Table 6-2, and 13.5 is the average fleet economy in 1976, the year for which the model was developed. Equation 6-14 results from modifying equation 6-7 by this adjustment factor and simplifying.

$$E = \frac{FYV}{13.5} \times \frac{1}{0.0425 + \frac{0.6}{\bar{V}}} = \frac{0.732\,FYV}{0.0425 + \frac{0.6}{\bar{V}}} \qquad \text{Eq. 6-14}$$

where:

E = Passenger fleet fuel economy (mpg).

FYV = Overall passenger fleet economy for years after 1976 (mpg), from Table 6-2.

$\bar{V}$ = Average velocity (mph).

<u>Difference in Fuel Economy Due to Changes in Vehicle Composition</u>

The application of the fleet composition adjustment factor (FCAF) to Equation 6-14 is identical to the procedure applied to the GM1. Assuming that trucks have an overall efficiency of approximately 73 percent of the fuel economy for passenger vehicles, the resulting calculation is shown in Equation 6-15.

$$E = (1 - 0.0027P) \times \frac{0.0732\ FYV}{0.0425 + \frac{0.6}{\bar{V}}} \qquad \text{Eq. 6-15}$$

where:

E = Passenger fleet fuel economy (mpg).

P = Estimated percentage of light trucks in fleet from Figure 6-1.

FYV = Overall passenger fleet economy for years after 1976 (mpg), from Table 6-2.

$\bar{V}$ = Average velocity (mph).

Substituting the appropriate values of ***P*** and ***FYV*** for the year 1985 from Figure 6-1 and Table 6-2 into Equation 6-15 yields the relationship between average speed and fuel economy for the 1985 fleet of light duty vehicles operating under urban conditions.

$$E_{1985} = (1 - 0.0027 \times 23) \times \frac{0.0732 \times 18.25}{\left[0.0425 + \frac{0.6}{\bar{V}}\right]}$$

$$= \frac{1.253}{\left[0.0425 + \frac{0.6}{\bar{V}}\right]} \qquad \text{Eq. 6-16}$$

where:

E_{1985} = Passenger fleet fuel economy for the year 1985.
$\bar{V}$ = Average velocity (mph).

Similarly, Equation 6-17 for the year 2010 is calculated by applying Equation 6-1 for the year 2010, utilizing proposed Corporate Average Fuel Economy (CAFE) standards for the year 2000 given in Table 6-3 as the estimated light duty fleet fuel economy, and the estimated percentage of pickup trucks from Figure 6-1.

$$E_{2010} = (1 - 0.0027 \times 35.5) \times \frac{0.0732 \times 40}{\left[0.0425 + \frac{0.6}{\bar{V}}\right]}$$

$$= \frac{2.647}{\left[0.0425 + \frac{0.6}{\bar{V}}\right]} \qquad \text{Eq. 6-17}$$

where:

E_{2010} = Passenger fleet fuel economy for the year 2010.
$\bar{V}$ = Average velocity.

Comparison with Independent Data

Since the speed-fuel economy relationships for these two models are not strictly valid for speeds greater than 35 mph, additional data from an independent source (46) was utilized in an attempt to corroborate the relationship given by the two GM models. In an attempt to duplicate the relationships of Equations 6-12 and 6-13 for GM1, and Equations 6-16 and 6-17 for GM2, this independent data was manipulated in a similar manner. Table 6-4 summarizes the fuel economy of a number of vehicles operating under unconstrained conditions on sections of highway with zero grade.

A number of adjustments to the data in Table 6-4 were necessary to allow comparison with modified GM Models 1 and 2 (Equations 6-12 and 6-13, and Equations 6-16 and 6-17).

Table 6-4. Fuel Economy of Vehicles at Varying Operating Speed

Speed (mph)	Fuel Economy for Various Classes of Automobile (mpg)				
	Small Car[1]	Medium Car[2]	Medium Car[2]	Medium Car Average	Large Car[3]
10	15.9	17.9	18.0	17.9	17.0
20	28.5	25.5	26.2	25.8	23.1
30	42.1	25.3	28.2	26.8	24.8
40	37.7	26.4	26.6	26.5	22.6
50	42.8	23.9	22.8	23.4	20.5
60	35.5	19.4	18.8	19.1	17.8

[1] 1980 Ford Escort.
[2] 1980 Ford Fairmont.
[3] 1979 Oldsmobile Delta 88.

The process used to adjust this data was similar to the process used to adjust the GM1 and GM2 equations, and includes the following manipulations.

(1) Adjusting each value for economy to model years 1985 and 2010.
(2) Calculating a weighted new passenger automobile economy based on actual and predicted automobile class (small, medium, large) sales.
(3) Factoring the weighted economy to represent city driving conditions.
(4) Factoring the new passenger automobile fleet economy to obtain the whole passenger automobile fleet economy.
(5) Factoring the total passenger automobile fleet economy to allow for the estimated percentage of pick-up trucks in the light duty fleet, giving the estimated total light duty fleet economy under urban driving conditions for the years 1985 and 2010.

Adjustment to 1985 Conditions

The data in Table 6-4 was obtained from studies on 1980 model small and medium cars and a 1979 model large car. These values must be adjusted for improved efficiency in later model years by weight class. Table 6-5 gives the fuel economy and market share by weight class passenger cars for the years 1978 through 1987 passenger cars. The weight classes have been chosen to represent, as closely as possible, the weight classes represented by the vehicles given in Table 6-4. The small car in Table 6-4 weighs 2412 lbs, the medium car weighs 3006 lbs, and the large car weighs 4350 lbs (50).

Table 6-5. Fuel Economy and Market Share for 1978 to 1987 Passenger Cars by Weight Class

Year	Small					Medium				Large
	<2250	2250	2500	2750	Wtd Avg	3000	3500	4000	Wtd Avg	>4000
1978	34.9[1] 0.024[2]	31.9 0.079	27.9 0.070	24.8 0.045	29.5 0.218	22.5 0.081	20.2 0.268	18.0 0.200	19.7 0.549	15.8 0.233
1979	32.0 0.022	31.4 0.065	27.9 0.100	24.0 0.043	28.6 0.230	22.1 0.119	20.2 0.249	17.8 0.245	19.6 0.613	16.2 0.159
1980	33.0 0.030	32.4 0.123	28.0 0.124	26.1 0.103	29.3 0.380	23.6 0.215	20.7 0.227	18.8 0.139	21.3 0.581	18.9 0.039
1981	38.4 0.024	34.4 0.136	29.4 0.175	27.7 0.082	31.2 0.417	24.4 0.186	22.2 0.209	20.3 0.150	22.4 0.545	20.3 0.037
1982	40.3 0.020	35.6 0.113	31.2 0.184	28.8 0.123	32.1 0.440	25.7 0.199	22.4 0.182	20.6 0.155	23.1 0.536	20.7 0.024
1983	43.6 0.012	36.2 0.123	32.2 0.155	30.2 0.108	33.2 0.398	25.8 0.189	22.8 0.209	20.3 0.181	23.0 0.579	19.8 0.024
1984	44.3 0.009	37.1 0.084	32.7 0.143	30.1 0.192	32.6 0.428	26.4 0.187	22.9 0.208	20.6 0.159	23.4 0.554	20.0 0.018
1985	48.5 0.009	37.5 0.078	32.8 0.156	30.6 0.174	33.1 0.417	27.1 0.189	23.4 0.229	21.7 0.155	24.2 0.573	20.8 0.010
1986	47.4 0.013	38.8 0.069	34.0 0.140	30.4 0.162	33.8 0.384	27.8 0.250	24.6 0.261	22.7 0.095	25.6 0.606	21.1 0.012
1987	50.5 0.007	39.3 0.046	33.9 0.164	31.0 0.190	33.4 0.407	27.5 0.233	24.6 0.246	23.0 0.104	25.5 0.583	21.7 0.010

Source: Adapted From; Heavenrich et al. "Light-Duty Automotive Fuel Economy and Technology Trends Through 1987". SAE Technical Paper Series, No. 871088 (51).

[1] Fuel Economy (miles per gallon).

[2] Market Share.

The necessary adjustment factors for improved fuel consumption in later model years are given by:

$$F_{small} = \frac{1985_{Wtd\ Ave}}{1980_{Wtd\ Ave}} = \frac{33.1}{29.3} = 1.130 \qquad \text{Eq. 6-18}$$

$$F_{medium} = \frac{1985_{Wtd\ Ave}}{1980_{Wtd\ Ave}} = \frac{24.2}{21.3} = 1.136 \qquad \text{Eq. 6-19}$$

$$F_{large} = \frac{1985_{Wtd\ Ave}}{1979_{Wtd\ Ave}} = \frac{20.8}{16.2} = 1.284 \qquad \text{Eq. 6-20}$$

Applying these factors to the values in Table 6-4 yields the estimated 1985 fuel economy for new passenger cars by class and speed, given in Table 6-6.

Adjustment for Vehicle Class Market Share

For each speed, the average fuel economy for the 1985 new passenger car fleet is obtained by taking the market share from Table 6-5, multiplying by the respective fuel economy for each weight class from Table 6-6, and the three values representing the three vehicle classes. Table 6-7 shows the estimated 1985 overall new passenger car fuel economies by speed. The calculation for the 1985 average new passenger car economy at a speed of 10 mph is shown below.

$$\begin{matrix}\textit{Weighted Average}\\ \textit{Fuel Economy}\end{matrix} = (18.0)(41.7\%) + (20.3)(57.3\%) + (21.8)(1\%) = 19.4$$

Table 6-6. Estimated 1985 Fuel Economy for New Passenger Cars by Class and Speed

Speed (mph)	Fuel Efficiency by Class (mpg)		
	Small	Medium	Large
10	18.0	20.3	21.8
20	32.2	29.3	29.7
30	47.6	30.4	31.8
40	42.6	30.1	29.0
50	48.4	26.6	26.3
60	40.1	21.7	22.8

Table 6-7. Estimated Average Fuel Economy of the 1985 Year Model New Passenger Car Fleet

Speed (mph)	Fuel Economy (mpg)
10	19.4
20	30.5
30	37.6
40	35.3
50	35.7
60	29.4

Adjustment for Urban Driving Conditions

Table 6-7 represents the average consumption rate for 1985 new passenger cars. Because this analysis only considers urban driving conditions, adjustments to the values in Table 6-7 must be made. From Table 6-8, the ratio of the fuel efficiency under city driving condition to the average fuel efficiency is assumed to be the average for the years 1968 to 1984, which is 0.86. Thus the fuel economies in Table 6-7 must be multiplied by 0.86 to obtain the 1985 average new passenger car fuel economies under city driving conditions for various speeds.

Adjustment for Inclusion of Newer Vehicles

The average passenger car fleet efficiency for 1985 is 18.25 mpg, as shown in Table 6-2. From Table 6-1, the average new passenger car efficiency for model year 1985 is 27.3 mpg. Thus, to obtain the 1985 fleet average passenger car fuel consumption rate the values in Table 6-7 must be multiplied by the ratio 18.25/27.3 = 0.668.

Adjustment for Changes in Vehicle Composition

The fleet composition adjustment factor (FCAF) was developed earlier, for the year 1985, the FCAF is estimated as:

$$FCAF = 1 - 0.0027 * 23 = 0.9379$$

Applying this factor to the fuel conservation rates yields the fuel economy for each speed considering the increased percentage of pick-up trucks.

The independent data for 1985, adjusted to account for all of the discussed factors, is shown in the Table 6-9.

