Integrated Multi-Modal Transportation Planning: A Spatial Approach[1]

In the main, people are viewed [by social scientists] as parts of activities to be performed within each domain in isolation, and not as entities who need to make sense out of their paths between and through domains.

Torsten Hägerstrand (1970 p. 19)

[W]e must learn to see the hidden forms in the vast sprawl of our cities.

Kevin Lynch (1960 p. 12)

The city is a fluid text, meant to be read, seen up close and far away, scrutinized at leisure by the very people who fuel its overwhelming scale. These peculiar spectacles make the city a place of provocative insights and accidental passages that, in foot and meter, show us the naked honesty of our own condition.

The city is a story…

Travis Hugh Culley (2001 p. 323)

Toute grande image simple est révélatrice d'un état d'âme[2]

Gaston Bachelard (1981 p. 77)

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[2] "Every large simple image discloses a state of the soul."

Abstract

Effective inclusion of non-automobile transportation in transportation planning practice calls for tools that respond as effectively to the special needs of these modes as standard tools do to the needs of automobile transportation. Such inclusion is of particular concern when policy makers wish to encourage alternative travel modes and seek substantial guidance from planners regarding the effects of various enhancements and modifications to the transportation system. Bicycle and pedestrian modes, and to a certain extent public transit, raise a variety of special problems having to do with the different spatial and temporal scales on which such travel takes place. These include small-scale environmental features, constraints on trip chaining, and availability of suitable destinations. But many people who rely on non-automobile modes are forced to make such decisions at a very large scale, by making residential and job location decisions that place them in walkable or bikeable neighborhoods. Existing transportation planning tools have not proved particularly effective at addressing either of these concerns.

The present work begins with the postulate that the usefulness of alternative modes hinges on spatial arrangements of transportation facilities and potential destinations. However, rushing to characterize these arrangements in scalar measurements of travel time or cost risks obliterating important features that are critical to effective planning of enhancements. An equal peril, however, is to cease considering these arrangements as elements of a transportation system in order to consider them purely from a moral or aesthetic standpoint. This paper reviews a variety of theoretical and practical approaches to spatial relationships in transportation planning in order to outline the state of the art in relationship to the requirements of multi-modal, multi-scale, spatially aware transportation planning. Based on this review, certain field-based techniques seem to hold particular promise for transportation planning models that can integrate the disparate requirements of different transportation modes and guide further research into operational definitions of walkable, bikeable or transit-friendly urban spaces in a form that will support effective policy and infrastructure investment decisions.

This paper concludes with a concrete illustration of how scale and spatial analysis can inform multi-modal transportation planning. Simple estimation of density of destinations accessed by walking and driving trips were calculated from household travel data collected in the Research Triangle region of North Carolina (Raleigh-Durham-Chapel Hill). Further research is suggested to clarify and model the relationships between the observed spatial variations and specific physical features of the transportation system.

1. Contents

2. Introduction

Planning for non-automobile modes is often treated as a niche specialty with relatively little importance to the mobility concerns that have long dominated transportation planning. With rising concern over road congestion and air quality, as well as the social consequences of urban sprawl and low-density, automobile-dependent development patterns, more attention and funding has become available to transportation alternatives. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and its successor, the Transportation Equity Act for the 21st Century (TEA-21, 1998), both included significant components devoted to improving public transit, pedestrian and bicycle transportation systems. Yet despite interest in these areas, multi-modal planning currently occurs on a mode-by-mode basis, with little attention given to integrated planning that considers the complete transportation system and interactions between modes. The tools that are used to evaluate existing capacity, to develop forecasts, and to plan facility improvements remain segregated.

Frequently, the problem of multiple modes is framed in the form of how to get people to walk more, bike more, or use transit more, and (rarely explicitly) to use private automobiles less. The focus of transportation planning, in keeping with the choice models that are the most common tool for analyzing mode choice, is thus typically to seek ways to make these modes more desirable compared to automobile travel. Strategies that emerge may involve improving the desirability of an alternative mode (for example, by removing all bus fares as the Town of Chapel Hill, North Carolina did in 2002) or by reducing the desirability of automobiles (for example, through traffic calming techniques, restricted parking, or even explicit cash fees for entering certain parts of the city, as undertaken by the City of London in February, 2003).

Pedestrian enhancements frequently aim to improve the aesthetics and “liveability” of streets and neighborhoods, and bicycle enhancement often focus on perceptions of safety.

Yet concerns with environmental problems and traffic congestion that have motivated interest in non-automobile modes have also led to increasing interest in land use patterns, and the effect of those patterns on where, when, how and why people travel. The dominance of the automobile as a transportation mode is evidently related to those patterns, and it is quite reasonable to expect that shifting the balance of travel activity from automobiles toward other modes will be accompanied by shifts in land use. Yet the need to protect private property rights makes direct influence on land use problematic. Moreover, the current state of knowledge about the effects of land use patterns, either at the large scale of typical urban and suburban developments or at the much smaller scale of the micro-environmental features, is quite limited (and, as I shall suggest below, not simply for lack of research). Lacking the legal ability and the planning knowledge required to move swiftly and decisively toward a more balanced transportation system, it is very important that transportation planners attempt to develop greater sensitivity to incremental changes in the travel environment that may gradually increase the utility of alternative travel modes. A key component of that problem is to learn to recognize effective changes before they have begun to produce measurable results. Such recognition requires effective models of how travel modes interact with each other and of how a useful travel environment may be developed incrementally.

Planning modal alternatives in isolation from each other and from automobile planning is unlikely to permit such a comprehensive approach. The present work begins an exploration into how planning for multiple travel modes can be effectively integrated, both in theory and in practice, in ways that may permit us practically to address the problems outlined above. The first section explores the historical and methodological reasons for separating model planning in the first place, and ways in which that separation might be overcome. Of interest is not simply the fact that such planning is separate, but also the character of travel by different modes that makes it possible for such separation to seem as natural as it does. This investigation begins with a hypothesis that travel activity is a spatial process that is naturally unified but occurs at multiple scales. Rather than pick a single correct scale to analyze this activity, I propose that examining these processes consistently at multiple scales may yield better results.

In practice, planning for different modes is compartmentalized in various ways, employs different planning techniques, refers to different criteria for what constitutes a good solution, and yields quite different visions of how best to attain various policy goals. And there is, in fact, nothing intrinsically wrong with this state of affairs. This compartmentalization is a sensible and effective outcome of matching concrete planning goals with the reality of travel that happens at a variety of spatial scales. The main reason for looking beyond this state of affairs is thus not because it is necessarily erroneous or wrong, but rather because new policy goals require us to consider a range of new problems that are not conveniently handled within existing frameworks. Difficult problems of land use, traffic congestion and environmental quality mentioned above reflect new policy goals call for new tools that address those goals as directly and effectively as our existing tools have addressed our previous goals. By exploring conceptual and methodological alternatives that start with the properties of space and scale in travel activity, we may begin to envision a significant simplification of difficult planning problems, such as reducing urban roadway congestion while simultaneously encouraging urban spaces that are attractive and conveniently walkable.

The second goal of this work is to explore the ways in which spatial factors have been (and have failed to be) included in efforts to understand and describe travel activity. A variety of creative techniques have emerged in the literature. Yet while significant advances in the direction outlined in the first part of this work have occurred, the spatial structure of travel is typically conceived as a methodological afterthought rather than a first principle. Thus, critical factors such as the natural spatial scale of various modes of travel activity find no expression, and intuitively obvious relationships between travel activity and the urban environment consequently prove unexpectedly difficult to identify using these techniques. Since modes such as walking that happen at "small" scales tend to be very sensitive to that environment, this shortcoming presents a major obstacle to integrated multimodal transportation planning.

Pointing out such shortcomings is not intended to minimize the effectiveness of existing transportation planning tools: planning "at scale" remains a vital part of any integrated approach. Rather, it is meant to suggest that comprehensive transportation planning should consider each mode at various scales, and that doing this effectively may be facilitated by supplementing standard planning models with techniques of spatial analysis that have up to now found little application in the field.

The present work concludes with an illustration of an approach to travel activity as a spatial process, employing techniques that are common in geostatistics and spatial data analysis. Though limitations of scale, space and time (naturally!) prevent a detailed and rigorous exploration of the methodological possibilities in this work, spatial analysis does have the potential to tell us much about how people experience the environment in which they live and travel, and may help identify novel approaches to designing and implementing multi-modal transportation system improvements that are simultaneously popular and sustainable.

3. Elements of a Spatial Approach to Multi-Modal Transportation Planning

"It is essentially the scale of observation that creates the phenomenon."

Charles Eugene Guye (1922)

A fundamental problem in transportation planning is how to create policies and facilities that support stated policy goals. In the case of alternative transportation modes, the prevailing view is that these modes cease to be used as the automobile proves itself a convenient and affordable alternative, and most planning has thus focused on rendering these modes more attractive in some way. However, such efforts have met with mixed success. Raleigh, North Carolina, and Grand Rapids, Michigan, for example, each designed and constructed a large and aesthetically pleasing pedestrian mall in its downtown. Yet in both cases, the mall is now being considered for conversion back to a standard road since it has failed to generate significant walking traffic and its disuse has contributed to a sense of abandonment of the downtown (*Raleigh, NC, City Council Meeting of May 7, 2002*, 2002). At the other end of the spectrum, many communities now require new developments to build sidewalks (see for example, Chapel Hill, NC, *Chapel Hill, NC, Land Use Management Ordinance*, 2003), but little attention is paid to whether and how these facilities will contribute to viable transportation alternatives. Certainly, successful pedestrian facilities, including malls and new sidewalks, have often been constructed. The difficulty lies not in the fact that it is hard to build such facilities, but that existing planning tools do not provide a good framework for determining whether a proposed facility can reach its stated objectives nor if it can contribute to other transportation policy goals.

3.1 Goals and Tools

A significant shortcoming of most planning for bicycle and pedestrian facilities is that such planning is based on a substantially different set of criteria than automobile planning.

Whereas most automobile planning, for example, involves improving motorist convenience, the emphasis in bicycle and pedestrian planning is on aesthetic amenities, leading to goals such as sidewalk width, tree cover, benches and trash receptacles (*Chapel Hill, NC, Land Use Management Ordinance*, 2003). Relatively little thought is given to utilitarian concerns such as what one might have to do to walk, bicycle or even take transit to a useful number of destinations. Even less thought is given to physical and social impediments to non-automobile transportation, or to the overall utility of the complete set of facilities that may be available in a community or neighborhood.

Yet deficiencies also exist in automobile planning. It has long been accepted as a basic truth of transportation planning, for example, that building more roads is no answer to congestion (e.g. Meyer & Miller, 2001). Since linking destinations with roads is the only available planning strategy, it is very difficult to examine travel at a small enough scale that significant walking access might be modeled and forecast. Yet as many urban areas run out of available land area for significant increase of road and highway capacity, the need to plan for travel to happen at a scale where it is invisible on roads and highways leaves planners with little recourse but to find more expensive and elaborate strategies to increase capacity, or unpopular strategies to constrain demand.

The mismatch between goals and planning tools becomes more apparent when one compares the standards and goals established for different modes. Planning for specific modes typically prioritizes different aspects of travel, making a comprehensive approach difficult. Automobile planners are worried about time, transit planners about cost, bicycle planners about safety, pedestrian planners about aesthetics. It should be obvious that any of those parameters can apply (and are applied) to any of the modes. What is perhaps less obvious is that whatever planning we do for one mode is likely to have repercussions for the others. For example, strategies such as rumble strips intended to alert dozing drivers as they drift out of their lanes create substantial road hazards for bicyclists using road shoulders. Making automobile travel fast and cheap can certainly make it harder for transit to be competitive. Routing bicycles onto paths shared with pedestrians can be a major safety risk. Building roads that constrain automobile travel can increase congestion and reduce air quality, yet making roads more capacious can inhibit walking and may, ironically, increase congestion. To deal with such incongruities, it is desirable to have tools that render the differing concerns of each mode commensurable, preferably in more comprehensive and systematic ways than by picking a small set of common denominators.

These incompatibilities need not be the result either of inattention or incompetence (though both of those may also play a role). Lacking a comprehensive framework for multi-modal planning, planning for each mode tends to focus on its most important characteristics. Transportation planners are in a situation not unlike that of the fabled blind men and the elephant, who concluded based on the part of the animal to which they stood nearest that the elephant is like a tree, a wall, a snake or a rope. What matters in the driving environment to a motorist differs significantly from what matters in the same environment to a pedestrian or bicyclist. Pedestrians and bicyclists are, by the nature of their travel, much more sensitive to small scale variations in the environment through which they move. Irregularities that may be beneath the attention of a motorist, such as broken glass, disconnected sidewalks, or irregular pavement surface heights can pose insuperable obstacles to the safe and efficient movement of non-motorized traffic.

