Title

Spatial and Temporal Factors in Estimating the Potential of Ride-sharing for Demand Reduction

Authors

Tsao, H.-S. Jacob
Lin, Da-Jie

Publication Date

1999

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Spatial and Temporal Factors in Estimating the Potential of Ride-sharing for Demand Reduction

H.-S. Jacob Tsao, Da-Jie Lin

California PATH Research Report
UCB-ITS-PRR-99-2

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

Report for MOU 272

January 1999

ISSN 1055-1425

SPATIAL AND TEMPORAL FACTORS IN ESTIMATING THE POTENTIAL OF RIDE-SHARING FOR DEMAND REDUCTION

ABSTRACT

Traffic congestion has been a pervasive problem in many urban areas of this country. This paper studies the potential of carpooling among unrelated partners (i.e., inter-household carpooling) for demand reduction during peak commute hours. Basic questions about this potential include the following. Can the current population density, origin-destination distribution, tolerable pick-up and drop-off delays, departure time distribution, and the tolerance for deviation from preferred departure time support a sizable carpooling population that can make a significant contribution to traffic demand reduction? Could the proportion of long trips that are likely candidates for carpooling (e.g., those long trips with same O-D) be so small that no significant traffic demand reduction could be expected from carpooling?

The potential depends on many factors, some of which are more amenable to quantification than others. Our approach to assessing the potential is to separate such quantifiable factors from the rest, and then, based on these quantifiable factors, identify likely upper bounds for the potential. This paper focuses on a simplified urban sprawl in which the densities of workers and jobs are uniform over an infinitely large flat geographical area. For our numerical study, we use the job and worker data of the city of Los Angeles to approximate the worker/job density. An entropy optimization model that is equivalent to the gravity model is used for trip distribution. Under the assumptions made in the paper, carpooling among unrelated partners has little potential for demand reduction.

Key Words: Carpool, Demand Management, Urban Sprawl, Trip Distribution, Entropy Optimization

EXECUTIVE SUMMARY

Traffic congestion has been a pervasive problem in many urban areas of this country. Basic research directions for solving the current traffic congestion problems include efficient operation of the current surface transportation networks, network capacity expansion and demand management. Demand management includes demand reduction and temporal demand shift. This report focuses on demand reduction and studies the potential of carpooling and vanpooling.

Although many conventional public-transit concepts have been proposed and implemented, the current societal reliance on automobiles and the companion persistence of urban sprawl seem so strong that these conventional concepts would likely not enjoy any significant increase in ridership in the near future.

Given the apparent inability of conventional public transit to attract additional ridership and the likely costliness and environmental impact of roadway network capacity expansion projects, carpooling may be a cost-effective and even inexpensive way out of traffic congestion and other related problems like air pollution. Note that carpooling involves mostly behavioral changes and does not require any major roadway or vehicle upgrade. Also note that carpooling may allow continuation of the current low-population-density life-style, which most people have clearly preferred for the past decades.

Basic questions about the potential of carpooling include the following. Based on spatial and temporal considerations, can the current population density, origin-destination distribution, tolerable pick-up and drop-off delays, and departure time distribution support a sizable carpooling population that can make a significant contribution to traffic demand reduction? Could the proportion of long trips that are likely candidates for carpooling be so small that no significant traffic demand reduction and hence congestion relief could be expected from carpooling? This report results from an attempt to answer these questions and documents our findings regarding the car-pool potential for demand reduction.

Although there has been much literature on carpooling, there is very little, if any, research into the realistic potential of carpooling. Nearly all the literature on car-pool potential was motivated by the need to counter the national energy shortage in 1973-1974. As a result, the focus of those studies was the maximal potential as a measure of the nation's ability to counter national emergencies like the oil embargo and, therefore, they concluded with very high potential. For example, for the metropolitan area of Boston, Kendall (1975) reported that 68% of the peak-period automobile commuter trips could be candidates for carpooling.

We take the following approach. Carpooling is a personal decision that depends on many factors. Since these factors affect a person's commute-mode decisions, they can all be regarded as behavioral factors. However, some of these factors are more amenable to quantification than others. Our approach to assessing the potential of carpooling is to separate such quantifiable factors from the rest, and then, based on these quantifiable factors, identify likely upper bounds for the potential. Such quantifiable factors include trip length, the tolerance for (absolute) pick-up/drop-off delay or distance, that for the pick-up/drop-off delay with respect to the trip length or time, and the tolerance for deviation from preferred departure time. This report focuses on these personal and societal spatial and temporal variables and develops models for estimating upper bounds of the potential as a function of these variables. Other factors such as loss of privacy during carpooling will be discussed in this report but will not be considered in estimating the potential. Further consideration of these behavioral factors would produce lower but more realistic estimate of the potential.

This report assumes a development pattern in which the densities of workers and jobs are uniform over an infinitely large flat geographical area. Due to this assumption, focusing on trip generation/distribution from one particular zone to all the other zones suffices for our purposes. To balance the quantities of workers and jobs, the two uniform densities are assumed identical. For our numerical study, we use the job and worker data of the city of Los Angeles to approximate the worker/job density. We also vary key variables to study the sensitivity of car-pool potential for demand reduction with respect to the variables.

Assuming that commuters would carpool with only those workers living in the same 2-mile-by-2-mile zone and working in a common 2-mile-by-2-mile zone, our results show that the trip numbers between the origin zone and any of the zones 10 miles or more away are very small. For example, when the density is 581 jobs/square-mile and the average commute distance is 16 miles, there are only 6.62 trips from the origin zone to any destination zones exactly 10 miles away, and there are only 2.44 trips to any destination exactly 18 miles away. Note that departure time has not even been taken into consideration yet. Also note that many other factors may negatively impact the potential of carpooling for demand reduction. These results indicate that, under the assumptions made, carpooling has little potential. However, despite our results, much carpooling continues perhaps because many households have more workers than vehicles and many workers do not possess vehicles and hence need rides for commuting to work locations. These phenomenon are not addressed by the proposed model.

I. Introduction

1.1 Focus

Traffic congestion has been a pervasive problem in many urban areas of the U.S.. Basic research directions for solving the current traffic congestion problems include improving operational efficiency of the current surface transportation networks, network capacity expansion and demand management. Demand management includes demand reduction and temporal demand shift. This report focuses on demand reduction and studies the potential of carpooling and vanpooling for demand reduction. For convenience of discussion, we will refer to the potential of carpooling for demand reduction simply as the CDR-potential.

1.2 Motivation

Increasing the capacity of the current urban highway systems is expensive, whether it is by way of highway capacity expansion through conventional means or through possibly implementing more advanced concept such as automated highway systems (AHS). Also, much traffic congestion occurs on arterials and city streets and cannot be solved by highway capacity expansion alone. Improving operational efficiency of highways and city streets, subject to cost-benefit considerations, should continue, but is often not enough to eliminate congestion. Carpooling seems a promising method to reduce demand. However, despite great efforts to promote ride-sharing and transit, both have steadily decreased in recent years.

Although many conventional public-transit concepts for moving people have been proposed and implemented, the current societal reliance on automobiles and the companion persistence of urban sprawl seem so strong that these conventional concepts would likely not enjoy any significant increase in ridership in the near future.

Given the apparent inability of conventional public transit to attract additional ridership and the likely costliness of roadway network capacity expansion projects, carpooling may be a cost-effective and even inexpensive way out of traffic congestion and other related problems like air pollution. Note that carpooling involves mostly behavioral changes and does not require any major roadway or vehicle upgrade. Also note that carpooling may allow continuation of the current low-population-density life-style, which most people have clearly preferred for the past decades.

There exist many interesting questions about the CDR-potential. Consider the following examples. Can the current population density, origin-destination distribution, tolerable pick-up and drop-off delays, and departure time distribution support a sizable carpooling population that can make a significant contribution to traffic demand reduction? Could the proportion of long trips that are likely candidates for carpooling be so small that no significant traffic demand reduction and hence congestion relief could be expected from carpooling? This report results from an attempt to answer these questions and documents our findings regarding the CDR-potential.

To understand the state-of-the-art in estimating the CDR and to develop an approach complementing the existing literature on carpooling, we conducted a literature review. Although there has been much literature on carpooling, there is very little, if any, research into what the realistic potential of carpooling is for congestion relief. Nearly all the literature the CDR-potential was motivated by the need to counter the national energy shortage in 1973-1974. As a result, the focus of those studies was the maximal potential as a measure of the nation’s ability to counter national emergencies like the oil embargo and, therefore, they concluded with very high potential. For example, for the metropolitan area of Boston, Kendall (1975) reported that 68% of the peak-period automobile commuter trips could be candidates for carpooling.

1.3 Approach

Carpooling is a personal decision that depends on many factors. Since these factors affect a person’s commute-mode decisions, they can all be regarded as behavioral factors. However, some of these factors are more amenable to quantification than others. Our approach to assessing the CDR-potential is to first separate such quantifiable factors from the rest, and then, based on these quantifiable factors, identify likely upper bounds for the potential. Such quantifiable factors include trip length, the tolerance for (absolute) pick-up/drop-off delay or distance, that for the pick-up/drop-off delay with respect to the trip length or time, and the tolerance for deviation from preferred departure time. The potential depends not only on the effect of these spatial and temporal factors on commuters’ mode-choice decisions but also on a critical external factor: the availability of potential car-pool partners. This external factor depends heavily on worker density (or general population density) and job density. This report focuses on these personal and societal spatial and temporal variables and develops models for estimating upper bounds of the potential as a function of these variables. Other factors such as loss of privacy during carpooling will be in this report as behavioral factors but will not be considered in estimating the potential. Further consideration of these behavioral factors would produce lower but more realistic estimate of the potential.

Various demand models addressing behavioral factors, e.g., the logit models, can be coupled with the model to be developed in this report to estimate the actual potential. In this report, we will refer to the potential estimated by considering only the spatial and temporal factors discussed earlier as maximum potential.

Note that carpooling may offer many advantages, e.g., stress reduction in stop-and-go traffic for the passengers, increase in productivity for the passengers while commuting, travel cost reduction for all car-pool participants (including fuel and vehicle costs), travel time reduction while travelling on those highways or toll booths equipped with HOV facilities, and personal satisfaction about reduced contribution to air pollution. These advantages can also be taken into consideration in the demand modeling.

1.4 Scope

This report focuses on an assumed development pattern urban sprawl in which the densities of workers and jobs are uniform over an infinitely large flat geographical area. To balance the quantities of workers and jobs, the two uniform densities are assumed identical. For our numerical study, we use the job and worker data of the metropolitan area of Los Angeles to approximate the worker/job density. We also vary key variables to study the sensitivity of CDR-potential with respect to the variables.

1.5 Organization of Report

Section 2 discusses the background of the problem and summarizes our literature review. Section 3 describes the problem and our approach. Section 4 formulates the problem and derives theoretical results. Section 5 first describes the data set and then summarizes our numerical results. Concluding remarks are given in Section 6.

II. Literature Review on Ride-sharing-Related Issues

Ride-sharing has been thought to be a good way to solve the transportation congestion problems on highways and surface streets for a long time. Much research has been conducted to understand ridesharing as a mode choice for commute, and many carpooling promotion programs have been designed, used, and evaluated. But there is little literature on the CDR-potential (i.e. the potential of carpooling for demand reduction) for relieving traffic congestion, which, we believe, is a more fundamental issue. In this section, we review car-pool literature to gain a clear understanding of the history, development, and achievements of ride-sharing.