Table 6-8. Comparison of City to Highway Automobile Fuel Economies

Year	Mileage (mpg)			
	City	Highway	Average	City/Average
1968	12.59	18.42	14.69	0.86
1969	12.60	18.62	14.74	0.85
1970	12.59	19.01	14.85	0.85
1971	12.27	18.18	14.37	0.85
1972	12.15	18.90	14.48	0.84
1973	12.01	18.07	14.15	0.85
1974	12.03	18.23	14.21	0.85
1975	13.68	19.45	15.79	0.87
1976	15.23	21.27	17.46	0.87
1977	15.99	22.26	18.31	0.87
1978	17.24	24.48	19.89	0.87
1979	17.70	24.60	20.25	0.87
1980	20.35	29.02	23.51	0.87
1981	21.75	31.12	25.16	0.86
1982	22.32	32.76	26.06	0.86
1983	22.21	32.90	26.01	0.85
1984	22.67	33.69	26.59	0.85
			Average	0.86

Source: (47)

Table 6-9. Adjusted 1985 Fuel Economy Data from Independent Source

Speed (mph)	Fuel Economy (mpg)
10	10.5
20	16.4
30	20.3
40	19.0
50	19.2
60	15.8

Adjustment to 2010 Conditions

The data in Table 6-4 were obtained from studies on 1980 model small and medium cars and a 1979 model large car. These values must be adjusted for improved fuel economy in later model years. It is assumed that the average fuel economy for the entire passenger car fleet in the year 2010 will be equivalent to the proposed CAFE standards for automobiles in the year 2001 (shown in Table 6-3), that is, greater than 33 mpg but less than 45 mpg; 40 mpg is assumed. It is also assumed that the average fuel economy for new passenger cars in 2010 is 45 mpg. In order to determine the new passenger car economies by class (as defined in Table 6-5), it is necessary to examine recent trends in new passenger car sales by class and the relative economies between the classes.

Figure 6-2 summarizes the sales data given in Table 6-5. Figure 6-3 indicates the economy of each class relative to the medium-sized class. The assumed average new passenger car fuel economy in 2010 is 45 mpg. Defining 2010_{medium} as the fuel economy of new medium-sized passenger cars in the year 2010, then from Figure 6-3:

$$2010_{small} = 1.3\ (2010_{medium}) \qquad \text{Eq. 6-21}$$
$$2010_{large} = 0.81\ (2010_{medium}) \qquad \text{Eq. 6-22}$$

From Figure 6-2, the relative market share (RMS) for new passenger cars in year 2010 is estimated to be:

$$RMS_{small} = 0.39$$
$$RMS_{medium} = 0.60$$
$$RMS_{large} = 0.01$$

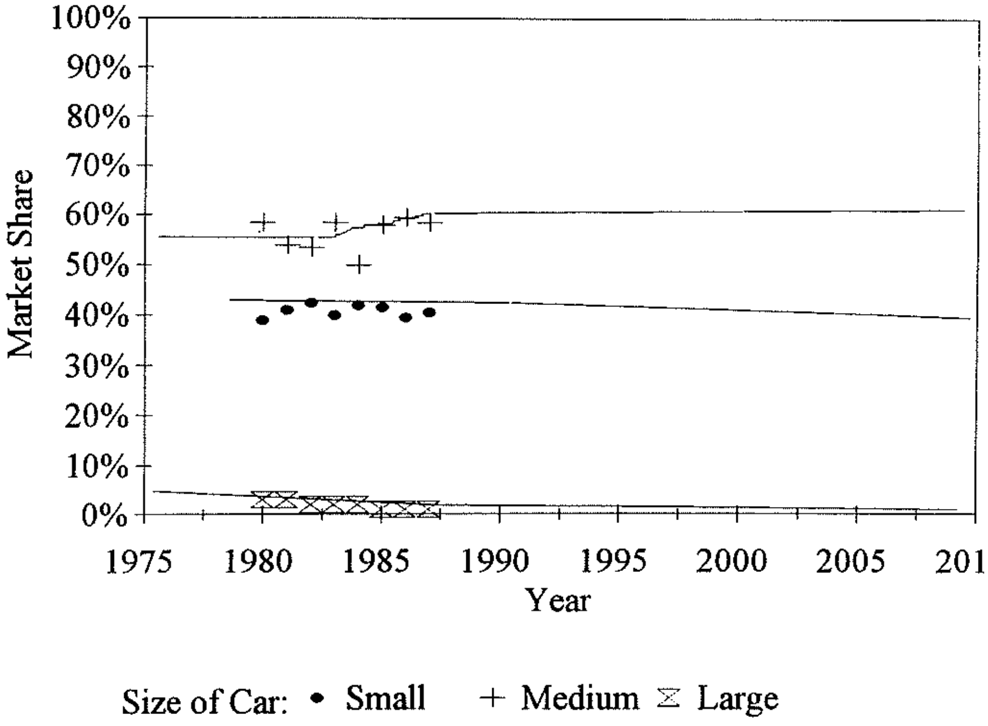


Figure 6-2. Market Share for New Passenger Cars by Weight Class

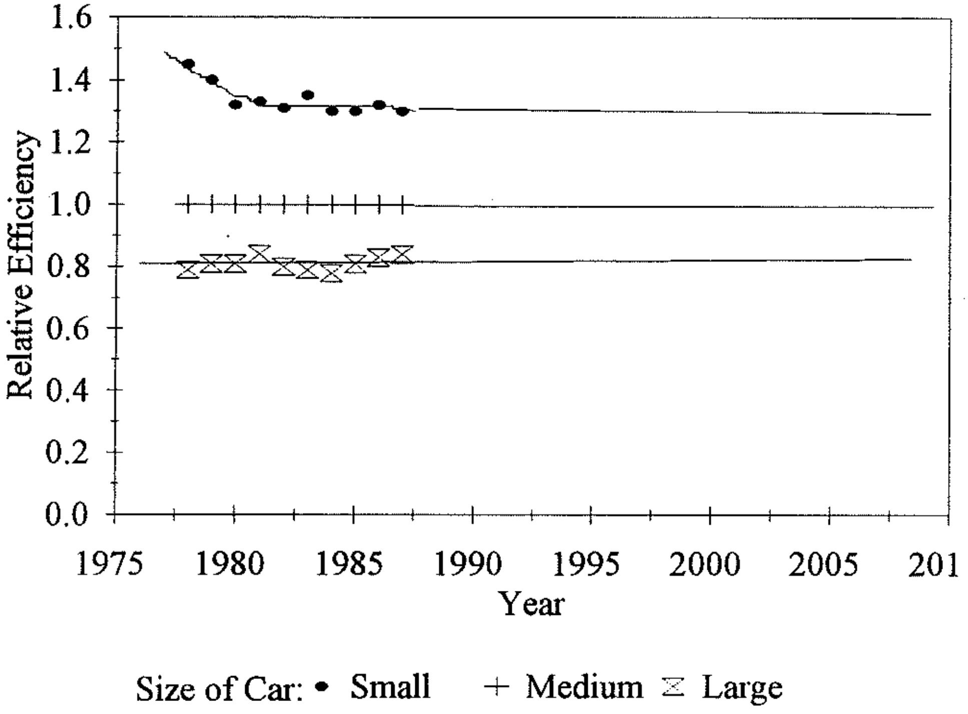


Figure 6-3. Relative Fuel Consumption of New Passenger Cars by Weight Class and Year

Since the overall new passenger car economy can be calculated from the market share and economy of the respective classes:

$$0.39\,(2010_{small}) + 0.60\,(2010_{medium}) + 0.01\,(2010_{large}) = 45$$

Substituting for 2010_{small} and 2010_{large}:

$$0.39\,(1.3 * 2010_{medium}) + 0.60\,(2010_{medium}) + 0.01\,(0.81 * 2010_{medium}) = 45$$

and solving for 2010_{medium}:

$$2010_{medium} = 40.4 \text{ mpg}$$

And, solving for 2010_{small} and 2010_{large} from Equations 6-21 and 6-22:

$$2010_{small} = 1.3\,(2010_{medium}) = 1.3 * 40.4 = 52.5 \text{ mpg}$$
$$2010_{large} = 0.81\,(2010_{medium}) = 0.81 * 40.4 = 32.7 \text{ mpg}$$

The adjustment factors applied to the fuel economy values in Table 6-5 to give the estimated 2010 new passenger car fuel consumption rates by class are given by:

$$F_{small} = \frac{2010_{small}}{1980_{Wtd\ Ave}} = \frac{52.5}{30.5} = 1.721 \qquad \text{Eq. 6-23}$$

$$F_{medium} = \frac{2010_{medium}}{1980_{Wtd\ Ave}} = \frac{40.4}{22.9} = 1.764 \qquad \text{Eq. 6-24}$$

$$F_{large} = \frac{2010_{Large}}{1979_{Wtd\ Ave}} = \frac{32.7}{17.2} = 1.901 \qquad \text{Eq. 6-25}$$

Applying these factors to the respective values given in Table 6-4 yields the estimated 2010 fuel economies for new passenger cars by class and speed, given in Table 6-10.

Adjustment for Vehicle Class Market Share

For each speed the average economy for the 2010 new passenger car fleet is obtained by taking the market share, shown in Figure 6-4, multiplying by the respective economy for each class, from Table 6-10, and adding. For example, at a speed of 10 mph, the 2010 average new passenger car economy rate is given by:

Table 6-10. Estimated 2010 Fuel Economies for New Passenger Cars by Class and Speed

Speed (mph)	Fuel Economy by Class (mpg)		
	Small	Medium	Large
10	27.4	31.6	32.3
20	49.0	45.5	43.9
30	72.5	47.3	47.1
40	64.9	46.7	43.0
50	73.7	41.3	39.0
60	61.1	33.7	33.8

$$\begin{matrix} \mathit{WeightedAverage} \\ \mathit{FuelEconomy} \end{matrix} = (27.4)(39\%) + (31.6)(60\%) + (32.3)(1\%) = 30.0$$

The values in the second column of Table 6-11 show the estimated 2010 overall new passenger car economies by speed.

Adjustment for Urban Driving Conditions

The values in the second column of Table 6-11 represent the average fuel economy for 2010 new passenger cars. From Table 6-8, the ratio of the fuel efficiency in urban areas to the average fuel efficiency is assumed to be the average for the years 1968 to 1984, this average value is 0.86. The fuel economies in Table 6-11 must be multiplied by 0.86 to obtain the 2010 average new passenger car economies under city driving conditions for various speeds (the adjusted values are shown in the third column of Table 6-11).

Adjustment for Inclusion of Newer Vehicles

The CAFE standards (shown in Table 6-3) indicate that the average fuel economy in 2010 will be no greater than 45 mpg, and the average fuel economy in 2000 will be no greater than 40 mpg. These values were used to estimate the ratio of passenger fleet to average passenger car fuel economy in the year 2010, this ratio is estimated to be 40 mpg / 45mpg = 0.89. To obtain the estimated average economy for the whole passenger car fleet, the values in Table 6-11 must be multiplied by a factor of 0.89, the adjusted values are shown in the fourth column of Table 6-11.