Conversely, a significant characteristic of the automobile is its tendency to blur the distinguishing features of space with increasing speed. The rate at which drivers (and even passengers) can process information about their environment tends to make small scale distinctions harder and hard to process as speed increases. Yet increasing the speed of automobile travel is the bottom line of transportation planning oriented toward greater mobility. Engineering a successful environment for automobile travel thus hinges on keeping the rate of information that drivers must process within reasonable cognitive limits. Where small scale variations in the environment clutter the driver's perceptual space, they tend to lower motor vehicle speeds substantially. And notwithstanding popular automobile ads, lonely wilderness without a paved road in sight is not a comfortable or efficient place to drive, even in a vehicle that is adapted to such irregular terrain. Travel environments that are tailored to automobile travel thus come to be dominated by large scale, simple structures that permit easy decisions by passing motorists. There is an active disadvantage in placing destinations close together, since such destinations will be hard to locate and maneuver a vehicle toward. The resulting pattern of land use and commercial development has been quite aptly characterized as a 'Geography of Nowhere" (Kunstler, 1993).

Following from these intuitively apparent modal characteristics, planning independently for different modes has typically engaged different professions. Pedestrian planning, for example, is largely the purview of landscape architects and designers seeking to create aesthetically pleasing spaces whose primary function is social and recreational and not transportation (Anderson, 1986b; Appleyard et al., 1981), and more recently of individuals concerned with rectifying obstacles to access by disabled persons as encouraged by the Americans with Disabilities Act. By contrast, the design and placement of motorized facilities have remained solidly in the realm of engineering, and reflect a different set of utilitarian criteria focused on traffic flow, road capacity and safety issues (see, for example, Papacostas & Prevedouros, 2000).

3.2 Spatial Structure and Scale of Travel Modes

All the different approaches to transportation planning discussed above seek to cope intelligently (though often not explicitly) with the fact that the very experience of space is radically different for users of different transportation modes. Travis Hugh Culley, in a memoir of his career as a bicycle messenger, expressed this difference in experience as follows:

> When riding, I do not concentrate on what my hands and feet are doing. I focus on the space at hand, what is there, what is not there, and what is coming into being. I rarely dodge It's more like I swim toward emptiness, analyzing what is in front of me by the speed with which it comes at me. I am not moving through space as much as I am expanding space where, in speed, it seems to fall away.
>
> In a car this shift is evident. On a motorcycle it is almost ever present: space is transformed by speed, flattened.(Culley, 2001 p. 155)

Rather than attempt to reconcile different strategies of planning, the goal of this work is to reorient the question. The problem is not to reconcile directly the various approaches to the modes of "walking", "bicycling" or "driving" taken separately. Rather, we will argue here that travel is first and foremost about the transformation of space, both *passively* as we create facilities for travel, but also *actively* as we travel, and that integrating multi-modal transportation planning is best undertaken by understanding urban travel is a spatial process, which operates differently at different scales.

Conceptually, this reorientation promises potential benefits even at the level of policy debate. It is a common trope in the discourse of smart growth and new urbanism that communities with alternative travel options are the antidote to sprawling, congested traffic systems (*What is Smart Growth?*, 2003). But such arguments are susceptible to criticism that they merely reflect a normative aesthetics, and even that they harbor a coercive inner logic that is based on depriving people of free access to the travel modes that make the most sense (Cox, 2002; Crane, 2000). To the extent that each side of this debate is focused on a single scale of travel, common ground is hard to find. Understanding travel as a multi-scale process, however, lets us think in different terms where travel activity and the travel environment are complementary representations of a single urban spatial process. Then the problem is neither simply about changing the travel environment (controlling sprawl) nor about changing travel activity (limiting use of the automobile). Instead, it is about seeing these as two aspects of a single process that happens at small and large scales, both in space and over time, and that if one controls sprawl effectively, one will necessarily find that automobiles are less useful. And where automobiles prove less useful, sprawl will be less likely to occur.

3.2.1 Spatial Structure and Modal Planning Tools

Resolving to consider travel activity at different scales is not simply a matter of applying the same old methods to brand new problems. Transportation planning for automobile uses first emerged in the early days of the computer age (after World War II). In order to plan large scale urban transportation systems in such an environment, it was essential to develop tools that relied on sensible simplifications of the problem (Meyer & Miller, 2001; Ortuzar & Willumson, 2001). Rather than deal with households, the unit of analysis was the census-block-sized unit of a Traffic Analysis Zone. Rather than deal with the real configuration of streets and land uses, travel was simplified from a topographical to a topological relationship and modeled as flows along network links characterized by direction of travel, volume capacity, maximum travel speeds, turning penalties and so on. Recently, such approaches have been challenged from many directions, both theoretical and practical (Boyce, 1998; Spiekermann & Wegener, 2000). Yet basic transportation planning models brilliantly reflect the relevant characteristics of automobile travel. In such a modeling system, design features and aesthetic properties are simply not relevant, just as they are irrelevant to the driver of an automobile who has no interest in or attachment to the space through which she passes and whose sole concern is the destination she seeks.

A fundamental problem for multi-modal planning is that building such simplifying assumptions into urban transportation planning tools encourages solutions to be formulated arbitrarily at too large a scale to account for the small environmental features and processes that are critical to non-automobile transportation modes. And given the requirements of the tools, it is hard to imagine how it could be otherwise. The infrastructure for alternative modes is not as formalized as automobile transportation, so it is harder to identify a network and assign flows to its links. These modes are constrained by a time and distance horizon that operates differently than for automobiles, and force the traveler into more careful consideration of trip sequences. And such modes are very often (particularly for those who are dependent on them) not a "one stop shop", as the same person may easily be a bicyclist, a pedestrian or a transit user on different days and for different trip purposes, constrained by the weather, local geography, facilities along the route and also at the destination. Finally, there are large scale factors which are just as critical to non-automobile modes, including the accessibility of suitable destinations within a range of travel possible for those modes. Concentrating on building small scale features such as sidewalks may be entirely useless to potential walkers if they still have no place to go.

With the steady and rapid growth in available computer power and sophisticated Geographic Information System (GIS) software, many specific simplifying assumptions are no longer necessary, and a number of creative and exciting efforts have been made to overcome them. Yet this same advance in computer power also makes it possible to tolerate substantially more detailed and complex models, and an unfortunate tendency to enlarge the modeling machinery is also apparent, adding greatly to model complexity without any corresponding improvement of the capacity of those models to respond to new planning needs. Technical alternatives to standard transportation planning techniques that incorporate the spatial and scale concerns discussed here will be considered in more detail in the second section of this paper, and some small examples of possible simplifying strategies are illustrated in the third section.

In order to realize the benefits of a conceptual simplification, however, one must look beyond the technical concerns of transportation planning to consider the phenomenon of travel itself. First of all, conceiving of travel as a spatial process does not simply mean that travel is something that happens in space. As Culley (2001) suggests in the section quoted above, space is created and transformed by our travel decisions. After all, it was generally not physical transformations of old urban centers that converted them from hubs of living activity to ghost towns; it was people's decisions to "go somewh ere else". Obviously, such decisions were not, in a traditional sense, purely about travel; alternative land use in other parts of the metropolitan area made such abandonment possible. But as one stops trying to analyze travel activity at a single scale (either spatially or temporally), the boundary between analysis of land use and analysis of travel activity becomes difficult to draw precisely and drawing it at all becomes optional. Given the difficulty some researchers have had in detecting the influence of land use patterns on travel activity, making such an apparently insurmountable boundary go away entirely is hardly a deficiency of this line of inquiry.

3.2.2 The Significance of Scale

One of the principle features of spatial processes that is well recognized in modern approaches to analyzing them is that they operate at a particular scale. Though we have already explored some evidence in planning terms of why scale is relevant, the term "scale" itself deserves some elaboration, since it does not simply mean "small" or "large" in the physical sense that a sidewalk works at a different scale than an urban arterial road because it is physically smaller. Scale is not a property of physical processes at all. Rather, it is a property of how we observe those processes. This point is made at some length in, for example, Christakos (2000) and Christakos et al. (2001). Attention to scale is one of the ways in which we match our purposes to the state of the world. By setting a scale to our observations, we explicitly designate some aspects of the phenomena as beneath our notice, and others as above it. The outcome of larger scale processes blur into background trends, and the outcomes of smaller scale ones appear as noise. To say that walking or bicycling happen at a different scale than operating a motor vehicle is to say that when we engage in these activities, we are observing space differently, noticing different things, placing a different value on the things we do notice. The speed and size of our vehicle changes what we see, elevating certain characteristics of the space and minimizing others. Consequently, scale is about our relationship as observers to spatial phenomena, and only secondarily about the size of the thing we are observing (or its duration, since time is subject to scales as surely as space). As we will see more explicitly in the second part of this work, many of the thorny problems of spatial analysis emerge from attempts to reconcile at one scale effects of processes which are best understood at another. It appears that in all kinds of spatial research, it is vital to ask not only at what scale one is considering the phenomena one is attempting to understand, but why at that scale and not also at (or instead of) others.

It is the fact that travel activity operates at different scales depending on its mode, that the diversity of goals and planning techniques observed above can develop at all and remain so disconnected. For the purposes of integrated multi-modal planning, it is important to think of travel activity at multiple scales. But this means more than just dropping one set of tools and policy goals and picking up another, or attempting to maintain all of them independently at the same time. Changing the world in ways that are visible at one scale can have profound (and unexpected) repercussions at other scales. Freeways subdivide neighborhoods and discourage walking, overloaded arterials discourage bicycling, bicycles used on walking trails can create a significant safety hazard. Every trip, as the old Confucian saying goes, starts with a single step, that is, it begins as a walking trip. Yet as travel gets pushed up to an auto-sized scale, walking trips are compressed and shortened, and the result, according to some, is an epidemic of diseases associated with sedentary lifestyles. We must therefore be prepared to examine travel activity not simply as a set of independent processes that happen at different scales, but also as interwoven processes that happen simultaneously at multiple scales. Thus, scale is not a simple property of a single process, but a position on a dimension that we can refer to as "scale space" [3]. And in the same way that spatial processes can operate across time and place, these processes can also operate across scales.

Temporal scale also has a direct impact on transportation planning. The time lag on major transportation projects is long. Residential and job location choices are decisions that have a direct effect on travel activity. Some of these decisions my be conceived of as travel at a

[3] The term is borrowed from image analysis, where it is recognized that to extract complete information from an image, one must consider how it appears at many different scales (ter Haar Romeny, 2002).

"slower pace". But one could also imagine travel as simply a land use decision that is operating on a higher pace and smaller temporal scale, as the uses of an office or commercial facility are undertaken anew on every business day. Land use itself is about constructing space, particularly in terms of possibilities and constraints, but the actual appreciation of that space, its practical evaluation by the people who are using it, reveals itself in the movements of people and goods that it engenders. Here too, we find that the distinction between planning land uses and planning transportation is hard to maintain except by confining our focus to a single scale.

3.3 Subjective and Objective Dimensions of Travel Activity

Yet scale is an artifact of measurement, not an intrinsic property of phenomena in space or time. Such observation has simultaneous subjective and objective components. But the "observation" that is relevant here is not simply the observation of travel activity undertaken by transportation planners and researchers, but the travel activity itself: travelers are also observers, and travel is a form of observing the world. Travelers encounter the world at different scales in their travels. Travel activity itself, observed by those who engage in it, reflects the active, practical and goal-oriented concerns of travelers, and happens at a scale which offers the best chance of reconciling one's goals with the spatial pattern of available opportunities for attaining those goals. Travel has a meaning to the traveler quite apart from its technical definition as physical displacement from one location to another. Travel creates space and invests it with meaning (and, if we are to believe writers such as Kunstler, can drain it of meaning as well). This perspective is not at all alien to the architects and designers who are often the key voices in local pedestrian planning. Yet the consequences of boxing up the social dimension of travel in local site plans can be every bit as detrimental to integrated multi-modal transportation planning as pretending that it is not at all relevant to automobile traffic engineering since it tends to fragment space into islands that have little or no relationship at larger scales.

From the perspective of transportation planning, this means that what is planned must "make sense" to those who participate in it. Getting more people to use transit implies not just that we make transit cheaper, more reliable or faster. Such criteria help us as planners to structure our models, but they do not necessarily form the best yardsticks of why and how people structure the spaces in which they live and move. Getting more people to use transit also implies that this change must make sense to people in terms that are relevant to them, and to their own habitual and deliberate construction of space through their daily activities. Though little discussed in the technical literature of scale, making sense or not making sense to various community members and stakeholders reflects another way in which the multiple scales of travel activity have relevance to the techniques of transportation planning. Scale, after all, is the measure of which processes we consider "appreciable", and there is a direct analog in the realm of social and policy decisions as we gloss over distinctions between social groups and local neighborhoods to operate at a large scale, or focus narrowly on the needs of a local community without wondering how that community fits into the larger urban environment. Issues of environmental justice, local community input, and concerns about community character are extrinsic to transportation planning as a large-scale engineering activity. But just as surely as concern for the character of different travel modes implies planning at multiple scales, so to do such community concerns. This is underscored by observing that the people most likely to benefit from improvements in non-automobile transportation modes are frequently members of social groups with a broad set of other interrelated needs. By neglecting non-automobile modes, one also neglects the needs of persons too young to drive, physically unable to drive, or economically unable to afford to buy or maintain an automobile.