2.1 Introduction to Transportation Demand Management (TDM)

The concept of Transportation System Management (TSM) became popular in the 1970's when energy crises occurred and environmental concerns intensified (Kostyniuk, 1981; Kendall, 1975). TSM tries to increase the productivity of surface transportation systems through both supply-side and demand-side methods, such as road expansion, HOV lanes, signal coordination, and freeway ramp metering. Transportation Demand Management (TDM) is a derivative of TSM and focuses on managing the demand to reduce congestion, i.e., "changing commuters' behavior to make better use of existing transportation facilities" (Beroldo, 1990). In addition to facility operation improvement and capacity expansion, TDM has been commonly adopted by transportation planners to deal with congestion.

The goal of TDM is to maximize people throughput in a transportation system, not the vehicle throughput. This is why TDM has become more and more important in highly congested urban areas, especially those areas where land and funding available for road expansion and construction have been limited (Giuliano and Golob, 1990). TDM is also preferred where, although land for roadway expansion is still available, environmental concerns make such expansion practically impossible (e.g., resistance of nearby residents to building new facilities) (Hwang and Giuliano, 1990).

According to an FHWA report (COMSIS Corporation, 1990), TDM programs can be grouped into three strategy categories:

1. Alternative Work Hours,
2. Improved Alternatives,
3. Incentives and Disincentives.

Examples of the concept of alternative work hours (AWH) include staggered work hours (i.e., groups of employees working on schedules with staggered starting times), compressed work weeks (i.e.,. employees working more hours daily in fewer than 5 working days per week, with the total work hours in a week remaining the same), flexible work hours (i.e., employees having some degree of freedom in choosing what time to start work and what time to leave work*)*. Examples of Improved Alternatives include telecommuting (i.e., formal off-site working arrangements), which is very popular in the computer software industry. Incentive strategies include provision of preferential treatment for carpooling, e.g., high-occupancy-vehicles lanes, free parking.

2.2 Background and Characteristics of Ridesharing

Despite multiple advantages and a large amount of effort in promoting ride-sharing, ride-sharing has actually been decreasing. “Attempts by agencies to increase its influence [influence of ride-sharing] through matching services or appeal to economic or public concerns have thus been generally unsuccessful.” (Hartgen, 1977). “Ride-sharing program managers report that such services have become increasingly difficult to market (Stevens, 1990)”. Although there has been much literature on ride-sharing, there is very little, if at all, research into what the realistic potential of ride-sharing is for demand reduction.

Initially, ride-sharing was motivated to deal with the energy crisis in 1973 and 1974 (Kostyniuk, 1981; Stevens, 1990). Several reports in the literature discussed the maximum potential of ride-sharing in responding to national emergencies like energy shortage or oil embargo, and concluded with high potential. For example, for the metropolitan area of Boston, Kendall (1975) reported that 68% of the peak hour auto commuter trips could be candidates for ride-sharing. Briefly, the benefits of ride-sharing include less fuel consumption, lower emissions due to less fuel consumption, less congestion and travel time saving, less wear and tear on vehicles, etc.

Based on the relationship among car-poolers, carpooling can be categorized into two types: intra-household and unrelated (i.e., non-intra-household) (Teal, 1987). Intra-household carpooling, where two or more household members share the same automobile for their commute trips, is quite common. This household carpooling is most natural for those households in which the number of workers exceeds the number of automobiles. It is voluntary and does not need any external incentives (Kendall, 1975; Richardson and Young, 1982). From transportation census data, we know that, due to the limited availability of commuting vehicles, household members often carpool. Teal (1987) pointed out that there were also significant differences in trip distance and trip circuity between intra-household and non-intra-household carpooling. The importance of intra-household carpooling can be revealed by the following observations. A U.S. study found that 35% of car-pools were intra-household (Kendall, 1975). Hartegen (1977) estimated that one-third of all car-pools were of this type. An Australian study (in Melbourn) found that about three out of eight car-pools were intra-household (Richardson and Young, 1982).

One of the goals of transportation planners is to promote the other type of carpooling -- carpooling between unrelated individuals. There are two types of sharing: sharing of a single vehicle by two or more commuters (the same vehicle all the time) or a carpooling arrangement in which each commuter regularly contributes his/her vehicle to the pool. An U.S. study estimated that two-thirds of all unrelated car-poolers either drive or ride all the time (Kendall, 1975). Another study in Great Britain estimated that "about one-third of car-pool applicants are offering rides, another one-third are seeking rides and only one-third wish to pool their vehicle and share driving responsibilities (Bonsall, 1982), (Teal, 1987)." These numbers give us an idea about how the car-poolers share their vehicles.

2.3 Comparisons Between Carpooling, Driving Alone, and Transit

Carpooling is a mode of commuting. It popularity is second to driving alone but is higher than that of public transit. According to nationwide surveys, 18% to 20% of all commuters car-pool, the ratio between driving alone, carpooling and transit is 12 : 3 : 1 (Teal, 1987). In addition, most metropolitan areas have various kinds of promotion programs to encourage carpooling. To decide which promotion programs to implement and to set realistic expectations of the results, transportation planners need to understand the CDR-potential and identify those commuters who are likely to switch from driving alone to carpooling.

Compared to the other alternatives, carpooling has its strengths and shortcomings which will be discussed briefly below. Out-of-pocket costs of carpooling (including gas, parking, tolls, etc.) are shared by car-pool members. Therefore, it is more economical; out-of-pocket costs are at least 50% less than solo driving, a big saving (Teal, 1987). The disadvantages include the need to sacrifice time, flexibility, and privacy. For example, a driver has to drive extra distance to pick up and drop off car-pool members. Extra travel time and waiting time are also incurred by the other car-pool members. Sticking to the schedule to which all riders agreed results in loss of flexibility. Car-poolers also lose privacy when they have to share the same vehicle with the others. According to a survey, loss of privacy and lack of flexibility are major reasons why single drivers hesitate to switch to a carpool. The saving of the out-of-pocket costs is not enough to entice them to switch, and this implies that the monetary value of privacy and time is relatively high (Hartgen, 1977; Horowitz and Sheth, 1978). The reasons why reducing out-of-pocket costs is not a significant contributing factor to car-pool propensity include cheap fuel, short travel distance (which means less fuel saving), lack of incentives (e.g., no free parking, parking being always available, etc.). In short, although carpooling has an economic advantage over driving alone but might not be strong enough to entice commuters to carpool.

The dominant commuting mode is driving alone, which accounts for about 70% to 80% of the commute trips (Glazer, Koval, and Gerard, 1986; Teal, 1987). Compared with driving alone, carpooling and transit are inferior choices for most commuters due to the reasons mentioned above. But do those commuters who do not drive alone carpool or use transit? This depends on the quality (including reliability and comfort) and availability (including schedule and access time) of transit service.

Compared to public transit, carpooling is less flexible in schedule (except for late night workers, see below), especially where there is a high-quality transit system like BART in the San Francisco Bay Area. Car-pool members are constrained to a fixed schedule and a fixed route based on an agreement, but not the transit users (if the schedule allows). Transit users often plan shopping or recreational trips after work but this is impossible for car-poolers.

More often than not, public transit is also cheaper than carpooling (considering parking fee, toll, fuel consumption, etc.). On the other hand, public transit is more time-consuming. The average transit commuter trip takes about 70% more time than the average car-pool trip, even though the latter is somewhat longer in distance, according to data from Bureau of the Census (Teal, 1987). Public transit is less comfortable than carpooling because public transit tends to have more stops, more passengers, less privacy (car-pool members can establish friendship), and less accessibility (e.g., walking or driving needed between station or bus stop and home), and are not available at all times (e.g., late night workers not accommodated by public transit services), etc. The fact that there are three times as many carpooling commuters as transit commuters indicates that carpooling's superior availability, comfort, time saving more than offsets its relative disadvantages.

2.4 Studies on Factors Influencing Carpooling Propensity

Early studies of carpooling focused on economic factors as the primary reasons why people carpooled (Teal, 1987). Later, some researchers started to look at the other factors, and some of them suggested that attitudinal factors (e.g., attitude toward carpooling), as opposed to socio-demographic attributes or traditional time and cost variables used in conventional transportation mode choice models, are more influential in car-pool decision (Hartgen, 1977; Horowitz and Sheth, 1978). Hartgen compared the influences of socio-demographic variables and attitudes on traveler behavior, and concluded that "Few demographic factors distinguish car-poolers from non-car-poolers; attitudinal differences, while stronger, are also quite weak" (Hartgen, 1977). The research on attitudinal factors reported before Horowitz (Horowotz, 1975) only pointed out the differences in attitudes towards carpooling between solo drivers and car-poolers, but did not build up a methodology for measuring attitudes. Horowitz built a framework for measuring attitudinal factors and tested his framework in a marketing survey (Horowitz, 1975; Horowitz and Sheth, 1978). They made several conclusions. Demographic and travel characteristics are car-pool indicators and predictors of the commuters' car-pool decisions; public-interest issues of energy, etc. only affect the attitudes of the individuals with higher socioeconomic status; perceptions of economic advantage of carpooling only have minor influence, etc. They also suggested that the positive characteristics not well known to the public should be emphasized. For example, time spent in a car-pool could be a relaxing time, etc.

Margolin et al. designed a sequential study and carried it out in Washington, D.C. The process consists of three phases: (1) understanding consumers' preference, complaints, etc.; (2) hypothesis testing; (3) using the quantified results to build car-pool promotion strategies (programs). Their recommendations included a personalized system, local car-pool coordinator, parking-incentive strategies, car-pool lanes, etc. (Margolin et al., 1978).

There have also been studies that excluded attitudinal factors, and such studies suggested that carpooling could be predicted well by using transportation and socio-demographic variables (McCoomb and Stewart, 1982). They saw automobile passenger as a forgotten mode and found that a large number of urban trips are made by automobile passengers whose behavior characteristics are closer to transit users than solo drivers.

Urban transportation planning guidelines (U.S. Department of Transportation, 1975) placed an emphasis on enhanced utilization of the existing transportation system. Tischer and Dobson argued that the guidelines needed a planning element concerned with low-cost, short-term improvements for urbanized area (Tischer and Dobson, 1979). Some behavioral models have been formulated and tested in transportation research contexts. A research effort by Dobson *et al.* tried to identify (i) factors influencing the commuter decision to switch from driving alone to carpooling and (ii) effective policies to encourage this switch, and concluded that attitudes favoring carpooling can be translated into behavior if proper promotion activities is undertaken, e.g. improved car-pool matching process. They also confirmed that economic factors like cost would not be influential in commuters' car-pool decisions (Dobson *et al.*, 1976).

Dobson and Kehoe demonstrated "the usefulness of disaggregating a sample of respondents according to the viewpoints of individuals in the sample," and their results helped better understand the behavioral issues (Dobson and Kehoe, 1974). Ewing applied psychological theory to mode-choice prediction and developed “a modal split model with a sound behavioral foundation,” which is quite different from the other approaches (Ewing, 1973).