Table 6-11. Estimated Average Fuel Economy of 2010 Year Model New Passenger Car Fleet

Speed (mph)	Fuel Economy (mpg)			
	Weighted Average based on Weight Class Market Share	Adjusted to Account for City Driving Conditions[1]	Adjusted to Account for Inclusion of New Vehicles[2]	Adjusted to Account for New Fleet Composition[3]
10	30.0	25.8	23.0	20.8
20	46.8	40.2	35.8	32.4
30	47.1	49.1	43.7	39.6
40	53.8	46.3	41.2	37.3
50	53.9	46.4	41.3	37.4
60	44.4	38.2	34.0	30.8

[1] Multiplied by a factor of 0.86.
[2] Multiplied by a factor of 0.89.
[3] Multiplied by a factor of 0.906.

Adjustment for Changes in Vehicle Composition

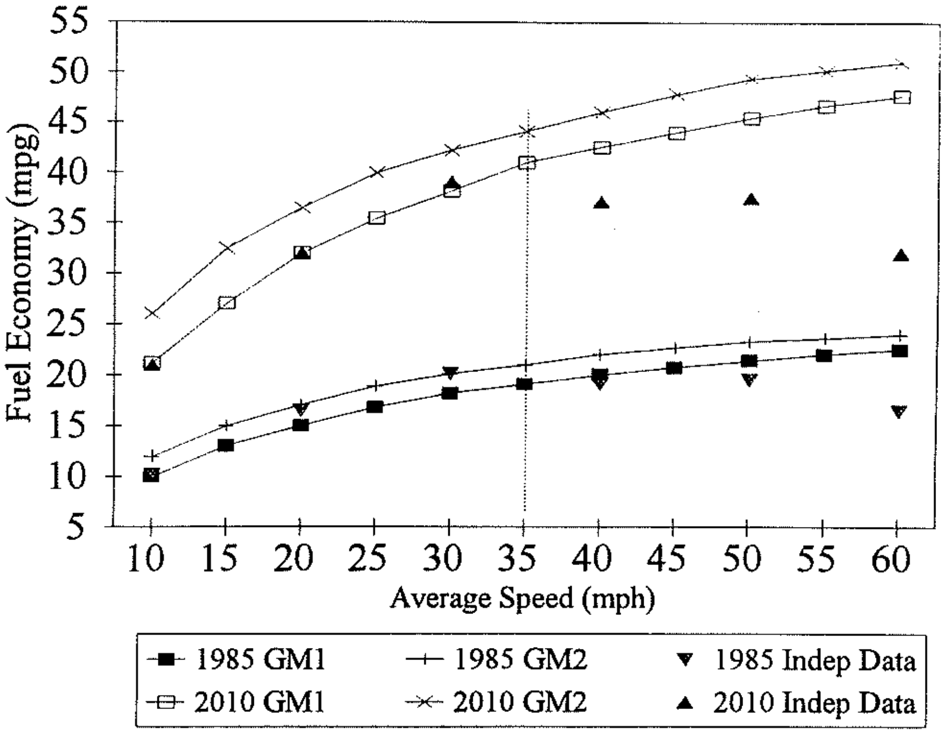
The fleet composition adjustment factor (FCAF) was developed earlier, and substituting the appropriate values for the year 2010 into Equation 6-10, the FCAF is estimated as:

$$FCAF = 1 - 0.0027 * 35 = 0.906$$

Applying this factor to the fuel conservation rates in Table 6-11 yields the fuel economy for each speed considering the increased percentage of pick-up trucks. The adjusted values are shown in the last column of Table 6-11.

Deriving Overall Equations for 1985 and 2010

Figure 6-4 shows the speed verses the estimated fuel economies for 1985 and 2010 as derived from the modified GM1 and GM2 equations (Equations 6-12 and 6-13, and Equations 6-16 and 6-17), and from the data from the independent source (46), which was adjusted and is shown in Table 6-11. The two models and the independent data exhibit similar speed-fuel economy relationships up to a speed of 35 mph after being adjusted to a common base year



* GM Models not considered valid over 35 mph

Figure 6-4. Speed-Fuel Economy Relationships for GM1 and GM2 and Data from the Independent Data Source for 1985 and 2010

(1985 and 2010). Thereafter the economies from the independent source decrease while the values derived from the two General Motors models continue to increase, but at a decreasing rate.

The optimum value, with respect to fuel economy, exhibited by the speed-fuel relationship indicated by the modified data from the independent source closely approximates the relationship that would be expected. For this reason, and because the equations derived from the GM1 and GM2 models are, strictly speaking, only valid for speeds less than 35 mph, it was decided to derive the overall speed-fuel economy equations for 1985 and 2010 by the following method:

(1) For speeds between 10 and 35 mph, data points were obtained by averaging the values from the modified GM1 and GM2 equations and from the independent data source.
(2) For speeds between 35 and 60 mph, data points were obtained by considering data from the independent source only.
(3) A least squares regression analysis was used to determine the best fit equation for each year.

Table 6-12 summarizes the data points used in the regression analysis.

Table 6-12. Estimated Fuel Economy Values Used in Regression Analysis

Speed (mph)	Fuel Economy (mpg)	
	1985	2010
10	10.9	22.6
20	16.2	33.6
30	19.5	40.1
40	19.0	37.3
50	19.2	37.4
60	15.8	30.8

The relationships that exhibited the best combination of high correlation (r^2) between speed and fuel economy, and ease of use are given by Equations 6-26 and 6-27 and illustrated in Figure 6-5.

1985 Equation ($r^2 = 0.93$)

$$E_{1985} = 25.5 - \frac{148}{\bar{V}} - 0.0018\bar{V}^2 \qquad \text{Eq. 6-26}$$

2010 Equation ($r^2 = 0.94$)

$$E_{2010} = 52.3 - \frac{298}{\bar{V}} - 0.0043\bar{V}^2 \qquad \text{Eq. 6-27}$$

Sensitivity Analysis

A sensitivity analysis was performed for the year 2010 by varying the predicted new passenger automobile fuel economy, the overall light duty fleet fuel economy, and the fleet composition by 10 percent, both higher and lower, and applying the parameters in combination to give a worst case and best case scenario. The base case scenario, which is given in Equation 6-27, assumes the parameters identified in Table 6-12. The parameters utilized to give the best case and worst case scenarios are shown in Table 6-13. The highest and lowest fuel economy scenario relationships are given by Equations 6-28 and 6-29, and shown in Figure 6-6.

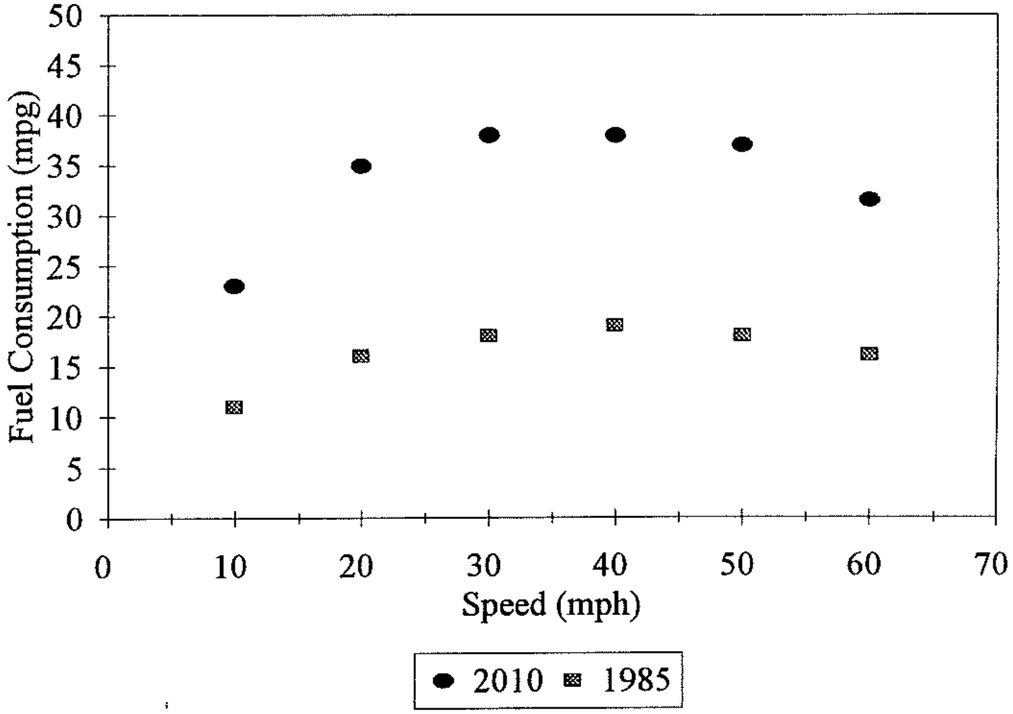


Figure 6-5. Speed-Fuel Economy "Best-Fit" for 1985 and 2010, US Light Duty Fleet

Table 6-13. Parameters Assumed in Best/Worst Case Scenario, Year 2010

	Base Case	Best Case	Worst Case
Average new passenger car fuel economy (mpg)	45	49.5	40.5
Average passenger car fleet fuel economy (mpg)	40	44	36
Percent pick-ups in light duty fleet	35	31.95	39.05
Economy of small cars/Economy of medium cars	0.81	0.81	0.81
Economy of large cars/Economy of medium cars	1.3	1.3	1.3
Relative market share for new passenger cars = fleet composition of passenger cars in the same year	$RMS_{small}=0.39$ $RMS_{medium}=0.60$ $RMS_{large}=0.01$	$RMS_{small}=0.49$ $RMS_{medium}=0.50$ $RMS_{large}=0.01$	$RMS_{small}=0.29$ $RMS_{medium}=0.60$ $RMS_{large}=0.01$

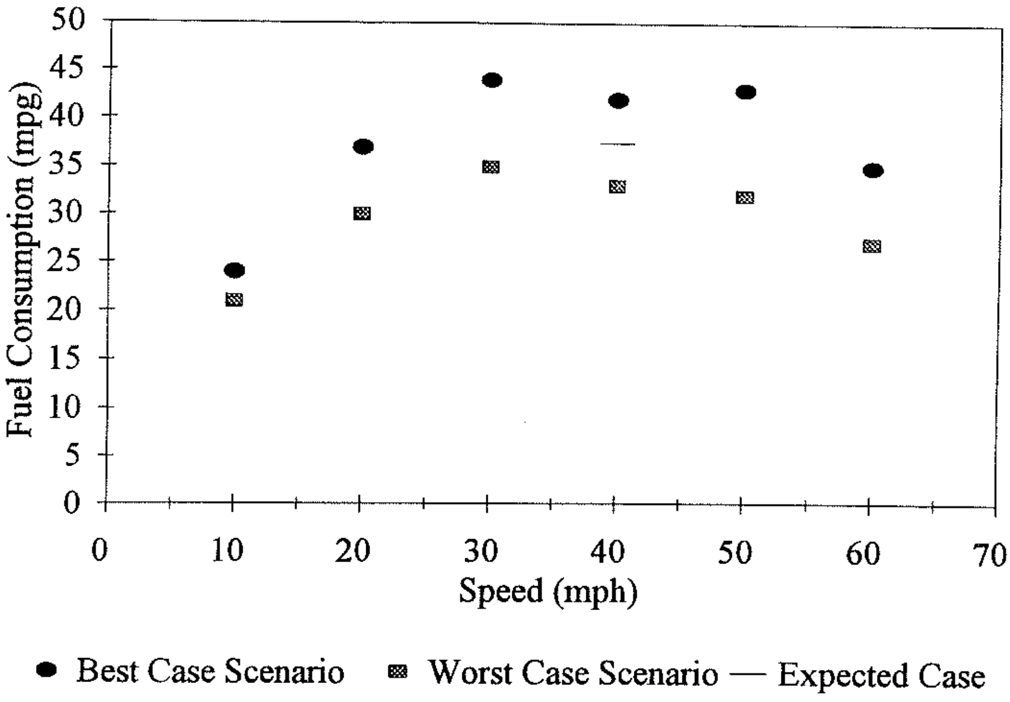


Figure 6-6. Speed-Fuel Economy Relationship for Best and Worst Case Scenarios in 2010

2010 Best Case Scenario

$$E_{2010\ Best\ Case} = 57.6 - \frac{331}{\bar{V}} - 0.0044\bar{V}^2 \qquad \text{Eq 6-28}$$

2010 Worst Case Scenario

$$E_{2010\ Worst\ Case} = 47.0 - \frac{265}{\bar{V}} - 0.0040\bar{V}^2 \qquad \text{Eq 6-29}$$

A comparison of Figures 6-5 and 6-6 indicates that considerable energy savings may be realized through the application of more stringent CAFE standards in the year 2010. Even under the low fuel economy scenario, the fuel economy of the light duty fleet could be between 60 percent (for mid-range speeds) and 100 percent (for low speeds) more than the 1985 estimated fleet averages. This includes the impact of a predicted increase in the percentage of pickup trucks in the light duty fleet, which is expected to lower fuel economy.