Yet identifying a subjective side to travel activity and observing that the subjective component also operates at various scales is in no way to suggest that one must give up rigor in one's approach to the phenomenon of travel. To say that something is "subjective" in the terms gathered here is not to say that it is arbitrary, but rather simply that the significance of various components of its structure (and of its operation at various scales) reflects the purposes of the observers. But while we might shorten this to a consideration of "why" people do something, the answer to such a question can be framed either causally (as a particular outcome determined by certain prior conditions) or teleologically (as an outcome which sought to realize certain posterior conditions). Compelling arguments have been put forward by philosophers of social science that strictly causal explanations are inadequate to the task, and that unless we take account of the purposes of people's actions, we cannot recognize the complete set of factors that are associated with how a particular activity unfolds (von Wright, 1971).

Practically, this means that where observers have different purposes, different analyses will be appropriate and different processes and structures will be observed. Thus, integrated multi-modal transportation planning relies on connecting the physical environment to the meaning that people invest in it, to diagnose the subjective situation from objective evidence, and to prepare explanatory and predictive models that incorporate the understanding and ambitions of travelers as well as their circumstances. Such analysis is quite common in designing pedestrian-scale spaces (Anderson, 1986b), but it also appears at a much larger scale, for example, in Kevin Lynch's classic work, *The Image of the City* (1960). Notwithstanding direct reference to terms such as "beauty" or "attractiveness" as motivations for that work, it is important to note that the goal is not normative or aesthetic, but rather simply to identify the "mental image of [the] city which is held by its citizens" (Lynch, 1960 p. 4). As Lynch also observes, the primary focus of his work is on "what might be called the 'public images', the common mental pictures carried by large numbers of a city's inhabitants: areas of agreement which might be expected to appear in the interaction of a single physical reality, a common culture, and a basic physiological nature." (p.7).

Another way to assess the importance of modeling a subjective component to travel activity is that the "common culture" Lynch refers to suggests that people do not everywhere evaluate physical features of the travel environment by the same criteria, and there is a body of evidence to suggest that, particularly for non-automobile travel modes, a local culture does exist[4]. The prevalence of bicycling and walking in some unlikely communities illustrates that travel activity is more than just an outcome of the sum of the facilities available. San Francisco has a substantial bicycling community, despite a terrain that is extremely steep and challenging even for motor vehicles. Likewise Madison, Wisconsin, has a large share of year-round bicycle riders despite long hard winters (FHWA, 1998). A number of approaches to this problem have been developed, since the problem is ubiquitous in social science research, and these will be reviewed for their adequacy for multi-scale spatial analyses in the second part of this work.

As we shall see in the next section, allowing that travel has objective and subjective aspects that operate at multiple spatial and temporal scales does not necessarily call for new methods. Rather, it suggests that we need to get much clearer about the scope and limitations of the methods that planners rely on, and to understand how these limits contribute to (and often detract from) a full appreciation of how an urban space is formed by those who move within it.

[4] The legendary awfulness of Boston drivers, and more generally the purported existence of various regional personality types among drivers, suggests that were research to be done, such an effect might also be observed for automobile modes as well.

Public involvement, community design initiatives, and the existing self-understanding of a community as expressed in its citizens patterns of travel activity are all just as important to transportation planning as the simplified technical representations of travel which are often the only basis for planning decisions. This enlargement of vision is vital if we are to move transportation planning from the reactive mode of "getting people where they want to go" to a more active process that helps people conceive and then realize an ambition to use the urban environment differently.

3.3 Summary

This section began with a discussion of why it is becoming important to integrate transportation planning for multiple modes. Partly because of the data intensive character of transportation planning models, simplification had to be pursued, and such simplification reflects both societal goals (increased mobility, primarily in private automobiles) and the simplification of the problem of modeling automobile travel (and to a lesser extent, transit) to a set of parameters that was sufficient to capture those concerns. As societal goals have shifted to include a more expansive interest in supporting non-automobile goals, there is an evident strain on the capacity of existing tools to support those goals. Non-automobile users have a different experience of urban space, and it is essential to approach that experience with tools that are as well-suited to it as standard tools are to the experience of space through automobile travel.

To provide a framework in which to think about the strengths and limitations of transportation planning models, we observed that spatial processes such as travel are inevitably measured and accounted for at certain scales, and that models that operate well at one scale may be ineffective at other scales. We noted further that scale is not a property of natural objective phenomena, but emerges from the requirements of observation and thus incorporates both a subjective and objective component in determining which scale is appropriate. Travel activity by different modes involves observing the world, and as such implicitly measures the space that is traversed at a certain scale, so it makes sense to speak of "walking scale", "bicycle scale" or "automobile scale". But when transportation models of travel activity are developed, they also incorporate the goals of planners and decision makers who are seeking to use those tools to measure success in moving toward certain social and political goals, and various social criteria that often become contentious issues in, say, neighborhood versus regional transportation planning, can sensibly be comprehended as a debate over the effects at various scales of planning goals and the adequacy at various scales of the planning models that support them.

Effective, integrated multi-modal planning should consider travel as a multi-scale spatial process, particularly in response to the shifting policy environment that has placed new emphasis on non-automobile transportation options. The next section considers some of the ways in which travel activity research has approached the spatial analysis of travel activity. This review of certain strengths and limitations of these methods does not aim to be comprehensive (that would take a book or more!) but rather to serve to sketch out some of the practical characteristics of models and tools that may be useful in approaching travel as a spatial, multi-scale process. The final section of this work will explore some of the possibilities of spatial analysis by applying simple spatial analysis tools to a travel activity data set collected in the Research Triangle area of North Carolina in 1995.

4. Tools for Understanding Travel as a Spatial Phenomenon

First of all, we need some way of finding out the workings of large socio-environmental mechanisms. To me, a physical approach involving the study of how events occur in a time-space framework is bound to yield results in this regard. In order to be realistic, our models would have to recognize the fact that the individual is indivisible and that his time is limited. Further, we would have to note that the individual in dealing with space not only considers distance, but also has a strong (and perhaps logically necessary) drive towards organizing space in sharply bounded territories.

Torsten Hägerstrand (1970 p. 20-21)

Interest in spatial approaches to social science research has been growing in recent years, and its application transportation and travel activity has also grown[5]. This section reviews a variety of approaches taken in the literature of transportation research that attempt to address travel as a spatial activity. Reviewing this literature has a two-fold purpose here. First, it aims to highlight the growing interest in travel as a spatial process and the creative techniques that have been brought to bear on it. Second, it seeks to illustrate the methodological ramifications of the key points of the first section: in particular, that by viewing space, time and scale as external to travel activity (for example as independent variables or as classes or categories), we create a much more difficult problem than if we begin with the view that they are simply different manifestations of a unified spatial process. Unfortunately, even promising approaches are undermined by attachment to unnecessarily restrictive methodological approaches such as choice models and zone-based analysis (both of which, ironically, became popular because they permitted circumventing even more onerous restrictions). Yet from this review, it will be clear that a variety of techniques are available that permit formulating a rigorous approach to the investigation of travel activity and the planning of transportation systems at various spatial and temporal scales, and with full respect for the constructive character of travel as an activity that creates space rather than simply uses it.

[5] A useful overview of this growing role of spatial understanding in many areas of social science research is found in Goodchild et al (2000)

Before launching into a review of spatial techniques, it is worth considering two important methodological limitations. The first has to do with the scale at which a problem is examined. A significant problem with respect to analytical tools is not simply the fact that they work at one scale. Rather, it has to do with how they integrate (or fail to integrate) information about processes occurring at other scales. The most common simplification of travel activity is to subdivide it into discrete segments: trips, tours, home-based-work, and so on. Segmentation of space and time is the primary means by which we bring a process into focus at a certain scale. Most transportation modeling methods rely on such subdivisions, yet they often confuse the question of scale in their consideration of the phenomena they represent, by casting off elements that either span multiple divisions or that blur significant differences that fall entirely within one division. One form of this problem is widely recognized within geographic information science as the modifiable area unit problem (MAUP) which occurs when information is summarized within different geographical boundaries (Hewko et al., 2002; Unwin, 1996).

A second important limitation of many methods is their neglect of the meaningful structure of travel activity either for the traveler or the investigator. By choosing a certain set of categories to investigate at any scale, one implicitly chooses a set of planning priorities and constrains both the phenomena that can be investigated and the solutions that can be developed. As planners and researchers, it is very important to be sensitive to the understanding people create for themselves about the structure and meaning of that environment since such understanding can vary significantly across communities and can manifest itself in unexpected ways. Simplification is an essential step in modeling human activity and planning changes in the urban environment that affect that activity. But forgetting that travel activity is about people "who need to make sense out of their paths between and through domains" (Hägerstrand, 1970) means giving up on an important half of the problem before one even begins.

The technical growth of GIS has greatly advanced the capacity to visualize and grapple with the spatial character of many natural and social processes. Ironically, though travel would seem to be a leading candidate for such investigation, the advent of sophisticated GIS has not led to an improved sophistication in methods. Rather, the same limited approaches are often simply mapped in space. A comprehensive recent review of such techniques is found in Miller and Shaw (2001). On the other hand, many effective spatial analysis techniques have been developed in other disciplines and have started to find their way back into transportation planning and modeling, and it is these to which most attention will be devoted in the following pages.

Econometric methods are a fundamental part of the regional transportation planning toolbox. This review will thus begin by looking at the field of *spatial econometrics*, including basic techniques and goals, how these can be applied to transportation models, and why these fall short of what is needed to accomplish the goals outlined in the first part of this paper. A related field of endeavor has no generally accepted name, but will be referred to here as the method of *spatial indices*. These approaches use various techniques, sometimes of considerable sophistication, to develop measurable indices of spatial and environmental features that can serve as parameters in standard non-spatial econometric models. Though such approaches can begin to identify small scale environmental features, this sensitivity is inconsistent, is obscured by the overall model, and prevents clearly focusing on the range of structures at different scales.

An older approach that holds out great potential at a theoretical level is the *time-geography* method of Hägerstrand and the Lund School. In addition to looking at the original concerns of this approach, this review will examine the state of the art in two main heirs to this tradition: the use of *accessibility measures* as a means of geographical analysis and *activity-based travel analysis*, both of which have tended to frame the problem of travel in ways that continue to be insensitive to issues of scale, as well as to constructive meaning for the participants. More in keeping with the motivations original Lund School approach is the notion of *affordances*. This provides a potential bridge between subjective and objective concerns by explicitly examining space from the standpoint of how people with a certain culture will deal with the things they encounter.

A separate line of inquiry that has been little explored in travel analysis, but which is particularly amenable to studying the spatial structure multi-scale processes in an urban environment, is the notion of *spatial fields*. This approach has been developed extensively in the realm of geo-statistics and widely applied to environmental problems, but only rarely to travel activity, yet it appears to hold the most promise for developing a multi-scale approach that responds to the needs outlined in this paper. While some steps have been taken toward using these techniques for travel analysis, their application as yet has not progressed very far in the directions identified in this paper. The final section will explore how these techniques may be deployed to create fully spatial models.

4.1 Spatial Econometrics

Econometric methods are important in regional transportation planning since they provide convenient models that relate simply measurable characteristics of sections of the urban population to aspects of travel activity. Simple and useful observations that persons with higher incomes tend to travel more, that lower income persons are more inclined to use transit, or that office parks tend to be the destination of fewer trips than shopping malls, all emerge from the application of econometric tools. Grounded in theories of market choice, the field of econometrics is broadly concerned with the economic behavior of individuals. Spatial structure in such behavior has drawn increasing attention in econometrics, but often for a much more basic reason than the ones I have raised so far in this work: statistics that rely on the classic assumptions of sampling from a set of points that are independent and identically distributed must be adjusted to deal with the skewed clusters of economic points in space. A fundamental insight of spatial analysis is Tobler's First Law of Geography that states that "everything is related to everything else, but closer things are more closely related"(Tobler, 1970). This shows up in statistical analysis as two potential distortions. First, data may be correlated, so that samples may not be independent. Second, data may not be identically distributed, so that samples may not be identically distributed. While it is not a difficult exercise to design sampling strategies to compensate for known spatial correlations, spatial correlations are not always obvious in advance of data collection and must be dealt with after the fact through suitable spatial adjustments.