2.5 Identification of the “Switchables” (from Solo Driving to Ride-sharing)

In order to promote carpooling efficiently, especially in a budget-constrained situation, we first need to know the attributes of those who are carpooling and the attributes of those who are not. Then, we need to identify the attributes of those who are most “switchable” among those who are not carpooling. We can then devise specific promotion programs to entice the most switchable commuters. Tischer and Dobson (1977) first tried to identify the switchable segment. They designed a study to uncover factors which would (1) influence the decision of single-occupant auto commuters so as to switch them to buses and car-pools and (2) suggest operating policies consistent with the intent to encourage the use of high-occupancy vehicles. They asked single-occupant auto drivers whether they would switch from driving alone to carpooling or public transit under different assumed situations. Those drivers who answered yes under five situations out of seven in total were categorized as “switchable” commuters. In their study, “Three groups of switchers are identified: those who are positively oriented to taking a bus, those who would only switch to a car-pool, and those who would consider both modes”. “Bus convenience is the most important variable associated with the shift intention. Perception of car-pool comfort does not appear to be important. Rather, perceptions of car-pool schedule flexibility, cost, safety and a shorter wait in the traffic are prime factors associated with potential car-pool shifting.” This research is an application of attitudinal-behavioral techniques in a market segmentation framework. Their approach is a heuristic approach and not a quantitative analysis.

Gensch (1981) proposed a method to predict the switchable segment by using the basic cross-sectional survey data sets collected to calibrate a logit model. That multinomial logit model estimated the probability of choosing each of the alternatives (driving alone, carpooling, and public transit) by individuals. The data used in his analysis were collected from users of Santa Monica Freeway in Los Angeles, and he concluded that the empirical experiment tended to support this proposed approach. He concluded that "switchables are found often in homes where the number of licensed drivers is low, there is a male head of household, and the individual is a blue-collar worker (non-professional / managerial)," and emphasized that the purpose of his empirical analysis was "to provide some empirical support for two concepts. First, the difference in logit probabilities (i.e., the difference in the deterministic utility component of the probability value) is related to the individual's propensity to try his second mode choice. .... In term of *actual behavior*, the empirical evidence supports the relationship for both bus and car-pool. The second concept is that there are demographic variables that can be related to groups with different propensities of switching modes." The author suggested spending most of the promotional budget on those segments (or groups of commuters) that have been identified as most "switchable".

2.6 Car-pool Promotion Programs and Concepts

This subsection reviews literature about programs aimed at promoting carpooling. The discussion is partitioned into six subjects:

- part-time carpooling

- flexible car-pool matching
- employer-based car-pool programs
- high-occupancy vehicle (HOV) Lanes
- preferential parking policies
- intelligent transportation system technologies for carpooling

2.6.1 Part-Time Carpooling

A common objection by solo drivers against carpooling is lack of flexibility. Due to this inflexibility, some researchers proposed strategies to remedy it. One approach is "part-time carpooling" (Glazer, Koval and Gerard, 1986). Their goal is two-person-two-days-per-week carpooling. Instead of inflexible every-day commitments, all participants were asked to commit to a two-person car-pool for only two days a week for three months. The authors concluded that "Because of the hard-to-please nature of the commuters in this target market, it appears that personalized matching attention is important to the success of a part-time carpooling promotional effort." Despite a high attrition rate (75 percent dropout in eight months), they still believed that "this demonstration project indicates that part-time carpooling is a promising technique for reaching beyond the commuter market traditionally served by conventional ridesharing programs."

2.6.2 Flexible Car-pool Matching

Another effort is "flexible car-pool matching" (Michael R. Ringrose, 1992). Flexible car-pool matching is a strategy for helping commuters to form car-pools with each other. The difference is that "the arrangements are made on a trip-by-trip basis, and thus do not require any long-term commitments." So this strategy combines the flexibility of driving alone with the benefits of using an HOV lane. Although the concept is conceptually appealing and technically feasible, its effectiveness has not been validated due to lack of empirical data, and there is still little understanding of the potential of flexible car-pool matching. Personal security could also be a concern.

2.6.3 Employer-based Ride-sharing Programs

One of the most popular TDM programs is employer-based ride-sharing program. In fact, during World War II, company buses, car-pools, and staggered work hours were widely used (Hwang and Guiliano, 1990). The current generation of programs were conducted in response to the energy crisis of 1973, especially in cooperation with large employers. Recently, increasing congestion and air quality concerns, especially where there is strong economic growth, are the major factor contributing to increased promotion of ride-sharing programs. Regulation XV, which was introduced in July 1988 for Southern California, is the most ambitious effort so far. It commands "significant reductions in AM-peak period trips for all companies in the South Coast Air Basin with 100 or more employees." It was estimated that 8,000 different companies in Southern California had been affected (Hwang and Guiliano, 1990). Every participating company had to submit an annual plan to achieve its designated vehicle occupancy goal. Each employer had to have a coordinator to coordinate all matters related to ride-sharing, and companies that failed to submit their plans would be fined. But there was no penalty for failures to achieve expected vehicle occupancy rate

Ferguson used Southern California data to analyze employer ride-sharing programs and employee mode choices (Ferguson, 1990). He found that firm size was the single most important variable in his analysis. Larger employers are more likely to provide ride-sharing incentives to their employees. He also tried to explain it by the hypothesis that "larger firms prefer high density locations more often than do smaller firms, …, may also utilize office, commercial, or industrial space more efficiently than do smaller firms." He also concluded that Personalized Matching Assistance was relevant to the increase of ride-sharing, and, without parking charges, any direct ride-sharing incentive such as preferential car-pool and vanpool parking is insignificant in promoting ride-sharing.

Denver's air pollution is very severe when compared to other major metropolitan areas. In 1976, Air Pollution Control Division encouraged commuters to use "alternate transportation modes" including carpooling, public transit, bicycling, etc. McClelland *et al.* conducted studies to evaluate employer programs encouraging the use of alternate transportation modes and concluded that: (1) employer programs can influence the employee's decisions, (2) external variables such as the availability of alternate transportation and pressure for its use are significant, and (3) preferential parking for car-pools, etc. did not generate expected results of ride-sharing increase.

As mentioned above, the concept of alternative work hours (AWH) has been well accepted by employees (Jones and Harrison, 1983). According to the results of one project conducted in downtown Honolulu in 1988, if the employer gives employees more flexibility and freedom in determining their work schedule, then it will become more popular (Giuliano & Golob, 1990).

The relationship between AWH and carpooling is still uncertain. Some researchers think that AWH complements carpooling because it helps employees to adjust to potential car-pool schedules (Jones and Harrison, 1983) while others claim that

AHW substitutes for carpooling because commuters may choose to shift their work hours instead of shifting their mode from driving alone to carpooling (Cervero and Griesenbeck, 1988, Guiliano, Levine and Teal, 1990).

2.6.4 High-Occupancy Vehicle (HOV) Lanes

"John L. Crain (1963) proposed the rapid transit bus concept. His idea was to combine the flexibility and low cost of a bus system with the speed of a rapid rail system. ...In the United States, this thinking made its way into the Urban Transit Administration, which in 1975 announced that as a condition of federal financial assistance for transportation, all urban areas must design and implement traffic management plans, which could include exclusive transit lanes." (Dahlgren, 1994). That is the very earliest idea of HOV lanes.

The objective of HOV (High Occupancy Vehicle) is to increase ride-sharing by providing a travel time saving to vehicles that have more than one rider to offset the extra time required to pick up and drop off passengers. The requirement to provide HOV lanes depends on local transportation authority. The strategy of providing HOV becomes more and more popular in heavily congested corridors where peak-period travel speed is particular low (Giuliano, Levine, and Teal, 1990). Travel time saving could be a reason why solo drivers might consider a car-pool. "...a study that compared potential time savings with the individual's perceived likelihood of carpooling showed that the two factors are positively related, ... However, the large discrepancy in perceived likelihood of carpooling compared to the results of an actual project is important to note."

By the end of 1980's, at least 17 metropolitan areas were using HOV lanes as part of their TDM programs (Guiliano, Levine and Teal, 1990). Although HOV lanes have become more and more popular as a way to promote ride-sharing, there are very few research reports on its effectiveness. Most studies so far have focused only on the traffic volume on HOV lanes and some estimates like trip or fuel consumption reduction. "None of these studies has addressed the more fundamental question of the source of increased ride-sharing. Do these HOV's attract new car-poolers and transit riders, or do they simply divert existing car-poolers and transit users from other routes or time periods?" (Guiliano, Levine and Teal, 1990). Guiliano *et al.* pointed out that HOV lanes can increase ridesharing only when the potential time-saving gains are large, and only those commuters who can take the full advantage of the lanes (e.g., a complete HOV system, a long trip distance) are more likely to shift to ride-sharing. They also noticed that alternative work hours (AWH) might even hinder ride-sharing because a flexible work schedule avoids peak hour traveling and may encourage driving alone. Dahlgren summarized several papers that found that a commuter's mode choice is not very sensitive to in-vehicle travel time, and people would value 1 minute of waiting the same as 10 minutes in-vehicle. She concluded that "if the HOV is converted from an existing lane, then it is better than doing nothing", but argued that "if the HOV lane is an additional lane, ... in many situations, adding a general purpose lane would be more effective." (Dahlgren, 1994). So far, the effectiveness of HOV lanes is not quite clear, but HOV strategy itself is still used in many urban areas. Flannelly *et al.* also concluded that the time saving from HOV lanes is not appealing enough to attract solo drivers to switch to ride-sharing (Flannelly *et al.*, 1991).

2.6.5 Preferential Parking Policies

To lower the number of solo drivers and encourage carpooling, local transportation authorities often use different parking policies. Parking management means "either regulating the supply of employee parking or pricing parking so that the cost of driving alone increases relative to other alternatives" (Hwang and Guiliano, 1990). ARCO was a very successful example for several years. Three-fourth of the company's employees ride-shared with each other, and this success was largely attributed to its parking pricing strategy. For example, the price of parking was scaled to the number of riders (the more riders in a car, the lower the rate). Also, the company provided a transportation allowance to employees (Kuzmyak and Schereffler, 1989).

The issue of "parking requirements" is noteworthy. "Parking requirements are local regulations specifying the amount of parking space to accompany new or refurbished buildings. ...The purpose of the requirement is to ensure that users of the building park their vehicles as little as possible on streets or in lots intended for others" (Higgins, 1985). In a study on parking requirements to support public parking and ride-sharing, Higgins concluded that in many cities where parking is very expensive or scarce, parking strategy is effective.

2.6.6 Intelligent Transportation Systems (ITS) Technologies for Carpooling

Niles and Toliver proposed some ideas to use Intelligent Vehicle Highway Systems (IVHS) technologies to improve ride-sharing (Niles and Toliver, 1992). (IVHS is currently known as Intelligent Transportation Systems or ITS.) They claimed that using new technologies like wireless telecommunications and computerized data processing could create a new transportation mode called Intelligent High Occupancy Vehicle (I-HOV). Through this system, commuters can request ride-sharing at any time and any place, and get responses very quickly due to the quick computerized matching process. A fixed-origin-and-destination appointment is no longer required as before. This quick processing overcomes a major drawback of traditional ride-sharing arrangements, i.e., lack of flexibility due to rigid appointments, and makes flexible ride-sharing more possible. They believed that this was a good approach to increasing ridesharing.

2.7 Assessing Effectiveness of Car-pool Promotion Programs

Predicting the impacts and evaluating the effectiveness of ride-sharing program is not easy since this process involves many non-quantitative factors. Understanding how to improve the effectiveness of ride-sharing programs is only possible after we know how to evaluate the effectiveness of ride-sharing programs.

Rubin *et al.* proposed a quantitative marketing method to estimate impacts of carpooling policies. "A specially designed survey and a trade-off model developed to quantify traveler preference were used instead of a traditional modal-split model to estimate the likely impacts of proposed policies for promoting carpooling." They considered a number of "soft" factors like safety, comfort and midday mobility in their study, and concluded this approach was a good alternative to traditional modal-split techniques (Rubin et al.).