As a final note, the relationships developed in this chapter are based on average speed data that range from 10 to 60 mph. Consequently, the use of the equations outside of this range should be analyzed closely to insure that the results are reasonable. For speeds in the 0 to 10 mph range, it should be sufficient to linearly interpolate from the origin. This would form a piecewise function for each year as shown in Equations 6-30 through 6-33.

1985 Equations

$$E_{1985} = 1.052\bar{V} \qquad 0\ mph \leq \bar{V} < 10\ mph \qquad \text{Eq. 6-30}$$

$$E_{1985} = 25.5 - \frac{148}{\bar{V}} - 0.0018\bar{V}^2 \qquad 10\ mph \leq \bar{V} \leq 60\ mph \qquad \text{Eq. 6-31}$$

2010 Equations

$$E_{2010} = 2.207\bar{V} \qquad 0\ mph \leq \bar{V} < 10\ mph \qquad \text{Eq. 6-32}$$

$$E_{2010} = 52.3 - \frac{298}{\bar{V}} - 0.0043\bar{V}^2 \qquad 10\ mph \leq \bar{V} \leq 60\ mph \qquad \text{Eq. 6-33}$$

where:
E = Fuel economy (mpg).
$\bar{V}$ = Average speed (mph).

Conclusions

The speed-fuel economy relationships derived in this chapter illustrate the impact that higher fuel economy standards in future years will have on fuel consumption. Burning less fuel per vehicle ultimately means, among other things, emitting less pollutants per vehicle, reducing the Nation's dependence on oil imports, and reducing the amount of money spent on gasoline.

The speed-fuel relationships developed in this chapter, which are based on individual average vehicle speed, should prove useful in modeling fuel consumption not only from a microscopic level (individual vehicles), but also from a macroscopic level (areawide). In order to utilize the relationships for macroscopic level analysis, however, areawide vehicle-miles of travel must be divided into speed intervals (for example, 5 mph intervals). The smaller the speed interval, the more accurate the model, and the more rigorous the data requirements.

CHAPTER 7. AN ANALYSIS OF POTENTIAL DELAY AND FUEL SAVINGS FOR HOUSTON, TEXAS

Introduction

Legislation such as the 1991 Intermodal Surface Transportation Efficiency Act and the 1990 Clean Air Act Amendments, and the lack of success resulting from efforts to reduce traffic congestion levels over the past 20 years, have prompted various policies to reduce urban delay, energy consumption, and vehicle emissions. It is expected that congestion will continue to increase on major U.S. urban roadway systems due to an increasing number of people traveling to locations dispersed throughout the urban area.

Many strategies exist to help alleviate congestion and improve urban mobility including alternative transportation modes, land use policies, and plans to increase roadway capacity, and improve the operation of the existing infrastructure. This chapter will focus on relative comparisons of four regional scenarios for Harris County (Houston), Texas.

This chapter examined the potential travel delay and fuel savings for four regional alternatives to improve urban mobility in Houston, Texas. The intent of the chapter is to provide a comparison between the alternatives, rather than an absolute solution. As such, the methodology and the analysis may be useful to transportation planners who must consider various policies to reduce urban delay and energy consumption.

Methodology

The methodology used in this analysis consisted of identification and development of the scenarios to be analyzed, and comparison of the relative savings in delay and fuel conservation between the alternative scenarios. The various scenarios represent approaches that might be taken in response to certain kinds of policy, such as a policy that favors the construction of additional mixed flow lanes, HOV lanes, or enhanced traffic management practices.

Development of the Scenarios

The four scenarios selected for comparison represent strategies that have either been suggested or are currently being implemented in Houston. The four alternatives are listed below, and discussed in the following sections.

(1) Providing additional roadway capacity to meet the region's Year 2010 Regional Mobility Plan (RMP) network (52).

(2) Providing a strategic arterial system in concert with the roadway improvements of the Year 2010 RMP network.

(3) Improving traffic management and operations.
(4) Freeway mainlane and high-occupancy vehicle lane improvements.

Additional Roadway Capacity

The first scenario, based on the region's Year 2010 RMP network, is assumed to be the result of a continuation of areawide trends and policies initiated in the late 1980s. The Year 2010 RMP network, is an optimistic "wish list" of mobility improvements that could be implemented only if funding levels are substantially increased. The goal of the RMP is to strengthen Houston's position in the economic market relative to other U.S. cities by significantly improving the region's mobility; the network may not be realized by 2010 due to financial and environmental limitations. Nevertheless, it provides a basis for comparison because it represents a continued commitment to roadway construction.

Strategic Arterial Network

The second scenario was first examined by Benson and Mullins in a 1990 Texas Transportation Institute (TTI) research report (53). They suggested implementing a system of strategic arterials in concert with the Year 2010 RMP network. The strategic arterial system proposed does not represent an entirely new system of streets, but instead represents improvements to key arterials. As a result, a major portion of the proposed strategic arterial system is currently represented in the baseline system.

Benson and Mullins divided the strategic arterial system into two alternatives for Harris County: a 460-mile system and a 250-mile system. The 460-mile system consists of 24 individual arterials and represents a very extensive system. The 250-mile system, on the other hand, consists of 15 individual arterials and represents a more conservative (although still significant) system. The effect of both strategic arterial alternatives were analyzed using two estimated speed advantages (5 and 10 mph) over the typical arterial. This approach resulted in the analysis of a total of four strategic arterial network scenarios: two 250-mile networks, and two 460-mile networks.

Management and Operational Improvements

Scenario three attempts to simulate significant traffic management and operational improvements throughout the region. The assumption is that a ten percent increase in vehicle throughput on freeways and principal arterials may be achieved as a result of various transportation systems management and operational improvement measures. This assumption was modeled as a ten percent increase in capacity on the affected roads. Two alternatives were examined under this scenario:

(1) A region-wide ten percent increase in capacity on freeways only.
(2) A region-wide ten percent capacity increase on freeways and principal arterials.

These two alternatives were then compared to the base system.

Although no single action will increase the capacity of the entire region by ten percent, a coordinated combination of management and operational strategies may result in such an overall improvement. Some of the strategies that might be included are: coordination of traffic signals along an arterial, improved signal timing at isolated intersections to eliminate bottlenecks, implementation of freeway ramp metering, motorist information systems, incident detection and response programs, construction of additional freeway lanes for short sections to eliminate congestion, addition of exclusive turn lanes at high volume intersections, and enforcement of access prohibitions along arterial streets.

Freeway Corridor Improvements

The fourth scenario involved the evaluation of alternatives on three freeways in the Harris County freeway network: I-10 West (Katy Freeway), I-45 North (North Freeway), and U.S. 290 (Northwest Freeway). The alternatives examined were: (1) maintain basic freeway operations, which was considered the base case for comparison, (2) add a high-occupancy vehicle (HOV) lane, and (3) add a general purpose lane in each direction, (4) add two general purpose lanes in each direction, and (5) implement freeway traffic management practices to increase the freeway capacity by 10 percent. Under the maintain basic operations alternative, it is assumed that the four freeways maintain their present number of lanes with no HOV lanes. The second alternative assumed an HOV lane was added to the first alternative. The third and fourth alternatives examined were the addition of one and two general purpose lanes in each direction to the freeway cross section evaluated in the first alternative. The fifth alternative examined the impacts of the implementation of freeway traffic management practices that would increase the freeway capacity by 10 percent. The goal of this comparison was to identify the effects of additional freeway or HOV lanes considering a range of congestion levels on the different freeways.

Summary

Each of the four scenarios was analyzed using various methods as dictated by the availability of data and resources. The intent of the analysis was to compare relative savings in delay and fuel consumption between the scenarios. As such, the primary measure-of-effectiveness was the percent savings, as compared to the base scenario, rather than an examination of the absolute savings among the scenarios, or the absolute performance of any single scenario.

Data Acquisition

The first and second alternative scenarios, the RMP and the strategic arterial scenario, were both modeled in the Benson and Mullins travel demand study (53). Their study utilized projected socioeconomic data and traffic assignment results for the forecast year 2010 from the 1989 Houston-Galveston Area Council (HGAC) summary. The results of the Benson and Mullins report provided data on projected vehicle-miles of travel (VMT), vehicle-hours of travel (VHT) and weighted average speeds for freeways, strategic arterials, principal arterials, other arterials, and collectors for the Harris County region.

Data for the improved transportation management and operation scenario, the third scenario, was obtained using the travel demand model employed by Benson and Mullins, which was used to model scenarios one and two. Benson's expertise was utilized to set up the network and model the travel demand for this scenario. Although the network utilized for this scenario may not be identical to the RMP and strategic arterial scenario network, it is very similar; both of the networks were developed by Benson, and no different major travel corridors were modeled. The results from the travel demand model are projected vehicle-miles traveled (VMT), vehicle-hours traveled (VHT), and weighted average speeds for the year 2010 for the various functional classifications in Harris County.

The freeway system alternatives scenario (Number 4) was modeled with FREQ10 (54) using 1992 volumes obtained from a TTI database on freeway and HOV lane operations (55). FREQ10 is a macroscopic deterministic computer program which simulates freeway operation. The program allows the user to analyze the effects of design and operational improvements. Output from the FREQ 10 model includes average speed, fuel consumption, total travel time (vehicle-hours and passenger-hours), and total travel distance (vehicle-miles and passenger-miles).

Recent fuel consumption data, based on vehicle speed, VMT, and vehicle mix for the Dallas-Fort Worth region, was obtained from the North Central Texas Council of Governments (NCTCOG) to update the FREQ10 model. Table 7-1 gives the fuel consumption rates used in FREQ10 for this study.

The auto fuel consumption values in Table 7-1 represent a weighted average of light duty gas vehicles, light duty gas trucks, light duty diesel vehicles, light duty diesel trucks, and motorcycle consumption rates obtained from NCTCOG. Table 7-2 shows the various vehicle classifications used by NCTCOG and the corresponding vehicle mix that was assumed.

Although the values in Table 7-1 are appropriate for modeling the general purpose lanes in the urban freeway scenario, they do not adequately approximate the characteristics of an HOV lane. An HOV lane will primarily carry light duty gas vehicles and buses. Consequently, the fuel consumption rates were adjusted to reflect the change in vehicle mix. It was assumed that diesel engine characteristics have not changed significantly over the past decade. This assumption is plausible, because heavy combination trucks have not experienced significant improvements in fuel economy since 1980.