Techniques exist to cope with these problems through covariance terms in the models, through second-order analysis of structure in the residuals after a model is estimated, and by analysis of the structure of the error term in the model. Many excellent introductions to these techniques are readily available (Anselin, 2000; Florax, 2001; LeSage, 1999a; 1999b). Practically, spatial econometric modeling can approach spatial variation as (i) a substantive effect that is a direct part of the model or as (ii) a nuisance effect that reduces confidence in the model because of spatial biases in the error terms. Coping with substantive effects typically consists of adding a spatial variation weight (substantive effects) and constructing what is known as a spatial auto-regressive model. Nuisance effects are commonly dealt with by relating the distribution of the error term to spatial location. In each case, the problem reduces to one that can be handled with standard statistical approaches. Mathematically, these methods are quite similar, since in each case, a spatial term is introduced that has the effect of normalizing the data so a single set of model coefficients can be extracted. An interesting recent additional approach is Geographically Weighted Regression (Brunsdon et al., 1996; Fotheringham et al., 2002; Fotheringham et al., 1996; LeSage, 2001). Here, a rather than analyzing spatial correlation in error terms or establishing a separate term to correct for spatial auto-correlation, that correlation is brought back into the primary model by developing a regression model whose parameters themselves vary over space.

It is undeniable that these approaches greatly improve the capacity of econometric models to build accurate and unbiased models of data that demonstrates spatial heterogeneity and spatial dependence. However, the goal is to "recover" from the irregularities of space, rather than to discover those and model them directly. Phenomena are pursued as the products of spatially-located economic processes (that is, processes that operate independently of space but whose parameters may be different in different places), rather than of spatial processes (that is, processes that operate directly in and through space). Thus, even though these techniques do not provide a ready tool for the kinds of analysis proposed here, they do promise to improve significantly the quality of econometric models of a type that is quite common in trip generation and trip distribution analyses.

4.1.1 Estimating Econometric Models

One additional problem with the application of econometric models to spatial analysis is how spatially-located models are estimated. Using maximum likelihood estimation presents an interesting challenge, since to evaluate model coefficients one must understand the covariance matrix, which effectively adds numerous degrees of freedom to the model. The result is a substantial increase in the data volume required to get unbiased results. One common approach to outflanking this problem is with Bayesian analysis. The central insight in this approach, derived from Bayes' Theo rem of conditional probability, is to take advantage of spatial autocorrelation, rather than simply to explain it or to compensate for it as one invents general models that do not depend on space. As has been commonly observed with respect to geo-statistics (e.g. by Isaaks & Srivastava, 1989), making additional observations of a spatially dependent process adds less and less new information, since the new points tend simply to "fill in" the gaps between the others and look like them.

A Bayesian statistical model develops a description of the probability distribution function of the phenomenon one is trying to explain given a set of independent random variables with their own probability distribution functions, along with other "priors" which describe known boundary values, constraints and expected values of both the independent variables and the dependent variable (Box & Tiao, 1973). These distributions can include a spatial component (that is, the distribution itself can include spatial location as one of the variables, perhaps even with a suitable probability distribution reflecting possible errors in measurement). Such models are commonly, and relatively easily, estimated using iterative numerical techniques based on Markov Chain Monte Carlo (MCMC) methods. Estimates of model parameters emerge from repeated sampling of results from the model via an iterative numerical process that gradually adjusts the model parameters through successive iterations, using the observed data as a benchmark suggesting whether or not the parameters must be adjusted (Congdon, 2001). Bayesian statistical models have been successfully applied to spatial econometric analyses (LeSage, 1997; MacEachern et al., 2001). It is worth noticing that MCMC estimation methods are in themselves tied to Bayesian statistical analysis; they are also used to estimate mixed (or kernel) logit models and are generally applicable as a means of estimating parameters in stochastic models.

The philosophy of Bayesian approaches is quite different from ordinary maximum likelihood approaches, and has a number of characteristics that commend it to analysis of complex multi-parameter problems such as travel activity in space (Congdon, 2001). We have to make explicit both our knowledge and the limits of our knowledge in the form, for example, of known (or anticipated) probability density functions of independent variables and constraints on admissible parameter values. Another important property is the ability to build a model incrementally by gathering data in different subsets of the sample population. By using prior knowledge, the maximum new knowledge possible can be extracted from new data. Also, since the Bayesian notion of confidence in the modeled results is usually measured through indexes calculated from the posterior distribution of the dependent variable, models constructed this way can be formally compared with respect to predictive quality even when these models are not nested (for example, when they include entirely different independent variables).

Most important to the utility of the Bayesian framework for the purposes outlined here, there is no requirement that all the uncertainty in the model be expressed in a single error term with a single probability distribution. Thus, each of the independent variables is a random variable with its own (possibly spatially varying) error term, the distributions of those errors can be completely dissimilar, and the resulting overall error in the model can be bimodal (or, dare I say it, multimodal) or otherwise analytically intractable. This important characteristic makes it possible to build multi-scale models quite easily, where the scale of a variable may be modeled through its variance (or more generally, the range of its distribution) and its expected value.

Certain terms in the model may appear as constants or insignificantly small at a particular scale of interest. Since a term that approaches a constant value diminishes in effect on the posterior probability distribution, it is quite easy to estimate a range of models at different scales. With such a range of models, and the ability to compare non-nested models, one can use such modeling to explore the range of scales at which certain inputs are significant and to suggest where processes operating at multiple scales may be present.

4.1.2 Discrete Choice Models

Discrete choice models are the Procrustean bed of the transportation planning toolbox, finding wide application to problems of mode choice, destination choice, route choice, trip generation, and trip assignment. Much work (some of which will be reviewed below in relation to spatial indices) has been devoted to coercing data into a form where these models can apply. A great deal of creativity has been evident in adapting these models to situations that do not conform to the original axioms of such models (as outlined, for example, in (McFadden, 1997)), but problems still abound. Good reviews of such problems, and some suggestions for rectifying them may be found in (Brownstone, 2001) and (Gärling, 1998), as well as in (Ben-Akiva et al., 1997; Ben-Akiva et al., 1999). A classic example of extending discrete choice models stems from the formal requirement of independence of choice probabilities (the "independence of irrelevant alternatives", or IIA, axiom). The IIA axiom requires that the presence or absence of a certain choice in the choice set of an individual not alter the relative probability of choosing other modes. In practice, different modes that become available often draw users disproportionately away from other modes. Modeling this situation is typically accomplished through a nested logit structure, where the choices are arranged in a hierarchy (transit versus non-transit, then within transit, either bus or rail). More recently, the mixed logit model (also known as kernel logit or the error components model) has been developed, which permits the coefficients of the utility function themselves to behave as random variables that have a certain distribution over the population being modeled (Ortuzar & Willumson, 2001 §§ 7.5.2, 8.6). Estimating such models is typically accomplished using iterative Monte Carlo techniques comparable to those used in Bayesian statistical modeling. These models permit the incorporation of variations of taste, and where prior knowledge regarding the distribution of such variations is available, this approach becomes quite indistinguishable from a typical Bayesian statistical model.

Where data is organized in zones, spatial choice models can be estimated explicitly using the standard approaches of spatial econometrics using area analysis with covariance matrices, possibly using Bayesian estimation techniques, as in (Smith & LeSage, 2002). A comparable multinomial logit formulation including spatial effects applied to residential choice decisions is found in (Bhat & Guo, 2003). However, while such models have the discrete choice structure, the specific example just noted is dealing with aggregate units as its elements, and the covariance matrix approach rapidly becomes computationally prohibitive as the units are disaggregated and become more numerous.

The problem of how to deal with spatial variation in a discrete choice model poses a number of other difficult problems as well. For example, estimating many choice models relies on synthetic disaggregation of data (for example, in constructing travel times and other modal characteristics for the modes not actually chosen by subjects in the data set) in ways that incorporate knowledge of the travel environment without making that knowledge, or its limitations, explicit. And when these models are applied to choices such as travel mode where the availability of the choice is not itself discrete, there is a potentially very complex interaction between choice set construction and influence of parameters. One might wonder, for example, at what point does the time taken to walk to a bus stop cease to be represented as a parameter in the utility function and start to be represented by dropping that mode from the choice set entirely. If one further examines choice models as disaggregate models of individual behavior with utility function coefficients that may vary in space, as in the mixed logit model, the problem becomes more complex still.

Sophisticated solutions to this problem typically involve considering spatial effects only in one aspect of the model, either by limiting consideration of spatial effects to formation of the choice set, as in (Kwan & Hong, 1998) or by limiting study to areas where choice sets can be considered uniform and incorporating spatial measures as independent variables in the model, as in (Srinivasan, 2001), where the study is limited to non-work travel in a subset of neighborhoods and spatial variation is reflected in a series of index variables (a strategy discussed further below). The probit model by Smith and LeSage discussed above represents a third possibility, where the utility function itself has a spatial structure, but the choice set is fixed and the independent variables in the utility function do not incorporate spatial effects except through the spatial covariance matrix.

The primary difficulty with the discrete choice model approach is not that such models are incapable of accounting for spatial effects. Rather it is that compensating for difficult preconditions such as IIA and unrealistic behavioral assumptions, though possible to some extent, rapidly leads to models that are operationally intractable: requiring vast amounts of data to calibrate; relying heavily on synthetic evaluation of alternative utilities which run their own risk of scale mismatch and aggregation bias; and using many levels of latent and explicit variables. The complexity is apparent in the attempt to incorporate behavioral realism in such models as reported in (Ben-Akiva et al., 1997) and (Ben-Akiva et al., 1999), and the attempts to incorporate spatial arrangement characteristics presented in (Ben-Akiva et al., 1996) and (Dong et al., 2002). More and more, advanced discrete choice models take on the complexity of Ptolemaic astronomy with the role of epicycles played by choice nests and latent variable constructions. The result, just as with Ptolemaic astronomy, may be highly accurate in certain situations, but there are clear limits to how far such models may be extended, particularly in the context of practical travel activity forecasting and decision support systems, and most importantly with respect to supporting decisions about policy and infrastructure improvements aimed to increase use of alternative modes.

4.2 Spatial indices

The particular problem of assessing, modeling and understanding the link between travel activity and the structure of urban space (which may include not only land use types but also modal amenities, topography, community norms and expectations, etc.) has most often been approached within an econometric framework through the formation of *spatial indices*. These indices are intended to capture features of the urban environment in a form suitable for inclusion as independent variables in some model and represent a large and growing literature that exploits summarizing techniques from many different fields, a small recent sampling of which includes (Boarnet & Crane, 2001; Cervero, 2002; Crane, 2000; Frank & Engelke, 2001; Greenwald & Boarnet, 2001; Handy & Clifton, 2001; Srinivasan, 2001; 2002).

Often these approaches are oriented toward creating measures of space that can be fed back into regression and choice models. These studies have had mixed results in revealing and assessing influence of spatial environment on travel activity. In general, they support the observations made earlier in this work relating to the relative local scale at which walking takes place, and mostly support the notion that socio-demographic characteristics are more important to travel mode choice in particular than are features of the urban environment. However, three particular issues in how these indices are typically developed and deployed are of concern. First, the factors that are involved in the model must operate at commensurate levels of detail. Thus, if a study detects relatively little influence of a particular set of urban features on travel mode choice compared to the background (as many do), this is not to say at all that the effect is negligible when the problem is to determine within a scope and scale suitable to that mode what the characteristics are that favor such activity. Rather, such a study simply confirms that walking (say) operates on a smaller scale than driving and uses the excuse that the effect is small (measured at the gross scale of automobile travel) to justify the classical solution: simply to drop such insignificant effects from practical consideration (these perils are alluded to in (Handy, 1996).

A second concern is to consider the scope of urban features. While it may be desirable, for example, to consider quality of connectivity of a travel network as a suitable index, and further to consider availability of local destinations such as grocery stores, there may very well be a synergy between these factors if the grocery store is poorly situated on the network. A number of mathematical techniques exist to consider such synergistic effects, particularly where there are clearly correlations in the data. For example, by indexing a fairly large number of factors and examining their covariance, one may apply principal factor analysis to determine a "rotation" of the co variance matrix (and the relative weights of each of the individual indices) to select a smaller set of transformed factors that captures most of the observed variance. This approach is used, for example, by Srinivasan (2001; 2002). However, while this is a useful way to reduce the complexity of the problem, issues of dimensional units and scope of the various contributing factors, along with the difficulty of translating back and forth between the transformed variables and their physical correlates can render this particular tool less useful than it might at first appear (see caveats on principal component analysis in (Duda et al., 2001) as applied to statistical image analysis). In practice, for instance, one might have to measure many features such as traffic intensity, network connectivity, average block length, density or proximity of relevant destinations. Factor analysis may reveal that a combination of these can function as a single parameter. However, when as a planner one wishes to reproduce the effect of that factor through specific neighborhood improvements, one has little guidance regarding the effects of specific incremental changes one might make.