Brownstone and Golob (1991) used discrete-choice models (consisting of three behavioral categories - "always ridesharing", "mixed mode", and "always solo drive") to understand the effectiveness of various ride-sharing incentives, and concluded that employer-provided preferential parking and HOV lanes are significant in explaining the choice between driving alone and carpooling. Combining these incentives with ridesharing cost subsidies and a guaranteed ride home program can effectively reduce the number of solo drivers. Significant non-incentive variables include household size, logarithm of commuting distance, etc. This study attempted to develop a quantitative method for evaluating the effectiveness of various incentives.

Hwang and Guiliano also evaluated the effectiveness of employer-based ride-sharing incentives such as marketing, personalized matching service, subsidies, alternative work hours, and parking management (Hwang and Guiliano, 1990). They concluded that the factors like high transit access are favorable and factors like suburban employer location are unfavorable for these programs, and also claimed that parking charge and transportation allowance, etc. are more effective than alternative work hours (AWH), marketing, matching service, etc.

2.8 Conclusions from Literature Survey

In the past, researchers agreed to believe that ride-sharing was a technically feasible and high-potential way to deal with urban traffic congestion problems. There is a large literature that tries to (i) understand the commuter behavior patterns and attitudes and the likelihood of ride-sharing given socio-demographic conditions, (ii) to identify effective strategies for promoting ride-sharing or (iii) to evaluate strategies based on empirical observations, experiments, or surveys. But there is little literature on the CDR-potential for the purpose of demand reduction. This is not surprising because (i) accurately estimating the potential requires quantification of factors influencing commuters' mode choice and (ii) many of these factors are not easily quantifiable.

Rather than attempting to accurately estimate the potential of carpooling for demand reduction, we are content with estimating upper bounds of the potential.

Although many car-pool decision factors are non-quantifiable or not easily quantifiable, some of them actually are amenable to quantification. Our approach is to consider only some of the major quantifiable factors and to develop upper bounds for the potential accordingly. The quantifiable factors considered are spatial and temporal factors.

The authors are not aware of any effort in the existing literature that posed the fundamental question of whether the CDR-potential after considering only spatial and temporal factors is large enough so that a commuter can realistically find a car-pool partner if he or she wants to carpool. This report focuses on estimating the upper bound of the CDR-potential when only spatial and temporal constraints are considered. If the upper bound is high, then other behavioral constraints can be further considered to assess the realistic potential. If, however, this potential is already very low, the actual CDR-potential among unrelated commuters may be even lower, and expectation of promotion results needs to be adjusted accordingly.

III. Problem Statement

This report focuses on spatial and temporal factors that impact commuters' decision regarding driving alone vs. carpooling. More precisely, we focus on the effect of worker/job densities, origin-destination distribution, commuters' tolerance for the additional driving required for picking up or dropping off carpool partners, and departure time distribution on the CDR-potential (i.e. the potential of carpooling for demand reduction) as a means to reduce demand on urban transportation systems during peak commute hours.

3.1 Fundamental Questions and Justification

We study several fundamental questions, including:

1. Carpooling incurs travel delay due to pick-ups and drop-offs. Can the current worker (population) density, origin-destination distribution and departure time distribution support a sizable carpooling population that can make a significant contribution to demand reduction during peak commute hours?
2. If so, what is the maximum impact carpooling can have on demand reduction, considering only these spatial and temporal factors?
3. Long trips are more likely candidates for carpooling. But, there may be fewer long trips and they may go to more diverse destinations, when compared to shorter trips. Could the proportion of long trips that are likely candidates for carpooling be so small that no significant demand reduction and hence congestion relief during peak commute hours could be expected from carpooling.

There are many other interesting questions regarding the impact of the spatial and temporal factors on the CDR-potential. Answers to these questions can serve as critical input to studying the behavioral aspects of carpooling and can ultimately lead to realistic estimates of the CDR-potential. Furthermore, the answers and further studies can help answer the question of how one would design strategies to encourage carpooling.

The three questions posed above will be answered in a parametric way, with the following factors as parameters: (i) the worker (population) and job densities, (ii) average length of commute trips, (iii) maximum pick-up/drop-off distance, i.e., the maximum additional distance at which a driver is willing to drive for picking up and dropping off car-pool partners, at the origin and the destination, (iv) minimum trip length for carpooling, i.e., the trip length below which carpooling will not even be considered, and (v) maximum departure time difference, i.e., the maximum difference between the preferred departure times of the commuters who carpool together.

There exists much literature on discrete-choice models for studying carpooling propensity. However, the literature seems to assume tacitly that as long as one wants to carpool, there is no problem in finding a car-pool partner who lives and works at nearby locations and has a similar work schedule. This tacit assumption has not been verified in the literature. Also, the temporal and spatial factors mentioned earlier have not been explicitly treated in the literature.

If our results (after considering the spatial and temporal factors) show that a car-pool candidate can have a large number of possible partners to choose from, e.g., 1000, then the tacit assumption is a good one. However, if the number is small, e.g., 2, then the tacit assumption is not well-founded.

In understanding commuters' car-pool decisions, it is important to know the distribution of the length of car-pool trips, the tolerance for additional driving required for pick-ups and drop-offs, the distribution of car-pool partners' desired departure times, and the deviation of the actual departure times from the desired departure times. However, there exists little literature about these quantities. As will be seen later, we will assume what we believe as reasonable assumptions about these quantities, and, based on the assumed values, the CDR-potential will be found to be very low for low-density metropolitan areas. Empirical data would help ascertain the validity of our assumptions and results and, more importantly, would help understand the true CDR-potential.

3.2 Continuous Approach

Modeling is needed for trip generation, trip distribution and departure time distribution. We focus on the first two because, as will become clear later, the potential before considering departure time distribution is extremely low and there is no need to consider departure time distribution.

To motivate our approach, consider a continuous trip generation and distribution problem where all trip production and attraction quantities are expressed as continuous density functions, rather than discrete numbers associated with zones. The approach consists of the following main steps:

1. To simplify the problem, assume that the area under consideration is an infinite two-dimensional plane, i.e., the x-y plane.
2. To simplify the trip generation problem, assume that the workers and the jobs are

both uniformly distributed over the entire plane with a common and known (uniform) density.

3. To further simplify, assume the knowledge of the average commute distance and assume that the average is constant throughout the plane. (Since there is no concept of network or network capacity in this study, we do not consider travel times and average travel time.)
4. As in conventional analysis of trip distribution, we use the gravity model, or, equivalently, the entropy optimization model to distribute the trips (based on the continuous density functions representing trip production and attraction).

Under the assumptions made in steps (1) - (3), it is intuitively clear that the origin-destination (OD) demand should be uniform across all OD pairs that have the same distance between them. This is because there exist no reasons why one OD pair with a particular distance should have more trips than any other OD pairs that have the same distance.

Given the assumption, all one needs to do is to find the demand for OD trips, in the form of a continuous density function, as a function of the distance between the origin and destination. Once this function has been obtained, the trip numbers can be calculated through integration.

Dealing with densities could be quite involved because one is no longer dealing with a finite number of variables and constraints. With densities, one will need to deal with an infinite number of variables and constraints. (However, the special structure of this problem may simplify the mathematical problem.)

Trips have traditionally been distributed among zones. A complication regarding estimating the CDR-potential with a plane without a zone structure is that the CDR-potential cannot be measured by a single number. In fact, the potential can fall between an upper bound and a lower bound. Note that, assuming that a car-pooler may carpool with only one car-pool partner and that a car-pooler can choose one when he or she has multiple choices, the actual CDR-potential varies depending on how the choices are made by car-poolers. Consider the following example. Assume that there are four commuters living on a straight line with 2 mile between each other, and they work at a common office building. Also assume that these commuters are willing to carpool only if the extra distance required for pick-up is no more than 5 miles. Label the four commuters as Commuter 1 through Commuter 4 from one end of the straight line to the other. If Commuters 2 and 3 decide to carpool, then only one car-pool is possible because the distance between the homes of Commuter 1 and 4 is 6 miles, which is larger than the maximum pick-up distance of 5 miles. However, if Commuters 1 and 2 decide to carpool together, then Commuters 3 and 4 can carpool too. Also, if Commuter 1 and Commuter 3 decide to carpool, then Commuters 2 and 4 can carpool. In the two latter cases, two car-pools are possible. In short, the lower bound and the upper bound for the CDR-potential associated with this geographical arrangement are 1 and 2, respectively.

In general, the actual potential can be larger than the potential associated with the “worst choices” by all the car-poolers and can be smaller than the potential enabled by the “best choices.” Therefore, to estimate the potential with this "non-zone" approach, two optimization problems are involved, one for calculating the upper bound and the other for calculating the lower bound.

Because of these complications, we adopt the following conventional discrete approach for this research.

3.3 Discrete Approach

We first make several simplifying assumptions and discuss their motivation and possible weaknesses. The approach consists of the following steps.

1. Consider a square region partitioned into a grid structure with equi-sized zones.

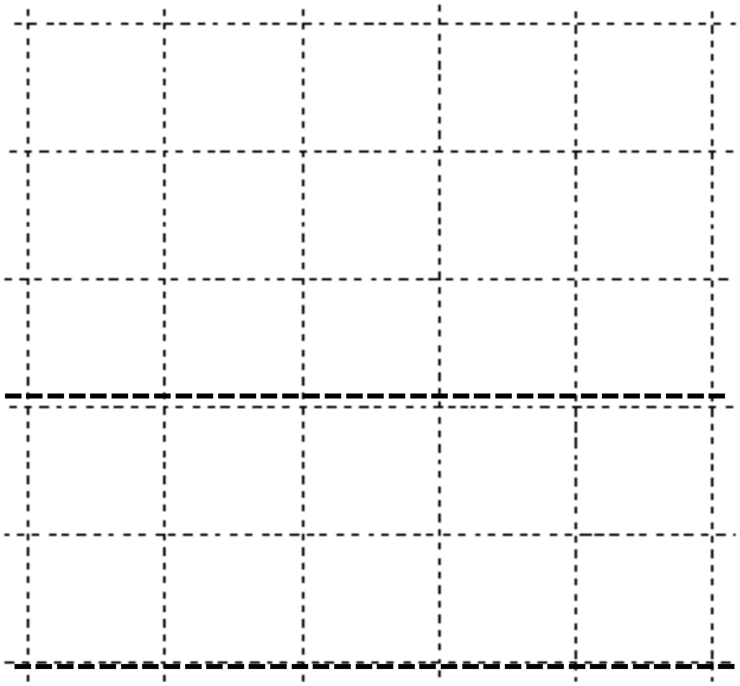


Fig. 1: Square-region-zone structure.

2. Define the distance between any two zones as the distance between the two centers of the two zones. The structure defined above will be referred to as the square-region-zone structure.
3. For each zone, assume a common number of workers and a common number of jobs.

Also assume that the number of workers equals the number of jobs. (In other words, we assume uniform worker and job distributions, with a common density.)