Thus, adjustments are required only for auto fuel consumption. The auto fuel consumption rates are obtained from the light duty gas vehicle rates given by NCTCOG. The adjusted values are shown in Table 7-3.

Table 7-1. Fuel Consumption and Emission Rates Used in FREQ Model Analysis

Speed (mph)	Auto Fuel Consumption (gal/mile)	SU Truck Fuel Consumption (gal/mile)	Comb. Diesel Fuel Consumption (gal/mile)
Idling	0.343 gal/hr[1]	0.695 gal/hr[1]	1.297 gal/hr[1]
5	0.068	0.150	0.252
10	0.059	0.125	0.197
15	0.049	0.099	0.141
20	0.047	0.096	0.122
25	0.045	0.093	0.102
30	0.047	0.099	0.108
35	0.049	0.104	0.114
40	0.053	0.115	0.129
45	0.057	0.126	0.144
50	0.061	0.135	0.151
55	0.066	0.144	0.158
60	0.070	0.155	0.169
65	0.074	0.165	0.179
70	0.078	0.176	0.190

[1] Obtained from the FREQ10 default values.

[2] Obtained using Equation 7-1.

Source: North Central Texas Council of Governments, FREQ10, and EPA's MOBILE4 data.

Delay

Delay is defined as the difference in travel time between free-flow or light traffic conditions and congested conditions. In congested conditions, travel is affected by the interaction of other vehicles in the traffic stream. Applying this definition, a simple estimation of delay can be made as shown in Equation 7-1.

Table 7-2. NCTCOG's Vehicle Classification and Assumed Mix

Vehicle Classification	Vehicle Mix in Percent
Light Duty Gas Vehicle[1]	64
Light Duty Gas Truck 1 (up to 6500 lbs.)[1]	15
Light Duty Gas Truck 2 (6500 to 8000 lbs.)[1]	10
Light Duty Diesel Vehicle[1]	1
Light Duty Diesel Truck[1]	1
Motorcycle[1]	1
Heavy Duty Gas Vehicle	3
Heavy Duty Diesel Vehicle	5

[1] These vehicles are assumed to fall into the general auto classification.
Source: North Central Texas Council of Governments.

$$\textit{Delay} = \frac{\textit{Vehicle Miles Traveled}}{\textit{Avg. Speed}} - \frac{\textit{Vehicle Miles Traveled}}{\textit{Free Flow Avg. Speed}} \qquad \text{Eq. 7-1}$$

Delay for all tested scenarios was calculated for each functional class based on the following assumed free-flow speeds: freeways, 55 mph; strategic arterials, 40 mph; principal and other arterials, 35 mph; and collectors, 30 mph.

The methodology used in this chapter to calculate areawide fuel consumption for scenarios 1, 2 and 3 is similar to calculations made in Chapter 3 of this report. The model is based on total VHT, average speed, and the average fuel efficiency in the region. The equation used to calculate fuel consumption (rearranged slightly from Chapter 3) is shown as Equation 7-2. Equation 7-2 calculates the total fuel consumption based on the total travel.

$$\textit{Fuel Consumption} = \frac{\textit{Vehicle Miles Traveled}}{8.8 + (0.25 * \textit{Avg. Vehicular Speed})} \qquad \text{Eq. 7-2}$$

Lindley's modification of Raus' model (Chapter 3, Equation 3-6) was used to determine the average fuel mileage from the average vehicular speed in the urban area. The equation assumes a linear relationship between average speed and average fuel mileage. Although this is not the case for individual vehicles, it does give more reasonable results on a region-wide

Table 7-3. Adjusted Values to Fuel Consumption and Emission Rates for HOV Lanes

Speed (mph)	Auto Fuel Consumption (gal/mile)	Comb. Diesel HC Emissions (gram/mile)	Comb. Diesel CO Emissions (gram/mile)	Comb. Diesel NO Emissions (gram/mile)
Idling	0.343 gal/hr	0.420 gm/min	0.760 gm/min	1.01 gm/min
5	0.072	8.80	71.69	34.04
10	0.061	6.83	50.62	27.28
15	0.050	5.45	37.12	22.95
20	0.047	4.47	28.25	20.25
25	0.044	3.76	22.31	18.72
30	0.045	3.26	18.27	18.14
35	0.046	2.90	15.53	18.41
40	0.049	2.64	13.69	18.59
45	0.052	2.48	12.53	21.87
50	0.055	2.38	11.91	25.62
55	0.058	2.35	11.76	31.53
60	0.061	2.39	12.10	40.82
65	0.064	2.39	12.10	50.11
70	0.067	2.39	12.10	59.40

Source: North Central Texas Council of Governments and FREQ10.

basis than do the individual vehicle curves developed in Chapter 6. This model is thought to be appropriate for the planning-level analysis being performed.

This method of calculating fuel consumption is employed for the RMP scenario, the strategic arterial scenario, and the improved traffic management and operation scenario. The fuel consumption for the urban freeway alternatives was estimated by the FREQ10 program with the modified fuel consumption rates discussed previously.

Results

This section provides the results of the comparison of the delay and fuel consumption analyses for the four scenarios evaluated. Note that these results are evaluated based on the percent savings, relative to the base scenario.

Strategic Arterial Scenario

Tables 7-4A and B show the delay and fuel consumption values calculated for each functional class of roadway in the RMP base network scenario and the four strategic arterial scenarios. Tables 7-4A and B, and 7-5A and B show an interesting trend between the four alternatives in terms of daily delay savings. Both the 250-mile and 460-mile strategic arterial networks reduced the delay incurred on the strategic arterials under the "+5 mph" alternative. However, both networks actually showed increases in the estimated delay under the "+10 mph" alternatives. The "+10 mph" alternatives for each of the strategic arterial networks "attracted" a significant increase (14 percent) in VMT over the "+5 mph" alternative. As a result of the increased volume, there was essentially no improvement in the average speed. Delay was calculated relative to the desired speed, which in this case was 5 mph higher than the "+5 mph," and the total delay increased incrementally for each additional vehicle mile traveled.

As shown in Tables 7-5A and B, each of the four alternative scenarios substantially reduced the areawide delay. Delay reductions from 11 to 23 percent were estimated, despite the increase in delay on the strategic arterials under the "+10 mph" alternatives. Note that both the freeway and arterial systems appear to significantly benefit from the implementation of a strategic arterial network. The results of this analysis indicate that Harris County freeways would benefit substantially from an improved arterial system; the current arterial network forces freeway facilities to carry a disproportionate amount of the VMT.

Improved Traffic Management Scenario

Table 7-6 shows the estimated daily delay and fuel consumption for the third scenario, which mandates operational improvements to the freeway system, and to the freeway and arterial street systems. With a ten percent increase in freeway capacity, freeway delay was reduced by 42,000 vehicle-hour per day, and areawide delay was reduced 13 percent, as shown in Table 7-7. One effect of this alternative was an increase in daily freeway vehicle-miles traveled of 740,000; most of these miles appeared to have been diverted from the arterial street system.

The alternative designating a ten percent increase in freeway and principal arterial capacity was designed to minimize the shift in vehicle travel. As was the case with the increase in freeway capacity alternative, there were significant delay savings despite increases of 610,000 daily VMT on the freeway system and 140,000 daily VMT on the principal arterial street system. Areawide delay savings with this alternative was calculated to be 16 percent, as shown in Table 7-7.

Both alternatives reduced the estimated delay on the upgraded facilities as well as on the facilities that were not upgraded. This reduction in delay on all facilities, even for which there was no increase in capacity, is the result of a shift in VMT from the unimproved facilities to the upgraded facilities which, in turn, increased the average speeds on the unimproved facilities.

Table 7-4A. Daily Delay and Fuel Consumption for the RMP and 250 Mile Strategic Arterial Scenarios

Facility	2010 Harris County Network with 250 Miles of Strategic Arterial					
	RMP (Base) Network		+5 mph Alternative		+10 mph Alternative	
	Delay (1,000 veh-hr)	Fuel (1,000 gal)	Delay (1,000 veh-hr)	Fuel (1,000 gal)	Delay (1,000 veh-hr)	Fuel (1,000 gal)
Freeways	281.2	2,835.1	267.2	2,693.4	235.7	2,619.2
Strategic Arterials	48.6	357.7	44.3	591.6	86.8	684.1
Principal Arterials	23.4	383.5	21.2	346.7	15.4	342.4
Other Arterials	151.9	1,600.6	112.0	1,443.1	109.3	1,408.0
Collector	5.1	134.9	4.8	127.8	4.7	125.6
TOTAL	510.2	5,311.8	449.5	5,202.6	451.9	5,179.3

Source: TTI Analysis

Table 4B. Daily Delay and Fuel Consumption for the RMP and 460 Mile Strategic Arterial Scenarios

Facility	2010 Harris County Network with 460 Miles of Strategic Arterial					
	RMP (Base) Network		+5 mph Alternative		+10 mph Alternative	
	Delay (1,000 veh-hr)	Fuel (1,000 gal)	Delay (1,000 veh-hr)	Fuel (1,000 gal)	Delay (1,000 veh-hr)	Fuel (1,000 gal)
Freeways	281.2	2,835.1	230.9	2,565.6	200.3	2,473.0
Strategic Arterials	57.6	479.7	43.7	836.7	78.6	939.6
Principal Arterials	23.1	377.9	20.6	338.3	14.9	331.4
Other Arterials	141.1	1,487.3	98.6	1,270.9	95.8	1,234.7
Collector	7.2	124.4	6.0	103.5	5.8	101.5
TOTAL	510.2	5,304.5	399.8	5,114.9	395.5	5,080.2

Source: TTI Analysis

Table 7-5A. Percent Savings in Delay and Fuel Consumption of the 250 Mile Strategic Arterial Scenario Relative to the RMP Scenario

Facility	250 Mile Strategic Arterial Network			
	+5 mph Alternative		+10 mph Alternative	
	Delay	Fuel	Delay	Fuel
Freeways	5.0[1]	6.0	16.2	7.6
Strategic Arterials	8.8	-65.4[2]	-78.6	-91.2
Principal Arterials	9.6	9.6	34.1	10.7
Other Arterials	26.2	9.8	28.0	12.0
Collector	5.3	5.3	6.9	6.9
Total	11.9	2.1	11.4	2.5

Source: TTI Analysis.

[1] Positive values indicate a decrease in delay or fuel consumption.

[2] Negative values indicate an increase in delay or fuel consumption.

Table 5B. Percent Savings in Delay and Fuel Consumption of the 460 Mile Strategic Arterial Scenario Relative to the RMP Scenario

Facility	460 Mile Strategic Arterial Network			
	+5 mph Alternative		+10 mph Alternative	
	Delay	Fuel	Delay	Fuel
Freeways	17.9[1]	9.5	28.8	12.8
Strategic Arterials	24.2	-74.4[2]	-36.4	-95.9
Principal Arterials	10.5	10.5	35.3	12.3
Other Arterials	30.1	14.6	32.1	17.0
Collector	16.7	16.7	18.4	18.4
Total	21.6	3.6	22.5	4.2

Source: TTI Analysis.

[1] Positive values indicate a decrease in delay or fuel consumption.

[2] Negative values indicate an increase in delay or fuel consumption.