Finally, as with any method of statistical aggregation, this approach also risks obscuring processes that happen not to be well reflected in the particular indices being analyzed. Information on the size of a feature, the scope of its effect, and the scale at which it interacts with other features are not directly expressed in the index. Thus, models that rely on such indices must pay particular attention to possible mismatches in these dimensions. At best, this makes it difficult to verify whether the indices are, in fact, capturing enough information about relevant processes, and at worst can lead to results where possible effects are obscured by inclusion of indicators that swamp the effects of others operating at a different scale. Structurally, this is simply the multiple areal unit problem once again, though in this instance the "multiple areas" of concern are the space (either physical or in scale space) over which the index is compiled.

4.3 Time Geography

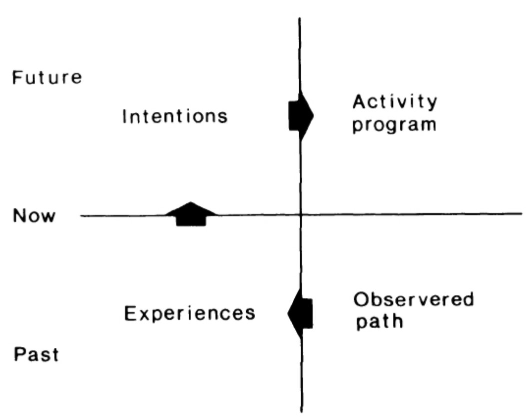
Perhaps the most striking limitation of econometric models is its emphasis on disaggregate modeling of individuals and the spaces in which they move. The individual is disassembled into a set of suitable demographic components, and the space is disassembled into a series of index measures. The model then describes a process for re-aggregating these measures into the observed travel activity. The theoretical consequences of this approach, as we have seen, are complex modeling apparatuses with many dark corners in which important insights can be lost. Such approaches, in words borrowed from V.I. Lenin, often "reveal… the observer as one who is overwhelmed by the mass of raw material and is utterly incapable of appreciating its meaning and importance" (cited in (Agrest, 1986)). As was noted in the previous section of this work, however, space is not something that simply stands as a physical, objective correlative to the subjective, active evaluation of individuals. An influential alternative to econometric methods is the time geography approach originally pioneered by Hägerstrand, who in his seminal paper of 1970 disparagingly referred to attempts to summarize the "mass probabilistic behavior" of individuals. The gist of the time geography approach is summarized in this passage:

> Several different ways of investigating the socio-economic web come to mind. One is to sample life paths…But it would be difficult to dig deeply enough to unveil the really critical events. Similarly, the short-term paths, days and weeks, can be sampled by observation or by some diary method. In either case, one risks becoming lost in a description of how aggregate behavior develops as a sum total of actual individual behavior, without arriving at essential clues toward an understanding of how the system works as a whole. It seems to be more promising to try to define the time-space mechanics of constraints which determine how the paths are channeled or dammed up. (Hägerstrand, 1970 p. 11)

The most famous specific technique proposed by Hägerstrand was the time-space prism, a means of identifying the range of possible paths available to individuals given constraints such as transit service, roadways, topography, time limitations and so on. The key element of this approach is to start at the other end of the spatial process. Rather than dwelling on the determinants of individual behavior, time geography is concerned with the possibilities inherent in the space in which travel activity happens rather than the actor's response to that space.

Purists in the tradition of time geography situate their work squarely in the realm of social analysis (Hägerstrand, 1975; 1976; Lenntorp, 1976; 1978; Pred, 1981). The key element that the present work wishes to call attention to is the idea that one gains insights into the structure of travel activity by looking at the structure of space – not simply in the quantitative sense through which spatial indices are constructed, but with respect to purpose and meaning such spaces have to the people who move within them. Of particular interest is how the original vision of time geography evolved into two other important lines of spatial inquiry in travel activity analysis, activity-based analysis and analysis of accessibility. Figure 4.1, reproduced from (Lenntorp, 1976), suggests an important constraint, which is the inability of analysts to examine the intentions and experiences of individuals (the left side of the diagram). Yet the model of time geography, that sees the interaction between individuals and the space they move in as a single process, suggests that by examining the structures of space that people delineate through their movements (the right side of the process) we can gain insight into the entire process, and as Hägerstrand noted, we can do this with much greater reliability than if we try to visualize the process indirectly through attempts to model individual behavior.

Figure 4.1



From (Lenntorp, 1976 p. 14)

Unfortunately, while the philosophical goal of this approach is quite in line with the goal of integrating multiple dimensions and scales, both physical and social, in planning multi-modal transportation, the actual techniques originally proposed have not proved resistant to transformation into something rather more crude.

4.4 Accessibility Measures

In keeping with the original project of time geography, which is to describe the social and physical boundaries of travel activity in space and time, Lenntorp (1976; 1978) took the approach of modeling activity programs in space, where these programs were described quite neutrally in terms of visits to particular locations in space. He pursues a model that is noteworthy for the nearly complete absence of an attempt to measure or classify individual characteristics, presuming instead that a complete catalog of the possibilities inherent in the spatial environment would delineate quite completely the travel activity in which people are engaged. This line of reasoning also has led to a considerable lineage of recent activity, particularly among geographers armed with GIS systems.

Time-space prisms are employed here as ways of measuring accessibility, and much of this research focuses on mapping out people's capacity to reach certain destinations within a transportation network. Good examples are found in work by Miller, Kwan and others (Kwan, 1998; Kwan & Hong, 1998; Miller & Wu, 2000; O' Sullivan et al., 2000; Pendyala et al., 2002; Weber & Kwan, 2002; Wu & Miller). Unfortunately, these approaches have largely sloughed off (following Lenntorp's own example) the larger philosophical problem of time geography, which involved mapping a social space, not simply a physical one. They are rarely concerned with issues of scale, mostly because they are typically not concerned with modeling but simply with measurement.

An approach that does illustrate (though without specifically referring to it) the time geographers' notion of describing space as a way of capturing the creative forces that drive travel activity was proposed by Penn et al. (1998). Attempting to overcome difficulties inherent in mapping "complex cost functions" onto "simple representations of the road network", these researchers proposed instead to give up entirely on cost and demand modeling in favor of exploring direct correlations between travel activity and the configuration of transportation facilities in space. This re-orientation was associated with their stated policy goal to "civilize the car" by exploring spatial features that are specifically associated with higher levels of pedestrian activity (these include building height and development density). They propose as well that this approach indicates a different role for the travel network, as a component around which travel activity is organized actively, rather than simply a locus of costs and utilities, much in line with Hägerstrand's notion that travel reflects the active attempt to make sense of the environment. Practically, their method involves "inverting" the travel network into a symbolic representation that includes treating intersections as links and road segments as nodes, in order to simplify the calculation of certain mathematical properties of the resulting graph. Their actual analysis then consists of observing walking and driving activity in a number of locations and seeking correlations between the quantified graph properties and observed travel behavior. It is not clear, however, that this approach can accommodate analysis of travel activity at various scales, nor how sensitive it might be to effects that occur at other scales.

4.5 Activity-Based Travel Analysis

An important school of transportation research that has continued to fascinate transportation planners, particularly (and perhaps ironically) those who approach the subject from an engineering perspective, is activity-based analysis. The earliest version of this approach that is still widely read is Chapin (1974). Chapin himself distinguished his method from Hägerstrand by emphasizing a dual approach that explores both propensity for certain activity (as might be modeled through discrete choice or other regression models) and constraints (as might exist due to physical, social and personal circumstances). The result was an attempt to characterize, as the title of his work suggests, activity patterns in the city by correlating how and where demographic characteristics of groups of individuals with the activities those individuals engage in. Though Chapin's work includes a rare (particularly in the era before the advent of desktop GIS) attempt to map out surveyed activities across a physical area, his emphasis is ultimately not on spatial relationships but on examining how activity patterns differ among distinct urban demographic groups. However, his definition of activity pattern includes developing categories based on interviews with his study participants, and letting their qualitative descriptions of what activities they were engaged in form the categories of his analysis. This commendable practice has not been common in subsequent activity-based research, where activity categories are streamlined and sometimes seem to have been pulled out of the researcher's hat.

A subtle difference of emphasis from time geography is already apparent in Chapin's work: the activity and its pattern (when and where it takes place) became objects to model and explain through statistical analysis of racial and demographic characteristics of the individuals engaged in those activities. This approach strongly resembles the econometric approaches described earlier, and is only incidentally interested in spatial analysis. The key aspect, however, that reappears in later activity-based research is the idea that a reasonable object of econometric modeling are individual activities and the activity pattern as a whole.

In practice, activity models are often based on discrete choice models (Bowman & Ben-Akiva, 2000; Dong et al., 2002; Ettema & Timmermans, 1997; Timmermans et al., 2002) , and thus reflect the same limitations discussed earlier in the context of econometric spatial models. Yet by focusing on tours and activities, rather than trips, activity-based approaches may actually constitute a step backwards with respect to spatial analysis of travel. The question of spatial scale risks becoming very muddied when some activities are mapped at a fine scale, including those that require no travel at all, while aspects of travel such as how far one walks to one's car or the bus stop fail to appear except implicitly. This problem is certainly significant with some travel activity diary information such as the TTA Regional Travel Survey that is the basis of the third part of this work (TTA, 1995).

4.6 Affordances

Activity- -based approaches and accessibility metrics as defined here both fall short of the requirements of integrated multi-modal planning, though such techniques do contribute a number of useful techniques. The failure of time geography's origin al project to make inroads in travel activity research and transportation planning suggests that it entails more than simply mapping physical parameters of a physical space. A significant question of method that is only partially addressed by any of the approaches discussed so far is how to measure space in such a way that one can imagine altering that space to support altered travel activity. An alternative approach that has been mentioned sparsely in the literature of GIS, but not to our knowledge in the realm of transportation planning, is that of analyzing "affordances". This approach, simply enough, attempts to describe what a space, place or object "affords" (makes possible) to a person who is confronted with it. Obviously, the possibilities for using a space or an object depend not only on physical characteristics of the object, but also directly on the prior knowledge, culture and other features of individuals.

The concept of affordances originated with Gibson (1979) and was popularized by psychologist Donald Norman (1988) who discussed the structure of objects that people use, ranging from doors and stoves, to telephones and calculators. A discussion of using affordances to structure a description of places in GIS systems was presented in (Jordan et al., 1998). They propose classifying not only physical features of a space, possible actions that may happen in the space, narrative descriptions of the space (not unlike the results interviews done by Lynch (1960)), symbolic representations as simplified descriptions of the space, socioeconomic and cultural factors, and typologies or categories of space with similar affordances but possibly quite different physical features.

Though he doesn't use the term affordances explicitly, Anderson's approach (1986a), emerging from design considerations and aimed at understanding how urban spaces emerge as useful architectural forms, is quite consistent with the emphasis on understanding of space in terms that make sense to the users (and creators) of that space. But mapping the social availability of space for culturally (and perhaps locally) significant purposes, at a level of social and spatial detail beyond the abstract economic categories that dominate trip generation models, must be considered an important component of any integrated approach to transportation planning.

4.7 Spatial Fields

The final stage in this review of methods of travel activity analysis in a spatial context is to consider approaches from geostatistics, and some close relatives from within the literature of travel research, that are explicitly suited to multi-scale analysis. A standard approach to exploring spatial processes at multiple scales is to examine continuous representations of relevant phenomena whenever possible, since this permits relatively simple re-aggregation of data at different levels (Perry et al., 2002). As we have seen, much transportation planning and travel activity research is based on segmenting the items of study at a "suitable" scale, either into network links, neighborhoods over which a spatial index is accumulated, or into zones. The continuous representation permits handling each of the three key aspects of scale: examining correlations at various distances, working with data that has been collected at different spatial resolutions, and working with spatial processes of varying sizes as may be necessary when considering modes that structure space at different scales (such as by walking, bicycling, or driving a car).

For the basic operations of travel demand forecasting, there is some precedent for techniques based on continuous representations of the travel environment that do not require segmentation of space into zones, and perhaps not even into network links. Angel and Hyman (1976) developed a simple analytical model of travel in an urban environment that completely eliminated references to zones and specific destinations. Their model "uses the density functions describing the distribution of residences and workplaces of car commuters, and the velocity field of a given city, to derive a spatial distribution of trips, accessibilities, and traffic flow." (Angel & Hyman, 1976 p. 52). This approach holds out the prospect of doing away with zonal analysis entirely and relating all travel to the interaction of several fields describing properties of the travel environment. The primary difficulty with their work is that it relies heavily on some extreme simplifying assumptions (such as all commutes happening radially in a symmetric monocentric city).

A similar approach that proposes to explore trip generation without reference to zones is proposed by Spiekermann and Wegener (2000). They created an accessibility surface using a GIS system to represent the travel time required to reach any point on the surface from any other point. They also illustrated approaches for disaggregating zonal population data at a census tract level by informing that data with known locations of high-, medium- and low-density housing, and using that to develop a continuous population density surface.