4. Assume that only people who live in a common zone and also work in a common zone would carpool. (Zone sizes reflect the maximum pick-up and drop-off distance.) Also assume that only trips longer than threshold are candidates for carpooling.
5. Assume an average commute distance across all trips.
6. Use the gravity model, or, equivalently, the entropy optimization model, to determine the trip numbers.
7. Let the size of the square region increase to infinity while keeping the size of the zones constant and hence letting the number of zones go to infinity. The trip number between any particular pair of origin and destination should converge as the size of square region increases to infinity. Use these numbers as the trip number for the origin and destination pair. Identify trips that are candidates for carpooling based on (4).
8. Divide the peak hours into time intervals in such a way that one can assume that only those people whose desired departure times (from home and from work) are within a common time interval would carpool. (Length of time period reflects the maximum amount of time that car-pool partners would be willing to sacrifice desired schedule in exchange for carpooling.)
9. Assume a distribution of desired departure times, and assign accordingly the car-pool candidates obtained in (7) to the time intervals obtained in (8).
10. The resulting trip number for each origin/destination/departure-time-interval

combination can be viewed as the maximum number of car-pool candidates for that combination.

3.4 Conjecture

Note that only trips longer than a threshold value are considered candidates for carpooling. As the size of the square region and corresponding number of zones go to infinity, the OD trip number between each particular pair of zones approaches a constant (i.e., the limiting trip number), and any two pairs of ODs with the same distance apart will have the same limiting trip number.

Given any finite square-region-zone structure defined above, the boundary makes the trip numbers associated with the trip distribution problem irregular in the sense that the trip numbers associated different ODs with a common distance apart are not identical. But this irregularity should tend to be more serious for those ODs where either the origin or the destination is near the boundary. Therefore, when the square-region-zone structure grows to infinity, any particular fixed pair of origin and destination will be getting farther and farther away from the boundary. Consequently, the trip number should converge, and the limiting trip number should depend only on the distance between the origin and the destination. These trip numbers can be further partitioned after considering the departure time distribution.

This basic model can be improved and refined for more realism. For example, in the basic model, the maximum pick-up/drop-off distance does not explicitly depend on the trip length, and can be made to depend on the trip length for refinement.

As will become clear in the next section, this discrete approach turns out to be quite involved too. We will further simplify the problem, but will do so without sacrificing solution quality.

IV. Formulation

Given a finite square-region-zone structure with common trip production and attraction characteristics for each zone and according to the discrete approach described in section (3.3), we use the following entropy optimization (gravity) model for trip generation and distribution.

$$\min \quad \sum_{i_1=-k}^{k}\sum_{i_2=-k}^{k}\sum_{j_1=-k}^{k}\sum_{j_2=-k}^{k} x_{(i_1,i_2)(j_1,j_2)} \ln x_{(i_1,i_2)(j_1,j_2)}$$

$$\text{s.t.} \quad \sum_{j_1=-k}^{k}\sum_{j_2=-k}^{k} x_{(i_1,i_2)(j_1,j_2)} = O_{(i_1,i_2)} \,,$$

$$\sum_{i_1=-k}^{k}\sum_{i_2=-k}^{k} x_{(i_1,i_2)(j_1,j_2)} = D_{(j_1,j_2)} \,,$$

$$\sum_{i_1=-k}^{k}\sum_{i_2=-k}^{k}\sum_{j_1=-k}^{k}\sum_{j_2=-k}^{k} c_{(i_1,i_2)(j_1,j_2)} x_{(i_1,i_2)(j_1,j_2)} = C \,,$$

$$x_{(i_1,i_2)(j_1,j_2)} \geq 0 \,,$$

where

$x_{(i_1,i_2)(j_1,j_2)}$ is the number of trips from origin (i_1, i_2) to destination (j_1, j_2),

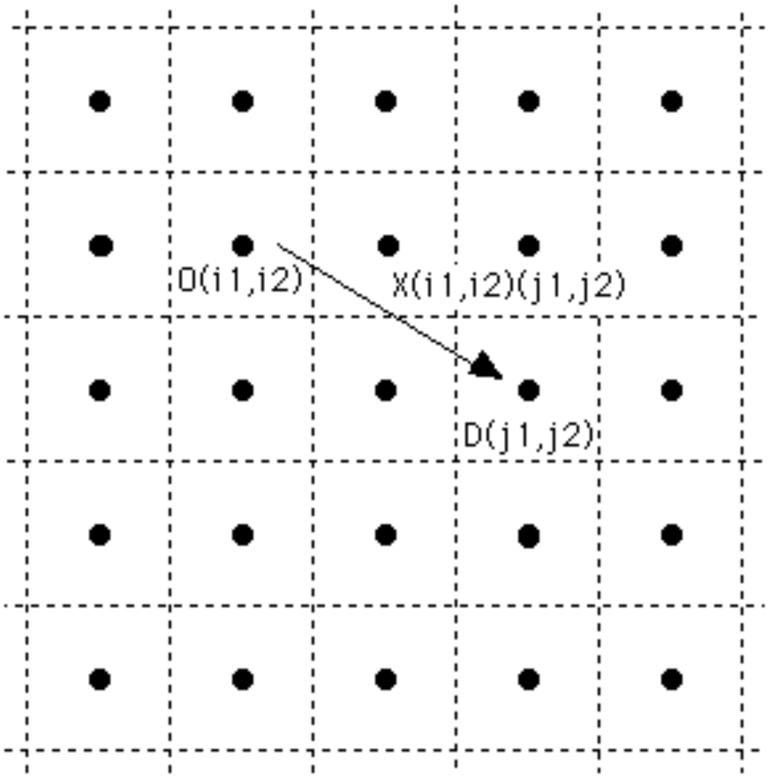
$O_{(i_1,i_2)}$ is the total production of origin (i_1, i_2),

$D_{(j_1,j_2)}$ is the total attraction of destination (j_1, j_2),

$c_{(i_1,i_2)(j_1,j_2)}$ is the travel distance between origin (i_1, i_2) to destination (j_1, j_2),

C is the total travel distance of all the commuters.

The figure below illustrates the square-region-zone structure:



------- boundary of zones in the conceptual grid network

● origin \ destination node

Fig. 2: Square-region-zone structure with centroids.

In fact, the formulation above is a special case of the following standard form of entropy optimization model:

Program P:

$$\min \quad \sum_{j=1}^{n} y_j \ln y_j$$

$$\text{s.t.} \quad \sum_{j=1}^{n} a_{ij} y_j = b_i, \qquad i = 1, 2, ..., m,$$

$$y_j \geq 0, \qquad j = 1, 2, ..., n.$$

We will solve this constrained entropy optimization problem by first obtaining its unconstrained dual, then solving the unconstrained dual and finally obtaining the optimal solution of this constrained problem through an effortless dual-to-primal conversion formula. To derive the dual, we utilized a simple inequality:

$$\ln z \leq z - 1, \qquad \text{for } z > 0. \tag{1}$$

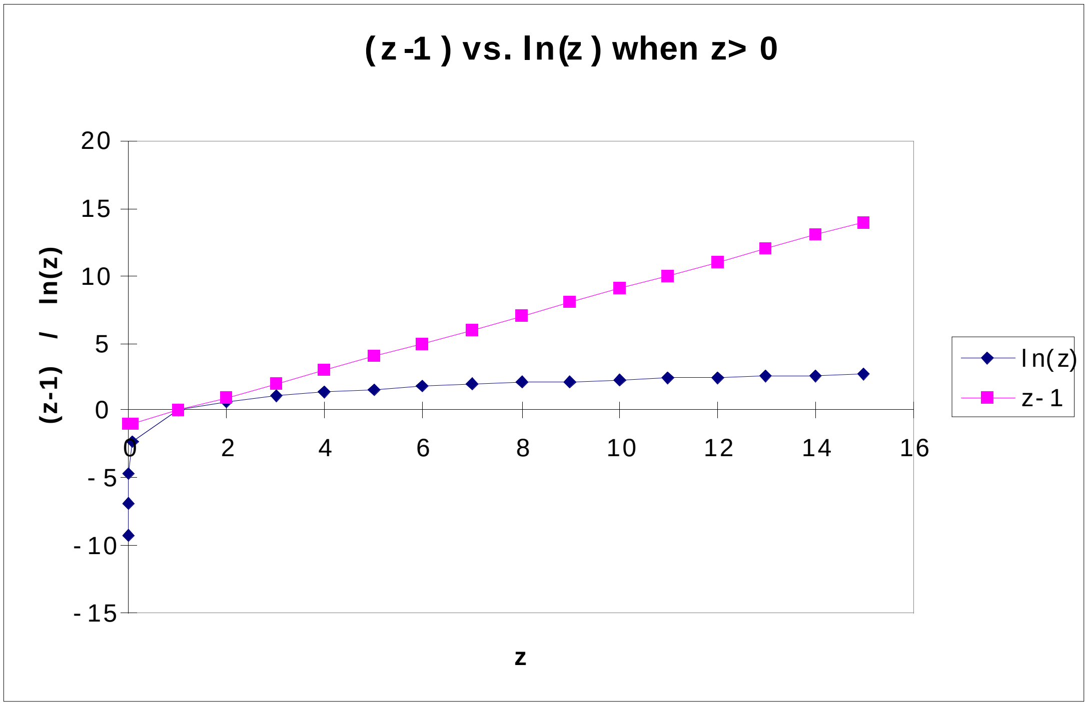


Fig. 3: the relationship between (z-1) and ln(z) when z > 0.

This inequality can be easily verified by the graph above, and notice that this inequality becomes an equality if and only if z = 1.

Now, for any $w_i \in$ R (i = 1, ..., m), and $y_j > 0$ (j = 1, ..., n), we define:

$$z_j = \frac{\exp(\sum_{i=1}^{m} a_{ij} w_i - 1)}{y_j}, \qquad j = 1, ..., m.$$

Then, by using the simple inequality, i.e. Inequality (1), we have:

$$\ln z_j = (\sum_{i=1}^{m} a_{ij} w_i - 1) - \ln y_j \leq z_j - 1 = \frac{\exp(\sum_{i=1}^{m} a_{ij} w_i - 1)}{y_j} - 1.$$

Consequently, for j = 1, …, n,

$$y_j\left(\sum_{i=1}^{m} a_{ij} w_i\right) - y_j \ln y_j \le \exp\left(\sum_{i=1}^{m} a_{ij} w_i - 1\right) .$$

Summing up all n equations above gives

$$\sum_{j=1}^{n} y_j\left(\sum_{i=1}^{m} a_{ij} w_i\right) - \sum_{j=1}^{n} \exp\left(\sum_{i=1}^{m} a_{ij} w_i - 1\right) \le \sum_{j=1}^{n} y_j \ln y_j . \qquad (2)$$

If y_j's satisfy $\sum_{j=1}^{n} a_{ij} y_j = b_i$, then

$$\sum_{j=1}^{n} y_j\left(\sum_{i=1}^{m} a_{ij} w_i\right) = \sum_{i=1}^{m}\left(\sum_{j=1}^{n} a_{ij} y_j\right) w_i = \sum_{i=1}^{m} b_i w_i .$$

By substituting $\sum_{j=1}^{n} y_j\left(\sum_{i=1}^{m} a_{ij} w_i\right)$ with $\sum_{i=1}^{m} b_i w_i$ in Inequality (2), we obtain

$$\sum_{i=1}^{m} b_i w_i - \sum_{j=1}^{n} \exp\left(\sum_{i=1}^{m} a_{ij} w_i - 1\right) \le \sum_{j=1}^{n} y_j \ln y_j .$$

We are now ready to define the constrained dual program:

$$\text{Max}\left\{ d1(w) = \sum_{i=1}^{m} b_i w_i - \sum_{j=1}^{n} \exp\left(\sum_{i=1}^{m} a_{ij} w_i - 1\right) \right\} .$$

It is easy to verify that w̲ is an optimal solution to the dual program and y̲ is an optimal solution to the entropy optimization problem, i.e., if $z_j \equiv \frac{\exp\left(\sum_{i=1}^{m} a_{ij} w_i - 1\right)}{y_j} = 1$. This is equivalent to:

$$y_j = \exp\left(\sum_{i=1}^{m} a_{ij} w_i - 1\right), \text{ for all j.}$$

Rewrite the dual program as:

Program D:

$$\min_{w \in R^m} \{d(w) \equiv \sum_{i=1}^{n} \exp(\sum_{i=1}^{m} a_{ij} w_i - 1) - \sum_{i=1}^{m} b_i w_i\}$$

Then, under some regularity conditions, Program D has an optimal solution $\underline{w}^*$.