Table 7-6. Calculated Daily Delay and Fuel Consumption for Improved Traffic Management and Operation Scenario

Facility	Base Network		+10% Freeway Capacity		+10% Freeway & Principal Arterial Capacity	
	Delay (1,000 veh-hr)	Fuel (1,000 gal)	Delay (1,000 veh-hr)	Fuel (1,000 gal)	Delay (1,000 veh-hr)	Fuel (1,000 gal)
Freeways	269.4	456.5	227.1	447.1	221.2	444.1
Principal Arterials	25.6	107.8	21.2	105.0	17.7	106.6
Other Arterials	124.2	311.3	116.6	303.9	112.6	300.6
Collectors	0.7	24.3	0.6	24.0	0.5	23.9
TOTAL	419.9	899.8	365.5	880.0	352.1	875.3

Source: TTI Analysis

Table 7-7. Percent Savings in Delay and Fuel Consumption for Improved Traffic Management and Operation Scenario

Facility	+10% Freeway Capacity Increase		+10% Freeway & Principal Arterial Capacity Increase	
	Delay	Fuel	Delay	Fuel
Freeways	15.7[1]	2.1	17.9	2.7
Principal Arterials	17.3	2.5	30.9	1.0
Other Arterials	6.17	2.4	9.3	3.4
Collectors	14.2	1.0	21.3	1.6
Total	13.0	2.2	16.2	2.7

Source: TTI Analysis.

[1] Positive values indicate a decrease in delay or fuel consumption.

The delay reductions on unimproved facilities shown in Table 7-7 are the result of both the higher average speed, and lower VMT. Areawide average speeds did not change for two freeway alternatives, but did increase by two mph when both the freeways and arterials were improved.

As was the case under the strategic arterial scenario, the significant savings in areawide delay do not appear to translate into fuel consumption savings of the same magnitude. Areawide fuel savings are minimal on a percentage basis (2 to 3 percent), although they are estimated to represent an annual savings of 25,000 gallons.

Comparison of Freeway Improvements

This section discusses the evaluation of the fourth scenario, the alternatives on three freeway corridors in the Harris County freeway network: I-10 West (Katy Freeway), I-45 North (North Freeway), and U.S. 290 (Northwest Freeway). The alternatives examined were:

(1) Maintain basic freeway operations.
(2) Add a high-occupancy vehicle (HOV) lane.
(3) Add a general purpose lane.
(4) Add two general purpose lanes.
(5) Implement freeway traffic management strategies.

Under the maintain basic operations alternative, it was assumed that the three freeways maintain their present number of lanes with no HOV lanes. The second alternative assumes an HOV lane has been added to the basic operations alternative. The second alternative is the existing configuration on the four freeways. The third and fourth alternatives add one and two general purpose lanes to the freeway cross section analyzed in the first alternative. The fifth alternative examined the effects of the implementation of freeway traffic management practices which would increase the freeway capacity by ten percent. The goal of this comparison was to identify the effect of additional freeway or HOV lanes on freeways, considering percentage changes in delay and fuel consumption.

The FREQ10 model was used to analyze the impacts of the alternative improvements on three Houston freeway corridors. This analysis provided an estimate of travel delay as part of the model output, in addition to estimates of the travel time and fuel consumption. The model was run with 55 mph representing the desired operational speed for each freeway; delay was defined by speeds below that level. Each of the four scenarios was then reviewed for each freeway corridor, and conclusions were drawn based on the results of all freeway corridors.

Table 7-8A provides the estimated travel time, delay, speed and fuel consumption for the various alternatives on the Katy, North, and Northwest freeways in Houston. Table 7-8B provides the percent change in these values compared to the base case, which is no additional freeway or HOV lanes. In Table 7-8B, the alternative that provides the greatest decrease in total delay, and gasoline consumption is shaded. For each freeway corridor, the addition oa a single HOV lane results in the greatest reduction in fuel consumption. For severely congested corridors like the Katy Freeway, the HOV lane alternative provided delay savings comparable to adding two freeway lanes. For moderately congested corridors like the North and Northwest Freeways, the HOV lane alternative compared favorably (in terms of delay reduction) to the addition of one freeway lane. It should also be noted that the addition of two general purpose lanes is typically not a feasible option in most freeway corridors due to cost and right-of-way considerations.

As shown in Table 7-8A, peak operating speeds and total delay from the three study corridors indicate that, under the basic freeway scenario, the Katy Freeway (I-10 West) is the most congested of the four Houston freeways, followed by the North Freeway (I-45 North), and the Northwest Freeway (US 290). When considering the results of this analysis, it is important to note that the congestion level on the freeway will have an impact on the relative improvement offered by the various alternatives.

The Katy Freeway is a radial freeway in west Houston. The section of freeway modeled with FREQ10 is eight lanes wide near the western end, but is six lanes over most of the length. As shown in Table 7-8B, the HOV alternative for the Katy Freeway provided an approximate 83 percent reduction in passenger-hours of delay, which compares favorably with the reduction provided by the addition of two general purpose lanes. The HOV alternative also provided the greatest reduction in fuel consumption and the largest increase in speed.

The North Freeway, a radial freeway north of Houston, also benefitted the most by the addition of an HOV lane when considering fuel consumption and vehicle emissions. In this case, implementation of an HOV lane resulted in a 6 percent decrease in fuel consumption. Because the North Freeway is less congested than the Katy Freeway, it resulted in a smaller reduction in passenger-hours of delay than adding either one or two freeway lanes.

Similar results were also obtained for the Northwest Freeway, a radial freeway northwest of Houston. This facility also benefitted the most by the addition of an HOV lane when considering fuel consumption. Implementation of an HOV lane resulted in a 7 percent decrease in fuel consumption. As was the case on the other three freeways, although the HOV option resulted in less fuel consumption, it did not result in the greatest reduction in delay. Adding either a single freeway lane or two freeway lanes resulted in slightly greater reductions in passenger-hours of delay. However, the addition of two freeway lanes in each direction is not a realistic option along any of the freeway corridors being analyzed.

Table 7-8A. Calculated Delay and Fuel Consumption for Freeway Corridor Improvements

	FREQ10 Results				
	Basic Freeway Case 1	Frwy with HOV lane Case 2	Add 1 Lane Case 3	Add 2 Lanes Case 4	Traffic Management Case 5
KATY FREEWAY					
Total Travel Time, Veh-Hours	48,298	13,512	37,490	29,646	37,444
Total Travel Time, Pas-Hours	59,012	16,482	45,684	36,031	45,813
Total Travel Distance, Veh-Miles	508,622	480,600	508,419	508,106	508,566
Total Travel Distance, Pas-Miles	620,250	620,250	620,250	620,250	620,250
Total Delay, Veh-Hours	22,486	4,417	14,562	3,966	20,409
Total Delay, Pas-Hours	27,421	4,607	17,765	4,841	24,891
Average Speed, MPH	16	41[1]	21	39	17
Gasoline Consumed, Gallons	37,345	31,706	36,100	40,011	33,840
NORTH FREEWAY					
Total Travel Time, Veh-Hours	19,590	14,778	14,239	11,507	15,594
Total Travel Time, Pas-Hours	22,801	17,962	16,577	13,379	18,159
Total Travel Distance, Veh-Miles	455,002	421,159	454,878	454,840	454,964
Total Travel Distance, Pas-Miles	529,578	529,578	529,578	529,578	529,578
Total Delay, Veh-Hours	7,296	3,028	1,798	0	5,804
Total Delay, Pas-Hours	8,492	3,363	2,093	0	6,756
Average Speed, MPH	29	42[1]	46	58	35
Gasoline Consumed, Gallons	29,532	28,900	32,406	34,252	29,166
NORTHWEST FREEWAY					
Total Travel Time, Veh-Hours	12,710	8,216	8,181	7,850	11,003
Total Travel Time, Pas-Hours	13,516	9,619	8,698	8,346	11,696
Total Travel Distance, Veh-Miles	452,051	403,843	452,051	452,187	452,187
Total Travel Distance, Pas-Miles	480,575	480,575	480,575	480,575	480,575
Total Delay, Veh-Hours	4,251	1,063	0	0	2,962
Total Delay, Pas-Hours	4,519	1,127	0	0	3,149
Average Speed, MPH	37	51[1]	58	58	41
Gasoline Consumed, Gallons	29,228	27,330	32,864	32,874	29,854

Source: TTI Analysis

Notes: [1] Average Speed Weighted by Passenger-Miles of Travel

Table 7-8B. Percent Change in Delay and Fuel Consumption for Freeway Corridor Improvements

	Percent Change from Basic Freeway Case			
	Frwy with HOV lane Case 2	Add 1 Lane Case 3	Add 2 Lanes Case 4	Traffic Management Case 5
KATY FREEWAY				
Total Travel Time, Veh-Hours	-72%	-23%	-39%	-23%
Total Travel Time, Pas-Hours	-72%	-23%	-39%	-22%
Total Travel Distance, Veh-Miles	-6%	0%	0%	0%
Total Travel Distance, Pas-Miles	0%	0%	0%	0%
Total Delay, Veh-Hours	-84%	-35%	-82%	-9%
Total Delay, Pas-Hours	-83%	-35%	-82%	-9%
Average Speed, MPH	156%[1]	31%	144%	6%
Gasoline Consumed, Gallons	-15%	-3%	7%	-9%
NORTH FREEWAY				
Total Travel Time, Veh-Hours	-27%	-27%	-41%	-20%
Total Travel Time, Pas-Hours	-23%	-27%	-41%	-20%
Total Travel Distance, Veh-Miles	-11%	0%	0%	0%
Total Travel Distance, Pas-Miles	0%	0%	0%	0%
Total Delay, Veh-Hours	-59%	-75%	-100%	-20%
Total Delay, Pas-Hours	-60%	-75%	-100%	-20%
Average Speed, MPH	27%[1]	46%	100%	10%
Gasoline Consumed, Gallons	-6%	10%	16%	-1%
NORTHWEST FREEWAY				
Total Travel Time, Veh-Hours	-36%	-36%	-38%	-14%
Total Travel Time, Pas-Hours	-29%	-36%	-38%	-14%
Total Travel Distance, Veh-Miles	-11%	0%	0%	0%
Total Travel Distance, Pas-Miles	0%	0%	0%	0%
Total Delay, Veh-Hours	-75%	-100%	-100%	-30%
Total Delay, Pas-Hours	-75%	-100%	-100%	-30%
Average Speed, MPH	38%[1]	51%	57%	11%
Gasoline Consumed, Gallons	-7%	10%	12%	2%

Source: TTI Analysis

Notes: [1] Average Speed Weighted by Passenger-Miles of Travel

Conclusion

The strategic arterial scenario resulted in significant delay reductions, from 11 to 23 percent, but minimal savings in fuel consumption (less than five percent). Similarly, the improved traffic management scenario resulted in significant savings in delay, in this case 13 to 16 percent, but minimal reductions in fuel consumption on a percentage basis (less than three percent). However, even small percentage reductions in the fuel consumption can make a contribution to overall fuel savings, for example, the reduction of two to three percent expected under the improved traffic management scenario represents an annual savings of 25,000 gallons of fuel.

With respect to the comparison of the freeway alternatives, the results of this analysis clearly indicate that addition of an HOV lane is the best solution to reduce fuel consumption. The second best alternative to minimize fuel consumption is the implementation of traffic management practices to increase the capacity of the freeway by ten percent. It is worth noting that while the HOV alternative reduces fuel consumption for all three freeways when compared to the basic freeway case, the implementation of traffic management practices results in an a minor decrease in fuel consumption over the basic freeway case for Katy and North Freeways, and a small increase for Northwest Freeway. However, the increase in fuel consumption is less than under any alternative other than the HOV alternative.