A final approach incorporating a model of continuous fields in travel activity analysis was proposed by Beckmann et al (1983a; 1983b) to model probability of access to various competing facilities. Here, the continuous field presents a possible strategy to supplant zone-based gravity models for trip distribution. The notion is that each possible destination has a probability field around it that permits assessing the likelihood that an individual will access that destination in preference to other possible destinations. The result is that one can map the desirability of destinations empirically based on surveys of actual travel and develop trip distributions without direct reference to trip time or other postulated variables. Aside from creating a scale-independent mapping of destination desirability that captures spatial variations, this approach also permits exploring which variables might be the best predictors of desirability, including spatial features with specific locations that might otherwise be difficult to condense into a single scalar value.

The problem of multi-scale modeling, as we noted in the previous section, is not just about space. Temporal concerns are also an issue. As noted by Kwan (2000), visualizing travel activity is a key step toward formulating plausible models. Kwan mapped travel diary information from a study done in Portland, Oregon using a variety of visualization techniques, some of which are directly applicable to the problems posed in this paper and are discussed below. Other tools for such spatial and temporal visualization are gradually entering the mainstream of transportation GIS; TransCAD 4.5 ("TransCAD," 2003) includes the ability to map geocoded travel diary information onto a network via shortest path routing. Such an approach is not adequate to address the concerns raised here, but does indicate a tendency to continue enhancing the desktop GIS environment with tools for visualizing travel activity in innovative ways.

An interesting visualization undertaken by Kwan (2000) creates a continuous surface representation of trip destination density. To develop the destination density maps, Kwan used a geo-statistical technique known as kernel estimation, which uses a weighting function (the kernel) to determine the effective destination density at all points in the study area by measuring its weighted distance from all the observed data points. A key parameter of kernel density estimation, known technically as the "bandwidth" or "scale" of the estimation, is the p arameter that describes how rapidly that function decays with distance. Where the scale is small, only nearby points are considered in the density summation and as the scale increases, points at greater distances gain enough weight to enter the summation. A limitation of Kwan's presentation is that she provides no discussion of how to select a suitable scale for the kernel function, since she is specifically interested in an attractive visual representation (and a suitable scale is thus simply that at which the data offers 'the clearest information'). Alternatively, one can recognize, as do image analysts who rely on kernel estimation approaches to extract features from noisy images, that the kernel scale is a key tool for explicitly quantifying the scale of an image and the objects found within it (ter Haar Romeny, 2002). The kernel estimation technique will be discussed further in the next section of this paper, with specific attention to the question of what constitutes an appropriate scale.

The association of scale with the variance of some kernel function provides an interesting perspective on the problem of the aggregation bias that occurs when discrete choice models are estimated from zonal average data compared to when they estimated from more disaggregate data. If one supposes that the residuals in the "correct" disaggregate estimation function are distributed with a certain variance, $\boldsymbol{\sigma}^2$, it can be shown (for example in Ortuzar & Willumson, 2001 pp 308-310) that substituting a zonal average with a possibly different variance, $\boldsymbol{\sigma_\tau}^2$, (since the zone is a subset of the total population) will lead to a different estimate of the model parameters. These parameters are related, however, by the ratio given by $\sqrt{\dfrac{\sigma^2}{\theta^2\sigma_\tau^2 + \sigma^2}}$, where θ is the value of the utility function coefficient estimated from the zonal aggregate estimate, and this ratio thus can be interpreted as a direct quantitative measure of the scale mismatch between models estimated from fully disaggregate data versus those estimated from aggregated subsets of the full data.

The problem of aggregation bias does need to be addressed explicitly in order to develop field representations of travel activity and parameters that may influence it. Data collection is greatly facilitated by point, line and area collection, and continuous surfaces are almost always constructed by interpolation from sampled points. Implicit in such collection is an inevitable degree of uncertainty and imprecision in the data we are modeling, and that uncertainty and imprecision is directly related to the "correct" value for the bandwidth of smoothing functions used to convert that data into a useful format for field representation. A common misconception regarding such smoothing is that it involves "loss of information". However, the practical r eality of common tasks such as lining up boundaries from Traffic Analysis Zones (developed from

Census TIGER/Line road files) with more accurate geographical data available from local sources, suggests that far from removing information, blurring boundaries of such zones can actually improve the usefulness of the data by rendering the gray areas as what they are. Any procedure that helps make explicit the limits of our data and models, particularly with respect to the scale of likely effects that might be observed in such data, is likely to be advantageous.

The final area of prior research to consider relates to building powerful general models of spatial processes that are influenced by spatially variant (and invariant) factors. What we want are techniques that permit modeling directly in spatial terms with full allowance for variance due to uncertainty and imprecision. Rather than have to construct spatial indices that obscure the issue of scale and that make it hard to demonstrate that the models we are building are constructed from compatible parts, it would seem desirable to model travel activity in an explicitly spatial format. Field-based approaches discussed above already hold out the promise of simplifying the representation of some aspects of travel activity. A more complete approach is suggested by random field models that are popular in earth sciences and other fields that are explicitly concerned with the distribution of phenomena in space. These models range from simple approaches, such as kriging that model trends in variables over surfaces, to elaborate multi-variable random field models that explore complex structures of random variables distributed in space. These models are typically estimated from trends in covariance structure over continuous (or fine grain discontinuous) fields rather than discrete covariance values between a finite number of zones. Christakos offers a good discussions of the general basis of random field model (Christakos, 1992). He and his associates have developed practical approaches for estimating random field models that vary both in time and space (Christakos et al., 2001).

Field methods are useful for two reasons: one can work from maximum resolution and adapt to different scales, and one can move to a scale appropriate for the information one has available and for the processes one seeks to investigate. Data can be compared with other levels at explicit scale, and biases introduced by rescaling data to fit models operating at different scales can be explicitly acknowledged and accounted for. Finally, and most important from the standpoint of this work, one can focus on the structure of the space, rather than attempting the mountainous (and perhaps futile) task of situating each individual one by one and assigning the individual to a spatial location, a project that has realized its most ambitious practical formulation in the immense TRANSIMS program that attempts to model (in simplified fashion, obviously) the individual activity of the entire population of an urban area ("TRANSIMS," 2003).

4.8 Summary

An irony of approaching travel activity by looking at individual behavior is that it leads us to overlook the very reason that people undertake travel activity in the first place: the fact that what they need is not in the same place they are. Yet even when the importance of spatial form is acknowledged, the structure of popular modeling approaches makes it difficult to sort out spatial arrangements, particularly when dealing with processes that interact at different scales. This is not to say that these methods are wrong, or even that they are necessarily inefficient. Rather, the difficultly lies in accounting for the spatial characteristics of the data, particularly the problem of scale.

Most of the methods that comprise the heavy guns of travel activity models deal with questions of scale implicitly. Relying upon the analyst to establish suitable boundaries for traffic analysis zones, network links, and demographic units without requiring explicit considerations of the scope, precision and area of influence of the data that are aggregated in them increases the likelihood of observing spurious connections and overlooking important distinctions. In particular, treating all modes of travel on the same scale runs the risk of rendering important features of the urban landscape indistinguishable at a level that supports effective planning. Tools that permit one to rescale data (within limits suitable to the scale of the original acquisition of the data) and to make explicit acknowledgement of scale are likely to prove much more effective in disentangling the effects of spatial arrangements on travel activity, both in research and in making plans for particular practical adjustments to the transportation infrastructure.

Measuring space rather than individual behavior, or perhaps more exactly, using individual behavior *as* a measure of space, provides a relatively convenient way of exploring travel activity. Such an approach permits full consideration for the scale at which a particular modes of travel operate, for errors and uncertainties in data collection, and for the physical and temporal scope of projects being planned. A variety of spatial analysis tools are available for these purposes, and I suggest that the most suitable of these will de-emphasize modeling travel in discrete units and instead encourage continuous representations of travel activity and field-based representations of the factors that may exert an influence on that activity.

The final section of this paper will be concerned with illustrating how issues of scale emerge in the spatial analysis of urban travel, and suggest how to being to incorporate spatial insights into travel activity analysis and transportation planning.

5. Visualizing Travel as an Active Spatial Process

In the first section, I argued that the spatial arrangement of travel activity is important, and that effective multi-modal planning should seek to represent travel activity as a spatial process. The second section assessed a variety of tools for modeling travel activity spatially. In this section, I will illustrate some practical aspects of spatial scale in exploring travel activity. The first sub-section introduces some practical methodological considerations of how to cope with spatial scale in analyzing transportation data. The second sub-section applies these lessons to a geo-coded travel activity survey compiled in the Research Triangle area of North Carolina in 1995.

5.1 Methodology

There are three main ways in which scale can be recognized in spatial processes, each of which suggests a restriction of our field of view in order to highlight structures at that scale. In formal terms (based on (Morse et al., 1994)), these can be identified as:

1. Neighborhood of influence (how big an area)
2. Level of detail (how detailed the representation)
3. Spatial precision (how precisely located within it)

These three dimensions of scale emerge from how we measure the phenomenon. While these scales will typically be chosen to have comparable magnitudes, they are not required to. The size of area reflects the type of process we are examining. It is natural, for example, to examine walking travel over areas that correspond to the length of typical walking trips. Within such areas, one may reasonably expect that smaller features may be significant influences, though large features such as significant hills may also be present. One can choose to examine large scale processes operating in small areas, or view small processes distributed over large areas. For example, large scale divisions within a community imposed by topography and existing road networks may delineate adjacent areas in which people walk more or less, and then focus at a much smaller scale on the physical characteristics at the boundaries of those areas which may create those limits.

Regardless of the area of influence of the process and the level of detail, it is also important to consider how precise the measurements are. Limitations of data precision can have a significant effect on the scale at which one can meaningfully analyze that data. Gathering the data itself is a process of measurement, and thus one that implies a certain range of scales. This dimension of scale reflects both inevitable errors in data collection, and possibly also weaknesses in the design of the data collection process that limit how small (or large) a scale a meaningful analysis can be performed. It also suggests that data collected at a high level of detail may nevertheless only be suitable for large scale analysis if the precision of data collection is low.

Finally, it is important to notice that the three dimensions of scale are only partly under the control of a planner or researcher. The area of influence, for example, may be selected by an analyst, but it is also influenced by the process under study. As I suggested earlier, various travel modes imply a measurement of space and thus have an intrinsic scale with respect to the ambitions of the traveler, and that scale should be acknowledged in the level of aggregation selected for study. Likewise, the level of detail may be constrained by the size of the study area and reflect limits on computer power and expense of data collection. Finally, particularly if one is analyzing data collected by others, it is essential to consider carefully the scale (or scales) implicit in the precision of the original data collection.

Problems of spatial scale thus have an effect that goes beyond simply drawing an attractive map. As one seeks to model travel activity, and to understand the influence of demographics, spatial arrangements of destinations, and transportation facilities and systems, one must also keep in mind suitable scales for each component in the model. In practice, this means that analyzing travel activity at a single scale, especially implicitly, risks blurring important spatial distinctions and hiding problems with scale precision. Likewise, it means that reaching for fine-grained data collection may not be as useful as it first appears. Collecting many small-scale data points using a methodology that yields results that are only precise at a larger scale may greatly increase the expense of data collection without significantly improving the scale at which one can draw meaningful inferences. In addition, fine-grained data may seduce the analyst into performing a small-scale analysis, when the processes that are relevant for understanding the pattern in the data are best accounted for at a larger scale (an effect that is memorialized in the old caution about 'hot seeing the forest for the trees"). A final practi cal problem lies in making sure that the scale at which one builds ones models is reflected consistently in the data (both its level of detail and its precision) and in the spatial mechanisms the model represents. Expecting to calculate an effect on number or length of driving trips based on the number of feet of sidewalks in a metropolitan area seems an obvious mismatch by these standards, yet in the literature investigating land use impacts on travel activity such a study might not seem out of place at all.

5.2 Examples

The final part of this work will explore travel activity by mode based on data collected as part of a regional activity survey conducted by the Triangle Transit Authority in the Research Triangle Region of North Carolina (TTA, 1995). I will explore this data at various scales and illustrate some of the problems of scale discussed above. Notwithstanding some apparent difficulties of scale mismatch, the data does suggest that interesting differences in walkability of areas of Chapel Hill can be quite accurately pinpointed.

The dataset contains results from two-day activity diary surveys and interviews of 2659 households, comprising 6238 individuals (household members over age 16). A total of 75446 activity records were gathered and geo-coded, reflecting 31296 identifiable trips taken between November 1994 and early April 1995.