Moreover, $\underline{y}^*$ defined by

$$y^*_j = \exp(\sum_{i=1}^{m} a_{ij} w_i^* - 1), \qquad j = 1, 2, ..., n,$$

is an optimal solution to Program P. Therefore, to solve the constrained Program P, one can instead solve the uncontrained Program D, which is much easier.

With the aid of general theory, we know that the solution to our trip distribution problem has the following form:

$$x_{(i_1,i_2)(j_1,j_2)} = \exp(u_{(i_1,i_2)} + v_{(j_1,j_2)} + c_{(i_1,i_2)(j_1,j_2)} * w_c - 1),$$

where

$u_{(i_1,i_2)}$ is the dual variable associated with the constrain corresponding trip production,

$v_{(j_1,j_2)}$ is the dual variable associated with the constrain corresponding trip constraint,

w_c is the dual variable associated with the constraint on total travel distance.

The conjecture is that the trip number between any two zones, when the size of the square region goes to infinity, will converge to a certain number. However, proving the conjecture using the above model seems quite complicated. Therefore, we simplify the model as follow. As before, we start with a small square region and increase the size of it progressively. At the same time, we simplify the model by considering only one origin and distributing the total trip production from the origin to all the destinations. The rationale is that as the size of the square region goes to infinity, trip distribution from any selected zone to all the other zones should be invariant under displacement of the origin. The graph below illustrates how the approach works.

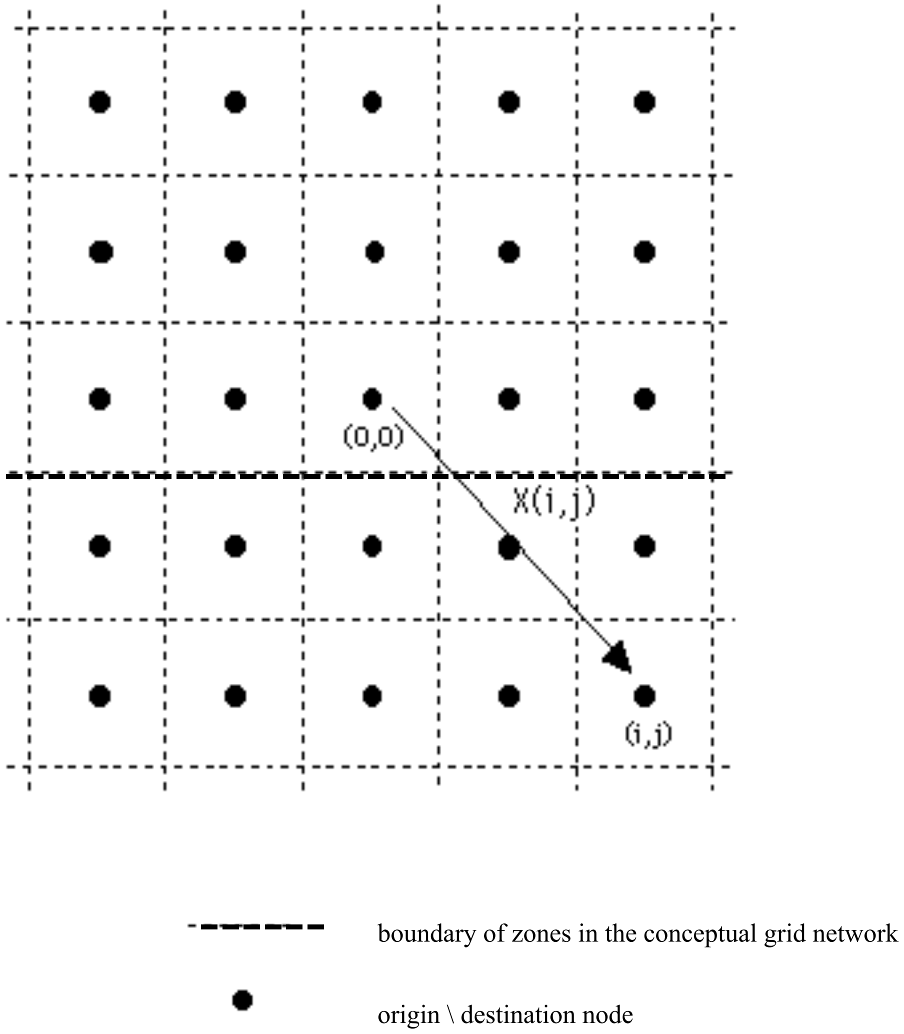


Fig. 4: Square region with a single origin zone at the center.

Also, the average commute distance for the workers in a particular zone should be identical to the average commute distance for all the workers. We also add a constraint on "transportation cost" based on the assumption on average commuting distance. Now our problem formulation becomes

$$\min \quad \sum_{i=-k}^{k} \sum_{j=-k}^{k} x_{(i,j)} \ln x_{(i,j)}$$

$$\text{s.t.} \quad \sum_{i=-k}^{k} \sum_{j=-k}^{k} x_{(i,j)} = O_{(0,0)} \, ,$$

$$\sum_{i=-k}^{k} \sum_{j=-k}^{k} c_{(i,j)} x_{(i,j)} = d * O_{(0,0)} \, ,$$

where

$x_{(i,j)}$ is the number of trip from origin (0,0) to destination (i,j),

$c_{(i,j)}$ is the travel time between origin (0,0) and destination (i,j),

$O_{(0,0)}$ is the trip production of origin (0,0),

d denotes average commuting distance.

With the aid of the general theory discussed earlier, we obtain:

$$x_{(i,j)} = \frac{\exp^{w_c c_{(i,j)}}}{\sum_{all(i,j)} \exp^{w_c c_{(i,j)}}} * O_{(0,0)} \, ,$$

$$d = \frac{\sum_{all(i,j)} c_{(i,j)} x_{(i,j)}}{\sum_{all(i,j)} x_{(i,j)}} \, ,$$

where

$x_{(i,j)}$ is the number of trip from origin (0,0) to destination (i,j),

$c_{(i,j)}$ is the travel distance between origin (0,0) and destination (i,j),

$O_{(0,0)}$ is the trip production of origin (0,0),

w_c is the dual variable associate with the constraint on travel distance,

d denotes the average commuting distance.

V. Data and Numerical Results

The urban sprawl of Los Angeles is already well known and has been intensively studied. Some studies focused on the impacts of sprawl on environment, air pollution, etc. and discussed whether a "compact city" or a Los Angeles-style sprawl was more desirable (Gordon and Richardson, 1997; Ewing 1997) while others tried to explain the sprawl itself by using the ideas of polycentricity or dispersed metropolis (Giuliano and Small, 1990; Gordon and Richardson, 1996). The truth is that Los Angeles is not a traditional CBD type metropolis, and employment opportunities are scattered in the whole region with varied density.

There are two different view-points on urban sprawl. The sprawl of Los Angeles can be viewed as a metropolitan area with several subcenters, with the definition of a subcenter varying with individual studies. Basically, the definition of a center/subcenter is based on several measures, e.g., employment density, minimum total employment, etc. For example, one study (Giuliano and Small, 1990) defined a center as a contiguous set of zones whose employment densities should be higher than both a pre-defined density and the neighboring zones' densities and whose total employment should be higher than a pre-defined minimum total employment. The peak of a center is defined as the density of the zone (or contiguous zones) with the highest density as subcenter and its peak can be defined similarly.

The alternative view is that the Los Angeles region can be more accurately described as a dispersed metropolis instead of a polycentric region. Gordon and Richardson (1996) conducted an analysis on the data collected from 1970 to 1990 for Los Angeles and found that only 12 % of the total employment is located in centers/subcenters. They claimed that even using different threshold values would still result in a small percentage (Gordon and Richardson, 1996). Although they were uncertain about whether the Los Angeles metropolitan region would become more and less dispersed, they believed that a dispersed metropolitan region would be a better descriptor of the sprawl. In this report, we deal with an completely uniform sprawl. In the rest of this report, we will use Los Angeles employment and residential data as a guide for our numerical analysis.

Gordon and Richardson (1996) studied the trend of Los Angeles urban sprawl from 1970 to 1990. They also provided job and worker densities for different areas of the metropolitan area. To illustrate the use of our model and to estimate CDR-potential (i.e. the potential of carpooling for demand reduction) for an uniform density development with realistic job and worker densities, we will use two job densities derived from the Los Angeles data. We use (i) the weighted average of AZ category 1 and AZ category 2 job densities and (ii) the weighted average of the job densities of all AZ category areas as the two input job densities. They are 581 jobs/square mile and 660 jobs/square mile, respectively. (AZ category 1 and AZ category 2 areas combined make up 99.8% of the Los Angeles metropolitan area.) The zone size in our conceptual network is chosen to be 2 miles by 2 mile. This means that only people who live in the same two-mile by two-mile zone and also work in another common zone will carpool.

Existing literature suggests that average commuting time ranges from 23 to 27 minutes. For example, according to 1990 Census Transportation Planning Package by Bureau of Transportation Statistics, the mean time to work is 26.5 minutes in Los Angeles. Since the “transportation cost” in our problem formulation represents distance, we translate the mean commute time to average commute distance. Since there is no concept of road network in our formulation, there cannot be a concept of speed. To avoid loss of generality, we vary the speed from 25 mph to 55 mph. This leads to a range of average commute distance from 10 miles to 24 miles. We now have all the data required by the model and begin the numerical analysis.

First, we try to show the convergence of the assigned OD trips when the size of the square region approaches infinity (while the zone characteristics are kept constant). For each of the possible average commute distance and each of the job/worker density, this is done in the following steps. First, we discuss how to grow the region. Start with a single zone, to be referred to as the origin zone, and let the region grow by enveloping the origin zone with eight additional zones so that the origin zone stays at the center of the region. Repeat this process so that the origin zone remains at the center of the enlarged region in each iteration. Suppose now that we have a finite region. We now discuss how to estimate the OD trip numbers between the origin zone and any particular zone on the finite region. Given the finite square-region-zone structure, calculate the trip number between the origin zone and any other zone using the gravity model. Then, let the size of the finite region grow to infinity. The limiting trip number is the trip number that we are seeking.

Consider the following numerical example. With the average commute distance assumed to be 20 miles, as the region size grows from 24 zones by 24 zones to 200 zones by 200 zones, Figure 5 demonstrates the convergence of the trip numbers between the origin zone and destination zones at varied distance away, with the distance ranging from 10 to 30 miles. In Figure 5, T.D. denotes the distance between the origin and destination zones, and a region with the size of 50 means a region made up by 50 zones along each of the X and Y axes.