The addition of an HOV lane will result in the greatest reduction in fuel consumption, when compared to the basic freeway case. For each freeway corridor, the addition oa a single HOV lane results in the greatest reduction in fuel consumption. For severely congested corridors like the Katy Freeway, the HOV lane alternative provided delay savings comparable to adding two freeway lanes. For moderately congested corridors like the North and Northwest Freeways, the HOV lane alternative compared favorably (in terms of delay reduction) to the addition of one freeway lane. However, the addition of two general purpose lanes is typically not a realistic option due to funding and right-of-way constraints.

The HOV lane alternatives also reduced delay by a lower amount than the add one lane alternatives for all but the most congested corridor. The Katy Freeway HOV lane analysis is indicative of the point at which travel time savings is greater due to the emphasis on person movement, than an alternative that focuses on vehicle movement.

CHAPTER 8. SUMMARY, RECOMMENDATIONS, AND CONCLUSION

Summary

The objective of this research was to explore the relationship between energy efficiency and transportation. In order to meet this objective, the relationship between energy efficiency and specific aspects of transportation were analyzed. This research analyzed the relationship between urban congestion and energy use, the energy efficiency of local bus operations, the energy efficiency of park-and-ride services, the relationship between energy efficiency and vehicle speed in an urban environment, and the energy efficiency and vehicle delay under various transportation scenarios in Houston, Texas.

Land Use Patterns and Transportation Energy Use

Chapter 2 identified various land use, transportation and socioeconomic variables affecting transportation energy consumption. Based on the analysis of data from 25 major international cities, it was found that 91 percent of the variability in the per capita energy consumption could be accounted for by seven independent variables: population density, employment density, concentration of employment, vehicle ownership, average income, percentage of mass transit ridership, and gasoline price. Although each variable had a meaningful impact on per capita energy consumption, no conclusions were drawn with respect to the relative importance of each independent variable.

Perhaps the most illustrative result of this analysis was that increasing gasoline prices have a significant influence on decreasing transportation energy consumption. This influence of gasoline price on transportation energy consumption explains the extensive urban sprawl characteristic of many modern U.S. cities. Generally, the results of this study have confirmed those found in the literature.

Mobility Trends and Energy Use

Chapter 3 examined the relationship between urban congestion and excess fuel consumption. This chapter presented a methodology for estimating the excess fuel consumption of vehicles operating in congested travel conditions, using estimates of delay, average vehicle speed, and average fuel efficiency to calculate the gallons of excess fuel consumed in congestion in fifty urban areas in the United States. In 1991, the amount of fuel wasted in congestion totaled more than 4.6 billion gallons. Wasted fuel correlated with congestion to some extent, six of the top ten most congested urban areas were also in the top ten with respect to the largest amount of wasted fuel. The most congested urban area, Los Angeles, was also the area had the largest amount of wasted fuel.

To further explore the relationship between excess fuel consumption and congestion level, the values of excess fuel consumption for each urban area were normalized by values of travel (VMT), population size, and vehicles for the respective urban area. The closest relationship ($r^2 = 0.58$) was demonstrated between congestion level and excess fuel consumption per 1,000 VMT. A model that estimated the gains in fuel efficiency for various levels of congestion indicated that in 1995, the Houston area could reduce wasted fuel by as much as 15 million gallons by reducing the congestion level.

Energy Efficiency of Local Bus Service

Chapter 4 examined the energy efficiency of local bus service. The results of this analysis indicated that socioeconomic factors usually associated with transit ridership are correlated with local bus transit energy efficiency. As might also be expected, the analysis indicated that peak-period operations are typically associated with higher transit energy efficiency than off-peak period operations. Furthermore, there appeared to be a general trend of increasing energy efficiency (measured in passenger-miles per gallon) with larger fleet sizes in the four Texas cities examined.

The factors studied in this analysis included the number of autos in the household, the population density along the route, the percentage of workers in the central business district, and the travel time to work. All of these correlated with increased energy efficiency. The one factor studied that did not correlate with increased energy efficiency was income, which may be due to the fact that transit is considered, in economic terms, an inferior good. The percent of work trips to the central business district (CBD) had the highest R^2 value, indicating the highest correlation with energy efficiency, with an R^2 value of 0.69. Although the R^2 values resulting from the analysis of this sample reflect some correlation in the data, these conclusions should be viewed cautiously since the sample was limited both with respect to size and the number of transit systems represented.

Energy Efficiency of Park-and-Ride Service

Chapter 5 examined the relationship between socioeconomic characteristics of park-and-ride lot market areas and the fuel efficiency of the park-and-ride service provided. The results of the regression analysis indicate little or no correlation between socioeconomic characteristics and energy efficiency in the three cities studied. The energy efficiency for park-and-ride lots varied from a high of 195 passenger-miles per gallon to a low of 21 passenger-miles per gallon. Despite this large range, the average fuel efficiencies for each city were relatively consistent, with 73 passenger-miles per gallon in Dallas and 63 passenger-miles per gallon in both Houston and San Antonio.

There was significant variance in the correlation of energy efficiency to socioeconomic factors in the three cities studied. This may have been partially due to the service differences between the cities, and due to the difference in the number of park-and-ride facilities operating in each city.

Additional data are needed to definitively determine the relationship between energy efficiency and socioeconomic characteristics. Based on the results of this analysis, ridership was the only factor that correlated with energy efficiency. Although the results of this analysis do not provide definitive conclusions to the issue of socioeconomic variables and energy efficiency, the analysis procedure developed in this research does provide an appropriate methodology for future research efforts.

Energy Efficiency and Vehicle Speed in an Urban Environment

The speed-fuel economy relationships derived in Chapter 6 illustrated the positive impact that higher fuel economy standards in future years will have on fuel consumption. The models indicate that optimal fuel economy can be expected in the range from 25 mph to 50 mph, with fuel economy decreasing at higher and lower speeds.

The speed-fuel relationships developed, which are based on individual average vehicle speed, should prove useful in modeling fuel consumption not only from a microscopic level (individual vehicles), but also from a macroscopic level (areawide). In order to utilize the relationships for macroscopic level analysis, areawide vehicle-miles of travel must be divided into speed intervals. The smaller the speed interval, the more accurate the model, and the more rigorous the data requirements.

Fuel Savings under Alternative Transportation Scenarios

Chapter 7 examined the fuel consumption, and delay under a number of alternative transportation scenarios in Houston, Texas. Although both the strategic arterial scenario, which consisted of improvements to key arterials, and the improved traffic management scenario, which consisted of the implementation of traffic management practices to result in a ten percent increase in capacity, resulted in significant reductions in delay, these scenarios did not result in large decreases in fuel consumption (decreases were all less than five percent).

The results of the freeway alternatives analysis indicate that, considering the alternatives studied, addition of an HOV lane is the best solution to reduce fuel consumption. The second best alternative to minimize fuel consumption was implementation of traffic management practices to increase the capacity of the freeway by ten percent. It is worth noting that while the HOV alternative reduces fuel consumption when compared to the basic freeway case, the implementation of any of the other alternatives results in an increase in fuel consumption over the basic freeway case.

While the addition of an HOV lane will result in the greatest reduction in fuel consumption, it will not result in the greatest reduction in vehicle delay, which can be accomplished by the addition of two freeway lanes. In every scenario, congestion was almost completely eliminated with the addition of two freeway lanes. However, this solution may not always be feasible due to funding, right-of-way, and environmental constraints. Furthermore, while this analysis does quantify the vehicle delay experienced in the freeway corridor, it did not quantify the vehicle delay experienced in the region. While the addition of two freeway lanes on each freeway corridor studied may result in a reduction in delay on the freeways, delay may increase on the adjacent and connecting arterials which the freeways serve, unless the capacity on the arterial system is simultaneously increased.

Research Findings

This research provided insight as to the effect that the development and implementation of transportation policy and transportation alternatives can have on energy efficiency, and provided a sample methodology that can be used for further studies in the area of fuel efficiency and transportation alternatives. Some of the findings of this research confirm the results of previous research, this confirmation may be considered significant, because it confirms the applicability of these general findings to the local conditions in Texas.

Findings

The specific findings of the research include:

(1) Land use factors and development patterns have a significant impact on energy consumption; population density, employment density, concentration of employment, vehicle ownership, average income, percentage of mass transit ridership, and gasoline price account for 91 percent of the variability in the per capita energy consumption.

(2) Excess fuel consumption correlates positively with congestion in an urban area. A reduction in congestion in an urban area will not only increase mobility, but will also contribute to a reduction in the amount of excess fuel consumed in congestion.

(3) Socioeconomic factors have an effect on the fuel efficiency of local bus service. The characteristics that correlate with energy efficiency include the number of autos in a household, the population density along the route, the percentage of workers in the central business district, and the travel time to work.

(4) The energy efficiency of park-and-ride service correlates with the ridership level. Analysis with additional data is necessary to determine the effect of other socioeconomic characteristics on the energy efficiency of park-and-ride service.

(5) The optimal operating range, in terms of fuel efficiency, is between 35 mph and 50 mph, for vehicles operating in urban driving conditions.

(6) HOV lanes provide the greatest reduction in fuel consumption, when compared to traffic management strategies and the addition of general purpose freeway lanes.

Applications of Research

The applications of this research can be correlated with the research findings, which were previously discussed. The results of this research can be used to reduce energy consumption and make components of the transportation system more efficient in a number of ways. The strong correlation between land use factors and development patterns and energy consumption, illustrated in Chapter 2, can be used as the basis for land development policies that promote an energy efficient transportation system. Furthermore, this relationship, and the relationship between socioeconomic characteristics and the efficiency of local bus service, discussed in Chapter 4, can be used as a tool by transit agencies to identify potential routes that can be expected to result in the most energy efficient service.

The results of this research also emphasize the importance of minimizing congestion and maintaining adequate mobility levels in urban areas, in order to maximize fuel efficiency. Excess fuel consumption due to congestion was illustrated on an urban area basis in Chapter 3; on a smaller scale, the speed-fuel economy relationship for urban driving conditions discussed in Chapter 6 illustrated how stop-and-go traffic characteristic of congestion in an urban area will significantly decrease the fuel efficiency of the auto, resulting in increased fuel consumption. In response to this finding, urban areas should calculate the potential fuel savings and increase in energy efficiency which might be expected to accrue due to a transportation improvement, and include this estimate in the calculation of the benefits, when determining the feasibility of a project. An example of this application was provided in Chapter 7, which illustrated an analysis of potential delay and fuel savings for various transportation alternatives in Houston, Texas.

Energy Savings

This research highlighted a number of findings that can have a significant impact on energy savings to the citizens of Texas. If the results of this research are utilized to develop policies that encourage energy efficient land development, policies that encourage the placement of transit routes in corridors with favorable socioeconomic characteristics, increased energy efficiency may be expected to result. Similarly, if the findings of this research which illustrate the fuel savings that are associated with decreased congestion provide the impetus for operational and other measures that reduce congestion to be implemented, then increased energy efficiency may be expected to result. Finally, if the methodologies presented with respect to the analysis of potential fuel savings are incorporated into procedures to analyze transportation alternatives, than significant energy savings may be expected to result.