It is worth observing that the gross numbers are only precise to a certain scale: the data include a number of miscoded trips that suggest people walking from Raleigh to Durham (over 20 miles) in less than 35 minutes, and relocations with no travel mode or travel time from one location to another. A further limitation of the data for purposes of spatial analysis is that it was geo-coded by street address. Aside from the obvious problem that street addresses are often located by interpolation along street segments, a significant problem lies in the fact that some major destinations, such as the University of North Carolina Hospital in Chapel Hill, were coded as point locations, even though these locations are quite large. Moreover, since this is also a destination at which parking is very limited, it is noteworthy that the survey did not clearly identify walking trips from car to destination – in principle, such walking trips are short and thus represent a decision about the smallest scale of data collection. Yet at large destinations with central, and often distant, parking facilities, such trips are significant in a complete picture of walkable space. Likewise, walking trips to bus stops and the wait for the bus also did not appear as separate trips unless they exceeded a total temporal threshold of 15 minutes. Notwithstanding these limitations, this dataset represents a rich and interesting snapshot of travel activity in a mid-size, automobile-oriented urban area.

Here, we will look at origins and destinations of walking and driving trips both over the region as a whole (a large scale) and within the town of Chapel Hill, a college town and residential community at the western end of the region. The method of analysis is kernel estimation of trip density based on the geo-coded location of trip destinations, and the default implementation of this technique in the Spatial Analyst extension of the ArcGIS 8.2 system was employed to prepare the maps. This is the same technique used by Kwan (2000) discussed in the previous section. The key difference from her analysis is that I have examined density by mode. Also, the emphasis here is on understanding what happens when one uses a different radius, or bandwidth, parameter for the estimation kernel function. Practically, as that parameter gets larger (implying a larger scale of analysis), points are gradually blurred into density estimates over successively larger areas. Information about specific data collection points is gradually submerged into a smooth image of density changes over the area. Though the ArcGIS kernel estimation function was chosen for convenience, the same analysis can be performed with arbitrary kernels, including simple inverse distance, squared distance, or even a horizon threshold that gives equal weight out to some distance from the point at which density is being estimated. The rate of decay of the kernel function is a relevant parameter in considering the scale, as is its implied spatial structure. Kernel functions can be designed to locate directionally-oriented variations in phenomena as well as omni-directional variations as is pursued here).

The first approach to the data involved selecting the subset of trips that were identified as walking trips and mapping them with a kernel density radius (scale) of 500 feet. The result for just for Chapel Hill is shown in Figure 5.1, and for the entire region in Figure 5.2. One can easily see that while the smaller scale makes some sense for a small subset of the region, the small scale makes the walking trips essentially invisible at a regional level.

Figure 5.1 – Chapel Hill Walking Trips (500 ft. scale)

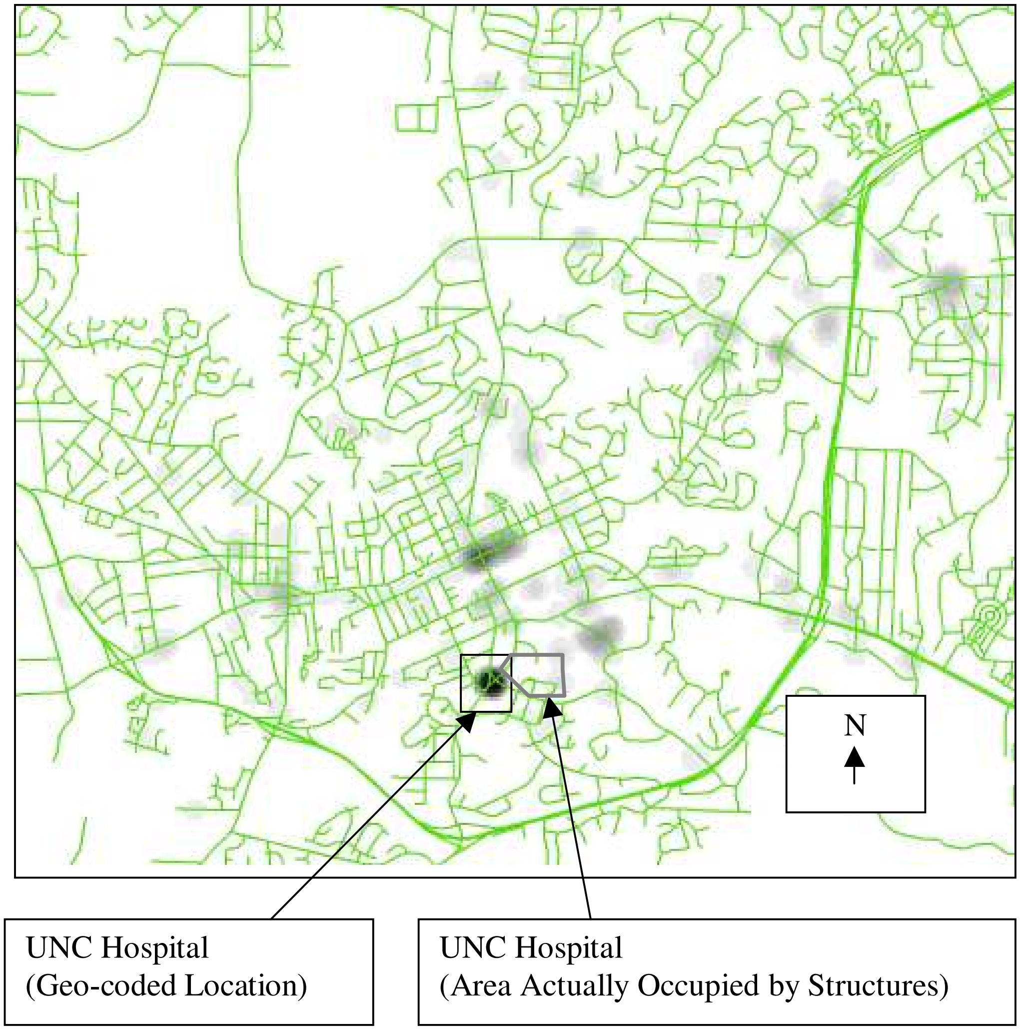
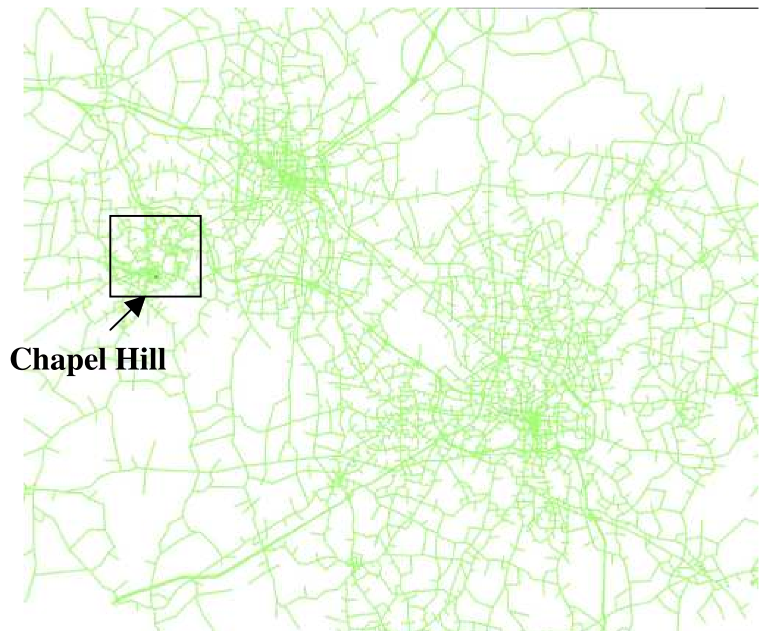
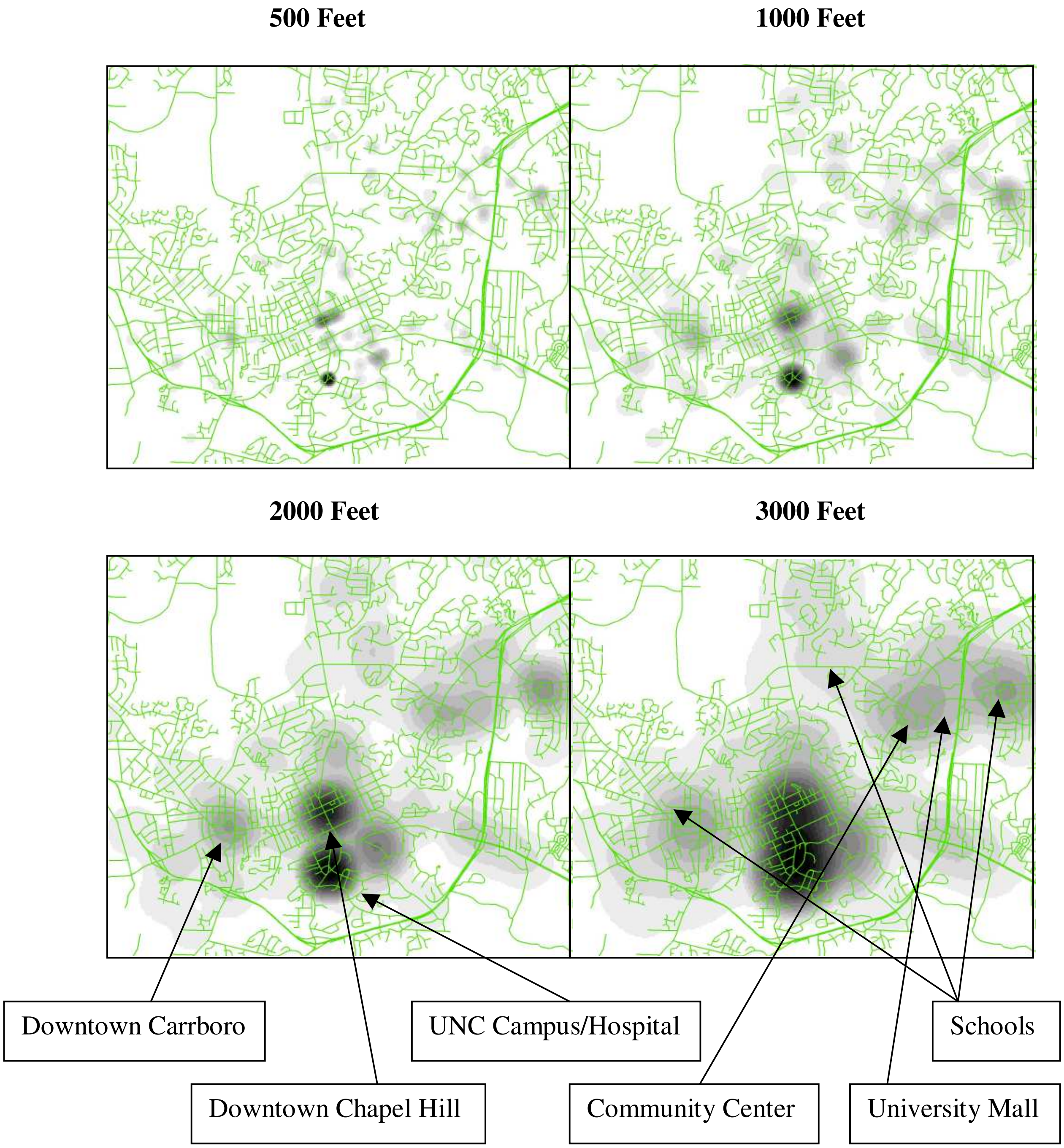


Figure 5.2 – Research Triangle Region Walking Trips (500 ft scale)



The small scale of 500 feet, however, may not be the most appropriate for exploring this data even at the reduced region of Chapel Hill. As noted above, a number of significant landmarks such as the UNC Hospital (see location in Figure 5.1) are coded as a single point, despite having a spatial structure that covers an area that is quite large compared even to the 500 foot scale of the original map. In Figure 5.3, several different scales are presented, including the original 500 foot scale, and scales at 1000, 2000 and 3000 feet. Note that as the scale increases, the individual points merge and a structure to the arrangement of points appears. The 3000 foot scale, based on the estimated size of the UNC hospital and other likely errors in the geo-coding process probably may represent the highest precision possible, but as the scale increase, details of local structure are lost. Moreover, this scale seems to delineate quite sharply certain areas that have a higher concentration of walking trips, including the UNC Campus and Downtown Chapel Hill (both having a large number of walking trips), a community center and regional shopping mall, and several school locations.