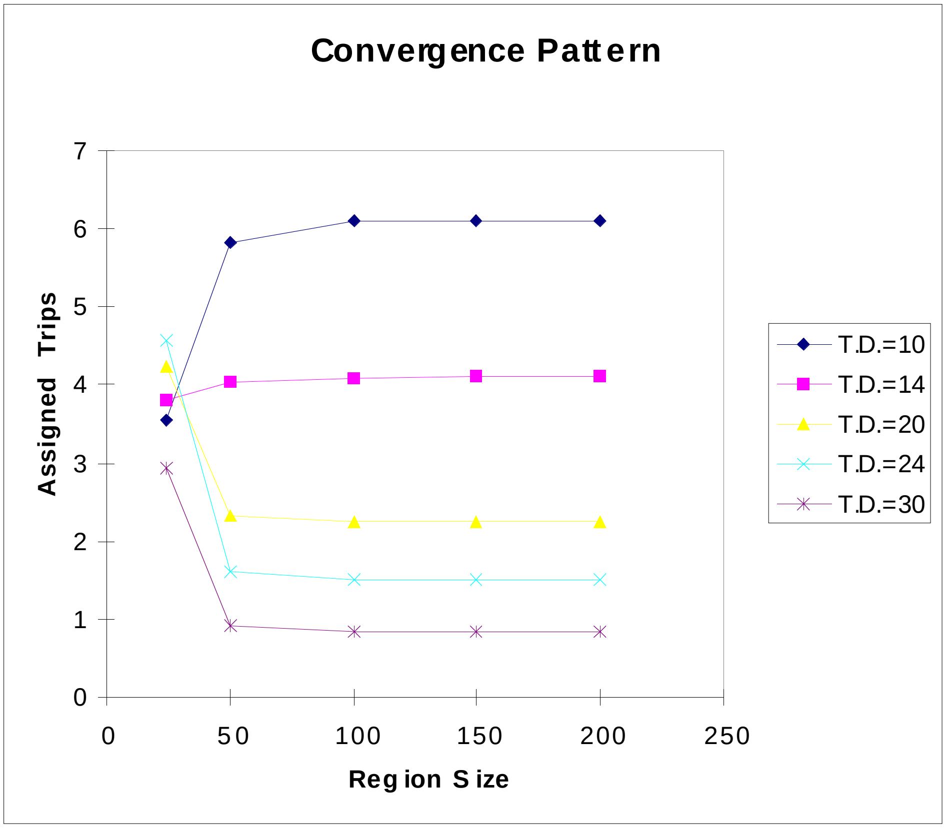


Fig. 5: Convergence pattern: average commute distance = 20 miles; zone size = 2 miles by 2 miles; job density = 660 jobs/ Sq. mi.; region size increases from 24*24 to 200*200.

Given that we have demonstrated the convergence and that the gravity model with a 200 zone by 200 zone region approximates the limiting trip numbers quite accurately, we will use this region size for estimating the trip numbers associated with the two job densities and for estimating the CDR-potential.

Recall that we will use two different job densities: 581 and 660 jobs/square mile. OD trips numbers are given in Tables 1 and 2, with the first corresponding to the job density of 581 jobs/square mile and the second corresponding to the job density of 660 jobs/square mile. Note that there are multiple zones whose distance from the origin zone is equal to any of the T.D. values (except 0). This is why the trip numbers in each of the columns of each of the two tables do not sum up to the total number of trips generated by the origin zone.

From Tables 1 and 2, it is clear that the trip numbers between the origin zone and any of the zones 10 miles or more are very small. For example, when the density is 581 jobs/square mile and the average commute distance is 16 miles, there are only 6.62 trips from the origin zone to any destination zones exactly 10 miles away, and there are only 2.44 trips to any destination exactly 18 miles away. Note that we have not even taken into consideration the departure time. If we took this factor into consideration, then the trip numbers would have been even lower. Also note that many other factors may negatively impact the CDR-potential. These results indicate that, under the assumptions made, carpooling has little potential for demand reduction.

Table 1: Trip Numbers at Density = 581 Jobs/Sq. Mi.

Density = 581 Jobs/Sq. Mi. (2324 Jobs/grid)								
	Avg. Commuting Distance							
T.D.	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**
0	58.64	40.88	30.09	23.06	18.24	14.78	12.22	10.27
2	39.36	29.31	22.62	17.97	14.60	12.10	10.19	8.69
4	26.42	21.02	17.01	14.00	11.70	9.91	8.49	7.36
6	17.74	15.07	12.78	10.90	9.37	8.11	7.08	6.23
8	11.90	10.80	9.61	8.49	7.50	6.64	5.90	5.27
10	7.99	7.75	7.22	6.62	6.01	5.44	4.92	4.46
12	5.36	5.55	5.43	5.15	4.81	4.45	4.11	3.78
14	3.60	3.98	4.08	4.01	3.85	3.65	3.42	3.20
16	2.42	2.86	3.07	3.13	3.09	2.99	2.85	2.71
18	1.62	2.05	2.31	2.44	2.47	2.44	2.38	2.29
20	1.09	1.47	1.73	1.90	1.98	2.00	1.98	1.94
22	0.73	1.05	1.30	1.48	1.58	1.64	1.65	1.64
24	0.49	0.75	0.98	1.15	1.27	1.34	1.38	1.39
26	0.33	0.54	0.74	0.90	1.02	1.10	1.15	1.18
28	0.22	0.39	0.55	0.70	0.81	0.90	0.96	1.00
30	0.15	0.28	0.42	0.54	0.65	0.74	0.80	0.84

Table 2: Trip Numbers at density = 660 Jobs/Sq. Mi.

Density = 660 Jobs/Sq. Mi. (2640 Jobs/grid)								
	Avg. Commuting Distance							
T.D.	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**
0	66.6	46.4	34.2	26.2	20.7	16.8	13.9	11.7
2	44.7	33.3	25.7	20.4	16.6	13.7	11.6	9.87
4	30	23.9	19.3	15.9	13.3	11.3	9.65	8.36
6	20.1	17.1	14.5	12.4	10.6	9.22	8.04	7.08
8	13.5	12.3	10.9	9.65	8.52	7.55	6.71	5.99
10	9.08	8.8	8.21	7.51	6.82	6.18	5.59	5.07
12	6.09	6.31	6.17	5.85	5.47	5.06	4.66	4.29
14	4.09	4.52	4.64	4.56	4.38	4.14	3.89	3.63
16	2.75	3.24	3.49	3.55	3.51	3.39	3.24	3.08
18	1.84	2.33	2.62	2.77	2.81	2.78	2.7	2.6
20	1.24	1.67	1.97	2.16	2.25	2.27	2.25	2.2
22	0.83	1.2	1.48	1.68	1.8	1.86	1.88	1.87
24	0.56	0.86	1.11	1.31	1.44	1.52	1.57	1.58
26	0.37	0.61	0.84	1.02	1.15	1.25	1.31	1.34
28	0.25	0.44	0.63	0.79	0.92	1.02	1.09	1.13
30	0.17	0.32	0.47	0.62	0.74	0.84	0.91	0.96

At the job density of 660 jobs/square mile and with the average commute distance assumed at 10 miles and 20 miles respectively, Figures 6 and 7 below show that most trips are between the origin zone and those nearby zones. It is reasonable to assume that people with short commute distances would not consider carpooling. On the other hand, those people who are most likely to carpool (i.e., those who commute a long distance) would have difficulties in finding a car-pool partner because of the small number of trips from the same origin zone to the same far-away destination zone.

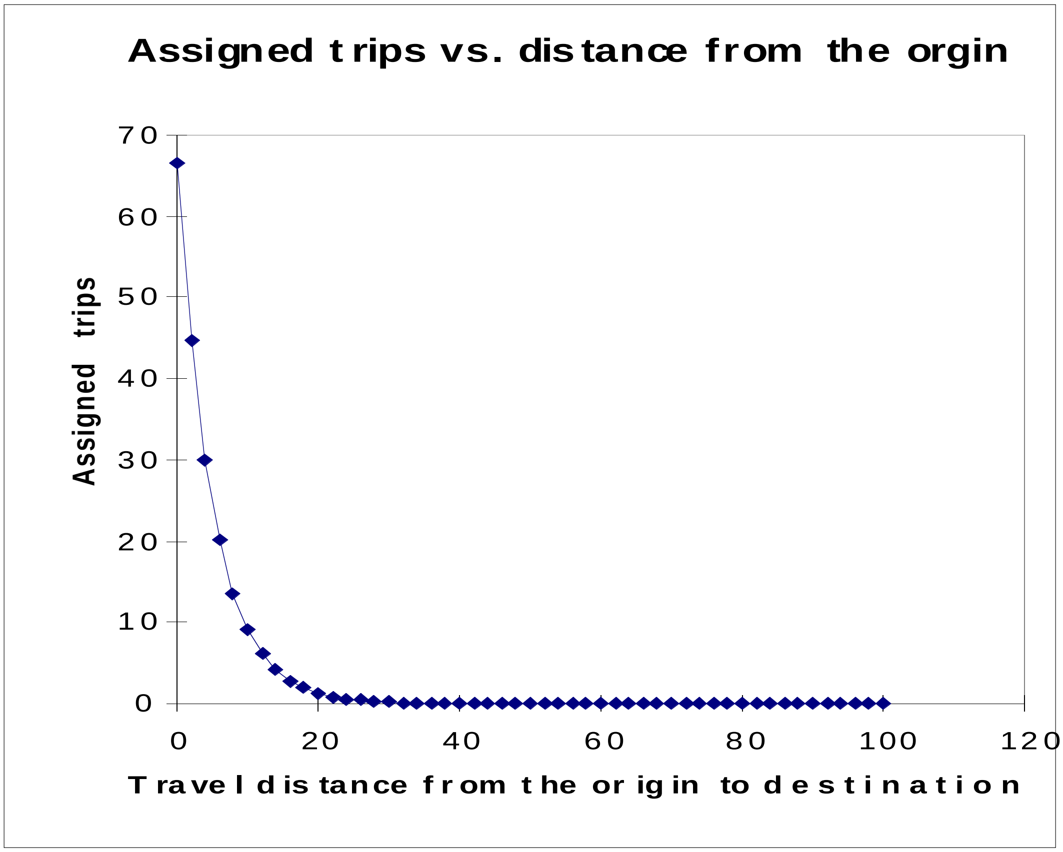


Fig. 6: Trips vs. travel distance when average commuting distance = 10 miles.