Recommendations and Conclusion

The specific recommendations that result from this study include:

(1) The development and implementation of land development policies should consider the effects that land development alternatives will have on energy consumption in the urban area.

(2) The identification of potential transit routes should consider the socioeconomic characteristics of the corridors on the route, and the areas served by the route, as a means of estimating the energy efficiency of the route.

(3) Urban areas should consider the impacts of reduced energy consumption when evaluating transportation alternatives, including those that will result in decreased congestion.

(4) Additional analysis of the relationship between the energy efficiency of park-and-ride service and socioeconomic characteristics should be conducted. This additional analysis should incorporate more cities in the database so that an adequate sample size is used, and more definitive conclusions can be drawn.

(5) The speed-fuel economy model developed in this research should be integrated into land use, transportation, and traffic modeling programs to provide an additional measure of effectiveness. The results of such modeling efforts would include a more comprehensive benefit/cost ratio, reflecting fuel consumption as an additional cost, or fuel savings as an additional benefit.

(6) Additional research of the relationship between the energy efficiency of urban development patterns and the historical price and abundance of gasoline should be conducted. The results of this research would help to clarify the long- and short-term impacts of fuel prices.

Conclusion

The research described in this document provided insight regarding the relationship between energy efficiency and transportation. The relationships between energy efficiency and specific aspects of transportation, including urban congestion, local bus operations, park-and-ride services, vehicle speed in an urban environment, and various transportation scenarios in Houston, Texas, were documented in this report. The findings of this research highlight the fact that transportation has a significant impact on energy consumption, and that energy efficiency should be considered when implementing policies and programs related to our nation's transportation infrastructure.

REFERENCES

1. Frederick A. Wagner, "Energy Impacts of Urban Transportation Improvements," prepared for the Institute of Transportation Engineers, August 1980.

2. Stacy C. Davis, "Transportation Energy Data Book: Edition 14," Oak Ridge National Laboratory, May 1994.

3. Testimony of Richard D. Morgenstern, Director, Office of Policy Analysis, U.S. Environmental Protection Agency, before the Subcommittee on Energy Regulation and Conservation, Committee on Energy and Natural Resources, United States Senate, One Hundred First Congress, First Session on Automobile Fuel Efficiency Standards, April 4, 1989.

4. Richard A. Margiotta, "Automotive Fuel Efficiency versus Emissions," Preliminary Research Report No. 137, Planning Research Unit, New York State Department of Transportation, February 1978.

5. Michael D. Meyer and Eric J. Miller, Urban Transportation Planning - A Decision Oriented Approach, McGraw-Hill Publishing Co., 1984.

6. Jerry B. Schnieder and Joseph R. Beck, "Reducing the Travel Requirements of the American City: An Investigation of Alternative Urban Spatial Structures," Transportation Research Record 499, Washington DC, 1974.

7. Jerry L. Edwards and Joseph L. Schofer, "Relationships between Transportation Energy Consumption and Urban Structure: Results of Simulation Studies," Transportation Research Record 599, Washington DC, 1976.

8. Robert L. Peskin and Joseph L. Schofer, "The Impacts of Urban Transportation and Land Use Policies on Transportation Energy Consumption," US Department of Transportation, Research and Special Programs Administration, Office of University Research, Washington DC, April 1977.

9. Kim Kwang and J.B. Schneider, "Defining Relationships Between Urban Form and Travel Energy," Transportation Research Record 1049, Washington DC, 1985.

10. Charles T. Stewart Jr. and James T. Bennett, "Urban Size and Structure and Private Expenditures for Gasoline in Large Cities," Land Economics, , Vol. L1, No. 4, November 1975.

11. Siim Soot and Ashish Sen, "Metropolitan Work-Trip Energy Consumption Patterns," Traffic Quarterly, Vol. 33, No. 2, April 1979.

12. Melvyn D. Cheslow and J. Kevin Neels, "Effect of Urban Development Patterns on Transportation Energy Use," Transportation Research Record 764, Washington DC, 1980.

13. Ardeshir Anjomani and Louis Chineme, "Urban Population and Employment Densities in Relation to Transportation Energy Consumption," Institute of Urban Studies, City and Regional Planning Department, The University of Texas at Arlington, 1981.

14. Peter Newman and Jeffrey Kenworthy, "Cities and Automobile Dependence: An International Sourcebook," Gower Publishing Company Limited, Vermont, USA, 1989.

15. Institute of Transportation Engineers, Transportation Planning Handbook, 1992.

16. John Neter, William Wasserman and Michael H. Kutner, "Applied Linear Regression Models," Richard D. Irwin, Inc., 2nd edition, 1989.

17. T.J. Lomax and D.L. Christiansen, "Estimates of Relative Mobility in Major Texas Cities," Research Report 323-1F, Texas Transportation Institute, Texas State Department of Highways and Public Transportation, 1982.

18. T.J. Lomax, "Relative Mobility in Texas Cities, 1975 to 1984," Research Report 339-8, Texas Transportation Institute, Texas State Department of Highways and Public Transportation, 1986.

19. T.J. Lomax, D.L. Bullard and J.W. Hanks, Jr, "The Impact of Declining Mobility in Major Texas and Other U.S. Cities," Research Report 431-1F, Texas Transportation Institute, Texas State Department of Highways and Public Transportation, 1988.

20. J.W. Hanks, Jr. and T.J. Lomax, "Roadway Congestion in Major Urban Areas, 1982 to 1987," Research Report 1131-2, Texas Transportation Institute, Texas State Department of Highways and Public Transportation, 1989.

21. J.W. Hanks, Jr. and T.J. Lomax, "Roadway Congestion in Major Urbanized Areas, 1982 to 1988," Research Report 1131-3, Texas Transportation Institute, Texas State Department of Highways and Public Transportation, 1990.

22. J.W. Hanks, Jr. and T.J. Lomax, "1989 Roadway Congestion Estimates and Trends," Draft Research Report 1131-4, Texas Transportation Institute, Texas Department of Transportation, 1991.

23. Federal Highway Administration, "Highway Performance Monitoring System," United States Department of Transportation, Washington, D.C., 1982 to 1989 Data.

24. M.D. Meyer, "Proceedings of a Workshop on Congestion Management Systems," Federal Highway Administration, August 26-28, 1991.

25. T.F. Fwa and B.W. Ang, "Estimating Automobile Fuel Consumption in Urban Traffic," Paper No. 920040, Presented at the Transportation Research Board's 71st Annual Meeting, Washington, D.C., January 12-16, 1992.

26. "Houston-Galveston Regional Transportation Study," Texas Transportation Institute, Texas State Department of Highways and Public Transportation, 1990.

27. J.A. Lindley, "Quantification of Urban Freeway Congestion and Analysis of Remedial Measures," Report FHWA/RD-87/052, FHWA, U.S. Department of Transportation, 1986.

28. J. Raus, "A Method for Estimating Fuel Consumption and Vehicle Emissions on urban Arterials and Networks," Report FHWA-TS-81-210, FHWA, U.S. Department of Transportation, 1981.

29. N. Janarthanan and J. Schneider, "Reducing the Energy Requirements of Suburban Public Transit Services by Route and Schedule Redesign," Transportation Research Record 994, Transportation Research Board, Washington, D.C., 1984.

30. "Cost Efficiency in Bus Transit Systems", Technical Council Informational Report, Committee CY-16, Institute of Transportation Engineers, Washington, D.C., 1981.

31. A. M. Khan, "Urban Public Transit Efficiency: Economic and Energy Factors," Journal of Advanced Transportation, Vol. 15, No. 3, 1981, pp. 213-230.

32. Daniel K. Boyle, "Effects of Small-Scale Transit Improvements on Saving Energy," Transportation Research Record 761, Transportation Research Board, Washington, D.C., 1980.

33. Mayo S. Stintz, Jr., "Energy Conservation Potential of urban Public Transit," Transportation Research Record 599, Transportation Research Board, Washington, D.C., 1976.

34. Alan E. Pisarski, "Travel Behavior Issues in the 90's," 1990 Nationwide Personal Transportation Survey (NPTS), U.S. Department of Transportation and Federal Highway Administration, July 1992.

35. Archie M. Rivera and Jeanette Silies, "Transit Bus Energy Efficiency and productivity-Bus Selection Handbook," Booz, Allen & Hamilton, Inc., National Cooperative Transit Research & Development Program Report No. 1, Transportation Research Board, Washington, D.C., July 1982.

36. Ann Muzyka, John F. Fantasia, and Joseph M. Goodman, "Bus Operations and Energy Conservation," Traffic Engineering, November 1975.

37. "Bus Stop Study for Montachusett Regional Transit Authority," Montachusett Regional Planning Commission, Fitchburg, MA, July 1985.

38. "Transit Profiles—Agencies in Urbanized Areas Exceeding 200,000 Population," U.S. DOT—Urban Mass Transportation Administration, November 1991.

39. Bullard, Diane, Texas Transportation Institute, Report 484-14F, College Station, Tx, September 1991.

40. Christiansen, Dennis L., et al, "Park-and-Ride Facilities: Preliminary Planning Guidelines", Texas Transportation Institute Research Report 205-2, College Station, Tx, August 1975.

41. "Cost Effectiveness of Park-and-Ride Lots in the Seattle Metropolitan Area," 1081 Transportation Research Board, Washington, D.C., 1986.

42. "Automobile Fuel Efficiency Standards," Hearing before the Subcommitte on Energy Regulation and Conservation of the Committee on Energy and Natural Resources, United States Congress, 101st Congress, First Session, April 4, 1989.

43. "Energy Savings and Road Traffic Management," Report of the Road Transport Research, Prepared by an OECD Scientific Expert Group, Organization for Economic Co-operation and Development.

44. J. Raus, "A Method for Estimating Fuel Consumption and Vehicle Emissions on Urban Arterial Streets," Report No. FHWA-TS-81-210, April 1981.

45. Frederick A. Wagner, "Energy Impacts of Urban Transportation Improvements," prepared for the Institute of Transportation Engineers, August 1980.

46. Zaniewski et al, "Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors," U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-PL-82-001, June 1982.

47. Robert W. Gondall, Howard K. Greenspecht, Theodore E. Keeler and Lester B. Lave, "Regulating the Automobile," Brookings Institute, Washington, D.C., 1986.

48. "Increased Efficiency Potential for the U.S. Fleet of Highway Passenger Vehicles," Statement of Steven E. Plotlein, Senior Associate, Office of Technology Assessment.

49. A. Henry Schilling, Director, Office of Legislative Analysis, Environmental Protection Agency.

50. Motor Vehicle Fuel Efficiency Act of 1990.

51. R. M. Heavinrich, J. D. Murell and J. P. Cheng, "Light-Duty Automotive Fuel Economy and Technology Trends Through 1987," SAE Technical Paper Series No. 871088, Government/Industry Meeting and Exposition, Washington, D.C., May 18-21, 1987.

52. Regional Mobility Plan for the Houston Area, 1989, Committee for Regional Mobility, Greater Houston Partnership, 1989.

53. James A. Mullins III and Jim D. Benson, "An Analysis of the Potential for Traffic Diversion to a Strategic Arterial System," Texas Transportation Institute, Report No. FHWA/TX-90/1107-2, June 1990.

54. FREQ10PL, REL T91, Institute of Transportation Studies, University of California, Berkeley.

55. Montie G. Wade, Dennis L. Christiansen, and Daniel E. Morris, "An Evaluation of the Houston High-Occupancy Vehicle Lane System," Texas Transportation Institute Research Report 1146-5, August 1992.