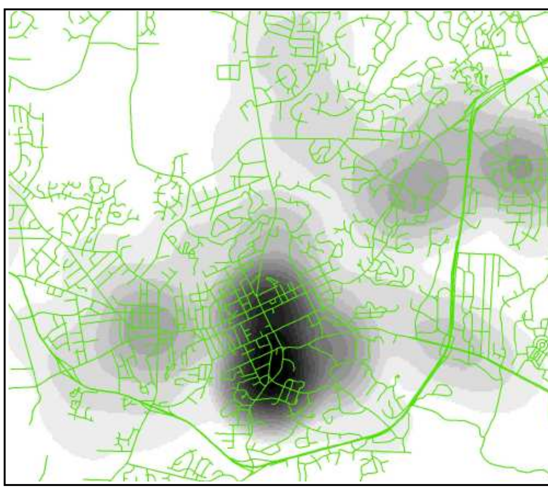
Figure 5.3 – Chapel Hill Walking Trips (Various Smaller Scales)



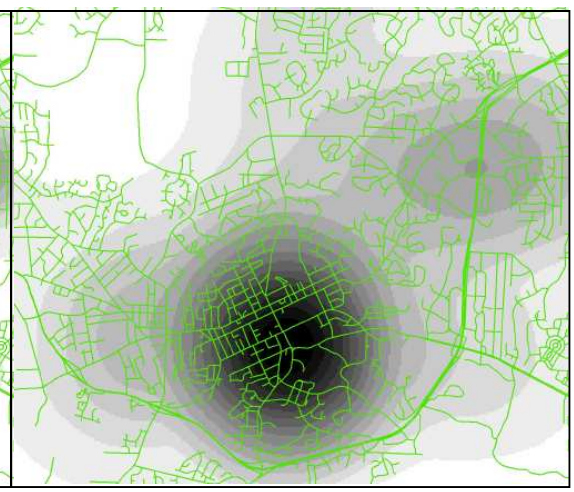
Continuing to increase the scale eventually passes over to a level where loss of detail starts to dominate the map. Figure 5.4 maps walking trips in Chapel Hill at a scale of 3000, 6000 and finally 11000 feet. Yet if we look at same data at a regional level, in Figure 5.5, the 3000 foot scale seems too small to convey useful information (much as the 500 foot scale did when examining the smaller area), and the images at 6000 and 11000 feet seem more useful, though they are expressing different information: regional concentrations of walking trips, rather than concentrations within smaller areas.

Figure 5.4 – Chapel Hill Walking Trips (Various Larger Scales)

3000 Feet



6000 Feet



11000 Feet

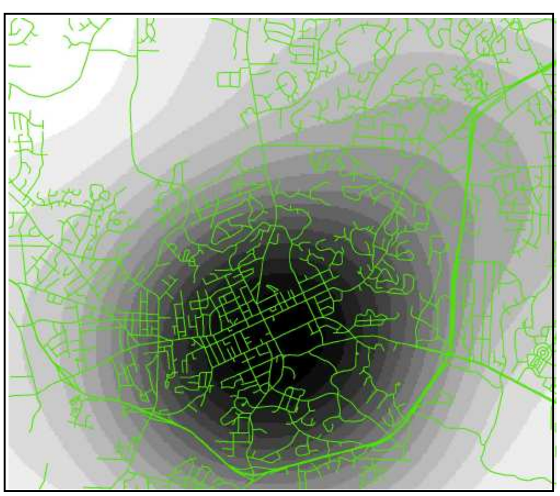
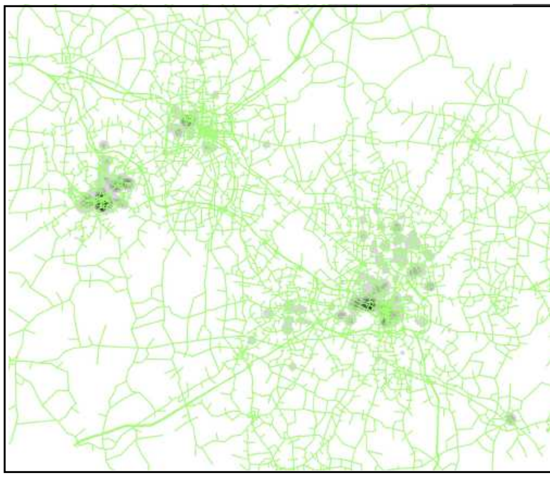
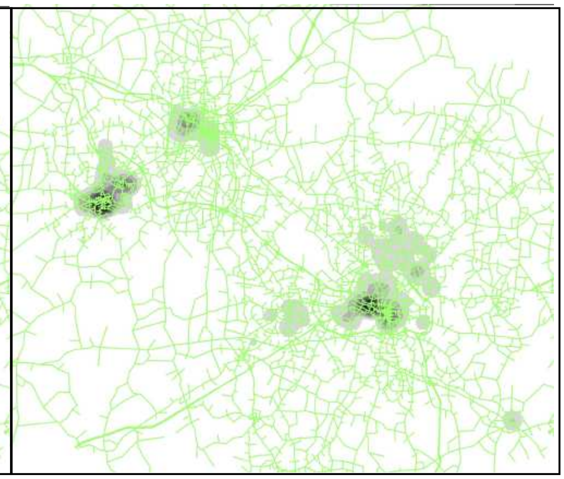


Figure 5.5 – Regional Walking Trips (Various Larger Scales)

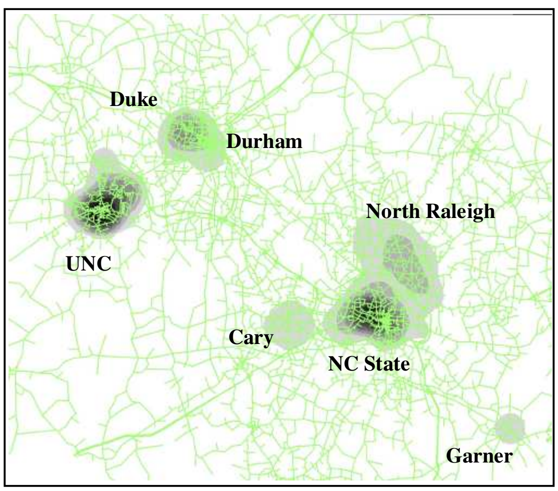
3000 Feet



6000 Feet



11000 Feet



Heavy concentrations of walking trips are associated with UNC (far left), Duke University (top left center) and North Carolina State University (lower right).

Medium concentrations of walking trips are associated with dense residential urban areas, including the north side of Chapel Hill, Downtown Durham (just east of Duke), Cary, North Raleigh, and Garner.

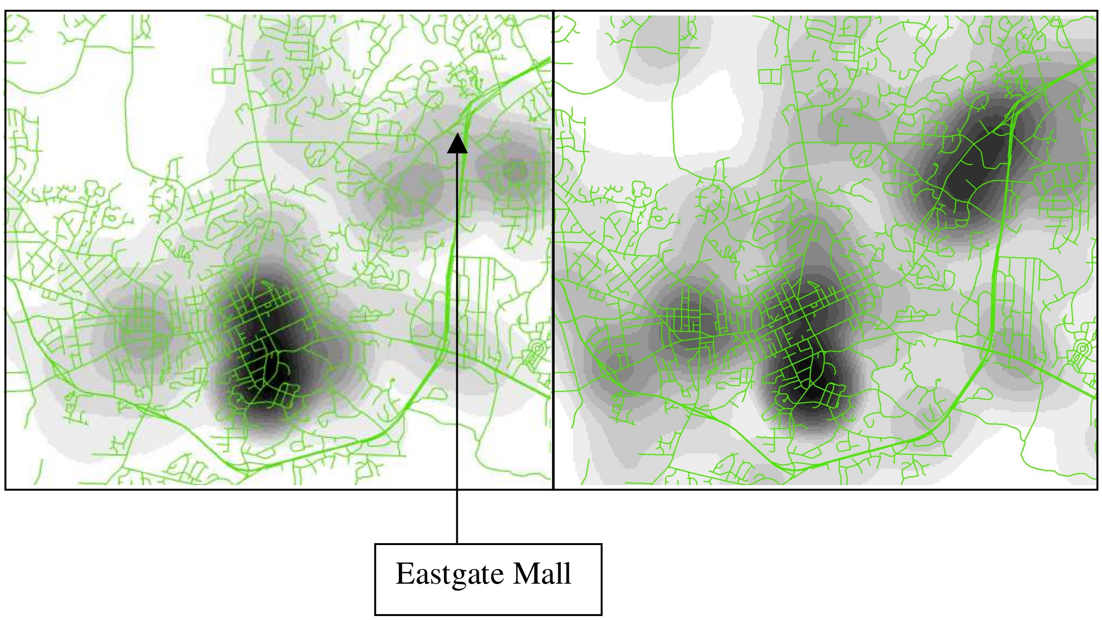
Note as well that these densities are not corrected for overall population or number of trips, and thus represent gross numbers of walking trips, rather than a fraction of walking trips.

Finally, this approach does permit us to compare walking and driving destinations. Where these modes are equally available within a community, we would expect patterns of trip destinations to have more or less the same pattern. Figure 5.6 presents density of walking and driving trip destinations in Chapel Hill at a 3000 foot scale. Note that the pattern of driving destinations at the northeast side of the map (Eastgate Mall) is somewhat different. While the mall is clearly within walking distance of both the nearby elementary school and the community center, it has a fairly high density of automobile trips, yet relatively few walking trips. This disparity is probably not accidental, since the Eastgate Mall was not accessible by sidewalk from surrounding areas until 2001.

While these analyses barely graze the surface of what it is possible to explore using the methods discussed here, they do illustrate the kind of problems that may be amenable to spatial analytic approaches. In addition, they help identify some of the pitfalls that result from scale assumptions implicit in data collection processes. At the least, this example should suggest that spatial modeling of travel activity may be a productive line of future research.

Figure 5.6 – Chapel Hill Walking and Driving Trips (3000Foot Scale)

Walking **Driving**



6. Conclusion

This paper has traveled from the lofty heights of the theory and philosophy of travel to mundane mapmaking with GIS. Along the way, however, I hope to have suggested that new and useful planning techniques do not necessarily imply a greater complexity of analytical tools or of data collection, but simply a shift in focus and attention. I have argued that spatial analysis provides a rich framework through which to investigate travel activity, and that it addresses some important limitations in standard transportation planning methods in fairly simple and straightforward ways.

Because each travel mode has its own operating characteristics that structure space and time at a specific scale, spatial analysis tools are of particular value in sorting out the complex relationship between urban form and travel activity. By structuring our analysis in scaled layers, rather than looking for all-in-one solutions, it becomes possible to directly address the specific needs of different travel modes without losing sight of interactions between these modes at other scales. Methodologically, this suggests that following steps may help address issues of spatial structure and scale when performing data collection and analysis:

1. Represent data so as to permit adjustment of the scale of analysis
2. Understand the precision of the data, and the variability due to measurement error, since this controls the scale(s) at which the data can be effectively analyzed.
3. Explore spatial representations of the available data to get a preliminary sense of spatial distributions at various scales
4. Frame one's questions in order to permit analysis at specific scales.

5. Focus on data whose scale is suitable to the questions being asked, and avoid a "one size fits all" methodology.
6. Examine possible explanatory variables with explicit attention to the scale of the data, the postulated explanatory process, and the scale of effects.
7. It may be very useful to consider smaller scale processes within regions defined by larger scale processes.

These suggestions emerge quite naturally from the standard considerations of spatial data analysis, but they appear to be quite novel in the realm of transportation planning. My interest in this approach grew from recognizing that problems of multi-modal transportation planning are intrinsically connected to issues of spatial arrangement and of scale in particular. Travel modes imply a measurement of urban space operating at a certain scale. Planning that favors one mode over another has typically operated at a specific scale suited to the mode itself, without an explicit sense that what happens at one scale can have quite different effects at other scales. I suggested that a number of difficult problems in multi-modal transportation planning may be effectively analyzed by considering these problems at multiple scales.

Integrated multi-modal planning based on such an approach does not conceive of alternative modes as direct substitutes for automobile travel. That would suggest that only one scale, that suited to automobiles, is the one that matters. The planning that results will either promote goals that have no chance of being implemented at a regional scale (e.g. getting 20% of the regional population not to drive to work) or by erecting obstacles that appear as arbitrary and oppressive (e.g. dramatically raising the cost of driving without investing in adequate alternatives or thinking about where, and at what scale, such alternatives might already exist). This problem shows up even in planning for single modes, as when a regional bus system has trouble reconciling the small scale issue of how people get from their house to the bus (most easily resolved by sending the buses down neighborhood streets) with the large scale issue that the greatest potential ridership for regional transit are people making commutes of as much as fifteen or twenty miles (suggesting that buses should make relatively few stops at key locations in order to minimize travel time). Rather than have one bus perform both duties, several scales of service might seem more appropriate, with careful attention to comfortable and time-efficient transfers between the two.

Effective multi-modal planning focuses on enlarging the useful space in which distances, terrain and opportunity permit the needs of daily life to be structured through a variety of travel modes. Such planning cannot occur without attention to the spatial details of travel, and the various scales at which travel occurs. But with such attention, it becomes possible to develop alternative modes in ways that require less sacrifice from travelers. As travelers begin to experience such travel as enhancing their quality of life and increasing the choices available to them, there is little doubt that use of those alternatives will increase.

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