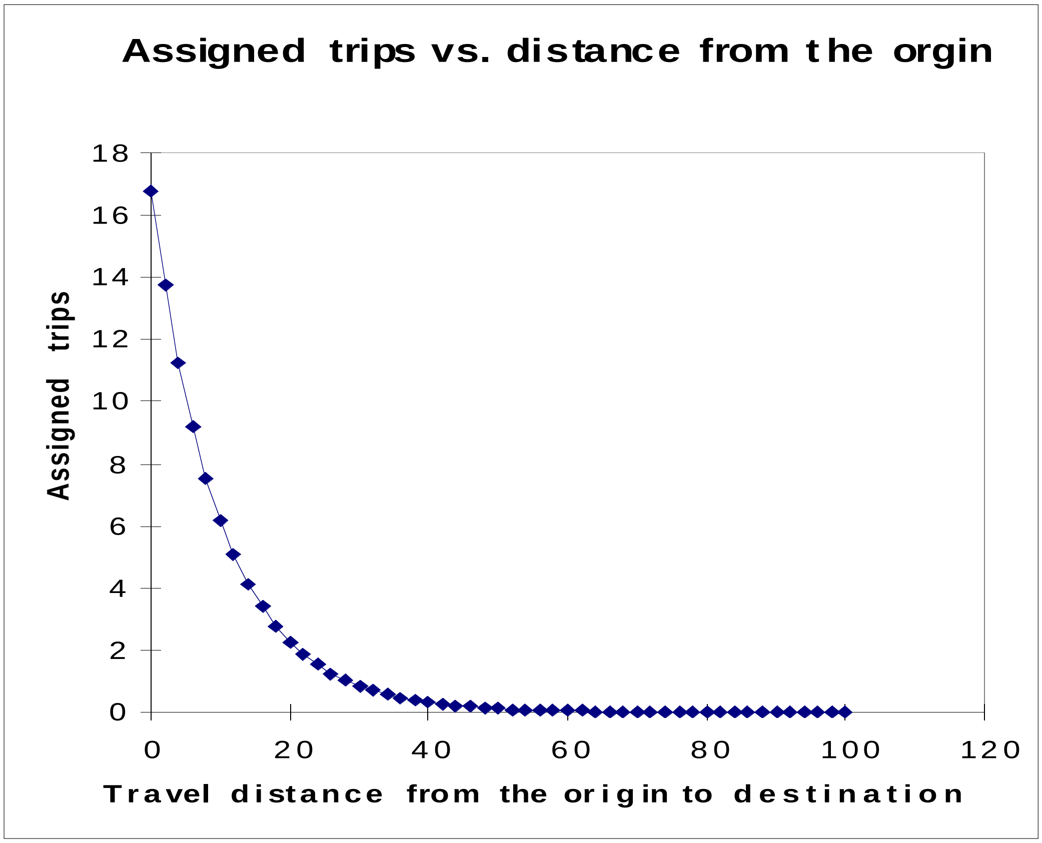


Fig. 7: Trips vs. travel distance when average commuting distance = 20 miles.

VI. Conclusion

We studied the potential of carpooling for reducing transportation demand for an uniform density development pattern. Based on assumptions and results, it appears that carpooling has little potential under such conditions. From our literature review about commute mode-choice, we learned that at least a decade ago, the ratios among solo driving, carpooling and using public transit was estimated to be 12:3:1 (Teal, 1987). If the ratios were indeed good estimates and continue to be good ones today for an urban sprawl like Los Angeles, then the number of car-pool trips in Los Angeles is much larger than the estimates produced by our model. In this case, reconciliation is necessary.

Since 12% of the jobs of the L.A. metro area are concentrated in L.A. downtown or other subcenters and such concentration of jobs would create a large number of car-pool opportunities, this explains at least partially the discrepancy. Recent estimates of car-pool popularity indicate that carpooling has become basically a family phenomenon (Pisarski, 1998). In other words, carpooling occurs predominantly among family members, and carpooling among unrelated partners is rare. This phenomenon is different from what were reported in the 1970's. Recall that Kendall (1975) and Hartegen (1977) estimated that 35% and 33% respectively of car-pools are intra-household. Car-pool behavior seems to have changed much in the past twenty years.

Teal (1987) pointed out that significant differences existed in trip length and trip circuity between intra-household car-pools and car-pools consisting of unrelated people. This difference, if it continues, may result in a higher potential than what is estimated by the proposed model. This observation and the observation of carpooling being a family phenomenon indicate another possible deficiency of the proposed model. Note that we assume that only people who live in a common zone and work in the same zone would consider carpooling with one another. This precludes the possibility of dropping a family member off at a location far from the work location of the driver. Another more fundamental limitation of the model is that two people who live on opposite sides of a street separating two zones would not carpool. This in some cases may be unrealistic. However, by controlling the zone size, this limitation can be minimized. We conducted some sensitivity analysis and found that the trip numbers do not increase significantly when zone sizes are moderately larger than 2 miles by 2 miles. Recent data are needed to assess the deviation of the proposed model from the actual car-pool popularity.

These point to several areas for future research. For example, the CDR-potential for a metropolitan area with a mixture of sprawl and work centers / subcenters deserves attention. Also, the work locations of car-pool partners do not have to be nearby, and car-pool partners can be dropped off or picked up along the driver's way to or from work. However, in this situation, only the driver's vehicle is used for the commute trips, and no mutual sharing of multiple vehicles is involved.

Acknowledgments

The authors gratefully acknowledge the funding of this research by California State Department of Transportation (Caltrans). They would like to thank Joy Dahlgren for many helpful comments on an earlier version.

References

[1] Beroldo, S. J., “Improving the Effectiveness of a Transportation Demand management Program Through Evaluation: A Case Study”, Transportation Research Record, No. 1280, pp. 22-29, 1990.

[2] Bonsall, P., “Car Sharing in the United Kingdom”, Journal of Transport Economics and Policy, pp. 117-145, 1981.

[3] Brownstone, D. and Golob, T. F., “ The Effectiveness of Ridesharing Incentives: Discrete-choice Models of Commuting in Southern California”, Working Paper, No. 93, The University of California Transportation Center, University of California at Berkeley, 1991.

[4] Cervero, R. and Griesenbeck, B., “Factors Influencing Commuting Choices in Suburban Labor Markets: A Case Analysis of Peasanton, California”, Transportation Research, Vol. 22A, No. 3, pp.151-161, 1988.

[5] COMSIS Corporation, “Evaluation of Travel Demand Management Measures to Relieve Congestion”, Report No. FHWA-SA-90-005, USDOT, Washington D.C., 1990.

[6] Daganzo, C. F., “Equilibrium Model for Capools on an Urban Network”, Transportation Research Record, 835, pp. 74-79, 1981.

[7] Dahlgren, J. W., “An Analysis of the Effectiveness of High Occupancy Vehicle Lanes”, Ph.D. dissertation, University of California at Berkeley, 1994.

[8] Dobson, R. and Tischer, M. L., “Beliefs about Buses, Car-pools and Single Occupant Autos”, Transportation Research Forum, XVII: 1, pp. 200-209, 1976.

[9] Ewing, R. H., “Psychological Theory Applied to Mode Choice Prediction”, Transportation 2, pp. 391-409, 1973.

[10] Feeney, B., “A Review of the Impact of Parking Policy Measures on Travel Demand”, Transportation Planning and Technology, Vol. 13, pp. 229-244, 1989.

[11] Ferguson, E., “The Influence of Employer Ridesharing Programs on Employee Mode Choice”, Transportation 17, pp. 179-207, 1990.

[12] Flannelly, K. J., McLeod, M. S. Jr., Flannelly, Laura, and Behnke, R. W., “Direct Comparison of Commuters’ Interests in Using Different Modes of Transportation”, Transportation Research Record, Vol. 1321, pp. 90-96, 1991.

[13] Gensch, D. H., “A Practical Segmentation Strategy to Increase Ride sharing”,

Transportation Research, Vol. 15A, pp. 331-338, 1981.

[14] Glazer, J. et al., “Part-Time Carpooling: A New Marketing Concept for Ridesharing”, Transportation Research Record 1082, pp. 6-15, 1986.

[15] Giuliano, G. and Golob, T., “Staggered Work Hours for Traffic Management: A Case Study”, Transportation Research Record, No. 1280, pp. 46-58, 1990.

[16] Gordon, P. and Richardson, H.W., “Beyond Polycentricity - The Dispersed Metropolis, Los Angeles, 1970-1990", Journal of American Planning Association, Vol. 62, No. 3, 1996.

[17] Hartgen, D., “Ridesharing Behavior: A Review of Recent Findings. Preliminary Research Report 130”, New York State Department of Transportation, 1977.

[18] Higgins, T., “Flexible Parking Requirements for Office Development: New Support for Public Parking and Ridesharing”, Transportation, Vol. 12, pp. 343-359, 1985.

[19] Horowitz, A., “An Attitudinal Model of Carpooling Behavior”, GM Research Report GMR-1969, General Motor, Michigan, 1975.

[20] Horowitz A. and Sheth J., “Ridesharing to Work: An Attitudinal Analysis”, Transportation Research Record 637, pp. 1-8, 1978.

[21] Hunt, J. D. and Mcmillan J. D. P., “A Stated Preference Examination of Attitudes Towards Carpooling to Work in Calgary”, Paper No. 97-0650, Transportation Research Board, 1997.

[22] Hwang, K. and Giuliano, G., “The Determinants of Ridesharing: Literature Review”, Working Paper No. 38, The University of California Transportation Center, University of California at Berkeley, 1990.

[23] Jones, D. and Harrison, F., “Off Work Early: The Final Report of the San Francisco Flex-Time Demonstration Project”, Institute of Transportation Studies, University of California at Berkeley, 1983.

[24] Kendall, D. “Carpooling: Status and Potential”, Final Report DOT-TSC-OST-75-23, U.S. Department of Transportation, 1975.

[25] Kostyniuk, U. P., “Demand Analysis for Ridesharing: State-of-the-Art Review”, Transportation Research Record 876, pp. 17-26, 1981.

[26] Margolin, J. B., Misch, M. R., and Stahr, M., “Incentives and Discentives of Ride Sharing”, Transportation Research Record, Vol. 673, pp. 7-15, 1978.

[27] McClelland, L., Marks, M., and Edison, M., "Evaluating Employer Programs Encouraging the Use of Alternate Travel Modes", Transportation, Vol. 10, pp. 247-256, 1981.

[28] McCoomb, L. A. and Steuart, G. N., "The Automobile Passenger - A Forgotten Mode", Transportation Research, Vol. 15A, pp. 257-263, 1981.

[29] Niles, J. S. and Toliver, P.A., "IVHS Technology for Improving Ridesharing", Surface Transportation and the Information Age : Proceedings of the IVHS America 1992 Annual Meeting, Vol. 2. pp. 537-547, 1992.

[30] Oppenheim, N., "Carpooling: Problems and Potentials", Transportation Quarterly, Vol. 33, No. 2, pp. 253-262, 1979.

[31] Pisarski , A., "Forces Shaping the Future Transportation Enterprise: Demographic and Social Change", University of California Institute of Transportation Studies, 50th Birthday Symposium, Berkeley, CA, 1998.

[32] Ringrose, M. R., "A Model for Estimating the Potential of Flexible Carpool Matching", Master Thesis, Department of Civil Engineering, Texas A & M University, 1992.

[33] Rubin, R. B. et al., "Use of a Quantitative Marketing Model to Estimate Impacts of Carpooling Policies", Transportation Research Record, Vol. 650, pp. 54-59, 1977.

[34] Stevens, W. F., "Improving the Effectiveness of Ridesharing Programs", Transportation Quarterly, Vol. 44, No. 4, pp. 563-578, 1990.

[35] Teal, R. F., "Carpooling: Who, How and Why", Transportation Research, Vol. 21A., No. 3, pp. 203-214, 1987.

[36] Tischer, M. L. and Dobson, R., "An empirical Analysis of Behavioral Intentions of Single-Occupant Auto Drivers to Shift to High Occupancy Vehicles", Transportation Research, Vol. 13A, pp. 143-158, 1979.

[37] Turnbull, K. F., Pratt, R. H., and Kuzmyak, J. R., "Development of a Short-Range Travel Demand Management Program: The I-35W Experience", Transportation Research Record, No. 1280, pp. 30-38, 1990.

[38] Wachs, M., "Policy Implications of Recent Behavioral Research in Transportation Demand Management", Reprint No. 81, University of California Transportation Center, University of California at Berkeley, 1991.