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Economic Implications of Transportation Investments and Land Development Patterns

Business Location in Today's Economy
Apogee/Haller Baily, Inc.

The Costs of Alternative Land Use Patterns
Parsons Brinckerhoff

Using STEAM for Benefit-Cost Analysis of Transportation Alternatives
Federal Highway Administration

Improved Speed Estimation Procedures for Use in STEAM and in Air Quality Planning
Science Applications International Corporation
Cambridge Systematics, Inc.

This is one of a series of reports issued periodically by the Federal Highway Administration's Office of Environment and Planning, Metropolitan Planning Division (HEP-20), 400 Seventh Street, SW, Washington, DC 20590. The purpose of the series is to share the latest information on metropolitan planning techniques and analytical procedures. This series will include the results of in-house and contract research, papers written or presented by staff, and summaries of workshops or conferences. Comments on these reports, and recommendations for material to include are welcome.

PREFACE

This is the eleventh in a periodic series of reports issued by the Metropolitan Planning Division, Federal Highway Administration. This document was produced and is being distributed as part of a continuing effort by FHWA's Office of Environment and Planning to provide timely and pertinent information to those involved in metropolitan planning related activities.

The report, *Economic Implications of Transportation Investments and Land Development Patterns*, presents four papers that can be used for evaluating the private, government, and social implications of alternative transportation and land use decisions. Three papers stem from research contracts sponsored and managed by FHWA's Metropolitan Planning Division. One paper, *Using STEAM for Benefit-Cost Analysis of Transportation Alternatives*, was prepared jointly by staff of the Metropolitan Planning Division and the *STEAM* (Surface Transportation Efficiencey Analysis Model) software developers.

The first paper, *Business Location in Today's Economy*, explores the relationship between changing business operating conditions and firm location needs. The implications of these changes to broader planning and policy goals are also discussed. The second paper, *The Costs of Alternative Land Use Patterns*, presents an analytical framework and a protoype model for estimating the full costs of alternative land use patterns. The paper also presents results from application of the full cost model to Portland, Oregon. Costs considered include both monetary and non-monetary costs associated with urban land development at the metropolitan scale.

The third paper, *Using STEAM for Benefit-Cost Analysis of Transportation Alternatives*, discusses application of FHWA's recently developed STEAM model for multi-modal transportation evaluation. STEAM utilizes speed relationships that account for the effects of queuing under recurring congestion as well as incidents. The fourth paper, *Improved Speed Estimation Procedures for Use in STEAM and in Air Quality Planning*, presents the speed relationships and methodology used to develop them. The principles underlying STEAM as well as the speed equations are discussed in FHWA's National Highway Institute Course No. 15257 "Estimating the Impacts of Urban Transportation Alternatives" available through the National Highway Institute.

For more information on the research presented in this report, please contact Patrick DeCorla-Souza at (202)-366-4076 or *patrick.decorla-souza@fhwa.dot.gov*. Copies of this report can be obtained via fax request to FHWA's Subsequent Distribution Office (fax no. 301-386-5394). Please provide the publication number shown on the back of this report.

A White Paper

Business Location in Today's Economy

Or

Does Location Still Matter?

Does Transportation?

How About Land Use?

Prepared For:
Federal Highway Administration
Office of Environment and Planning

May, 1998

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Apogee/Hagler Bailly, Inc.

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EXECUTIVE SUMMARY

Introduction

The urban-development phenomenon called "sprawl" and the forces that drive it are discussed and debated much more than they are analyzed. To the extent that linkages between sprawl and transportation are discussed analytically in the policy arena, the literature tends to focus on factors that influence household location decisions. The role of business location decisions in shaping urban form and development patterns, by contrast, has received very little analytical attention.

Whatever the other causes of sprawl, and whatever sprawl's costs and benefits, policy-makers are going to need to understand how economic agents making rational business decisions react to and affect regional development patterns. This study is a first step in what is expected to be a more thorough, long-term effort to analyze and understand business location decision-making and, in particular, linkages between business location, urban form, travel, and sustainability issues.

Change in the Definition of Access

The focus in this white paper is on the business-location factors that managers consider when they choose sites within an urban region (as opposed to location decisions *among* urban regions). The issues that are considered include:

- Access to customers
- Access to labor
- Access to supplies
- Rents.

While the importance of this set of factors has not changed much over time, the relative cost and character of access have changed considerably in recent years. Reductions in transportation costs, improvements in transportation service quality, and the rise of telecommunications as a substitute to and complement for many transportation services, have all combined to make it feasible for economic activities to separate spatially from one another. These developments together make it easier to avoid high rents associated with regional centers, while maintaining levels of access needed for viable business operations.

As in the past, some businesses still emphasize physical proximity to customers. for example, many high-end retailers locate in upscale districts of the urban core and in affluent, suburban communities. Most new retailing, however, takes place at suburban malls, "power centers," and through catalog shopping. Many retailers also expect internet sales to increase. For retailers in each of these areas, mode of access is as important an aspect of market segmentation as product line and pricing. Not only does mode of access affect market segment, but it also influences the economic trade-offs businesses confront when evaluating alternative business locations. In retailing, the business location impacts of these calculations include:

- High-end retailers locating physically near customers in urban cores and in suburban subcenters
- Big-box retailers locating at the intersections of suburban highways and arterials to maximize "shopper-shed" area.
- Catalog retailers such as Lands' End choosing rural, out-of-the-way locations

The growing diversity of access modes that is affecting the landscape of the retail trade affects other types of businesses in the same way. In each sector, some businesses adhere to the business location choices they have always made, while others change in response to new conditions and opportunities offered by suburban roads, better telecommunications, and the internet.

Changes in access to labor mirror changes in how businesses gain access to customers. Some businesses and business functions continue to be located primarily in urban centers (e.g., financial services). This is for many reasons, but it is often because urban cores provide access to certain kinds of skilled labor, and because of important "clustering" effects. The different labor needs of other businesses and business functions dictate different location decisions. The business location impacts of different labor-access calculations include the growth of major back-office processing centers in the suburbs and telemarketing establishments in small cities in the middle of the country. Both back-office processing and telemarketing rely heavily on well educated, non-unionized, "second-income" workers, and both contribute to increased profitability to the extent that they can gain easy access to this crucial resource.

Access to supplies differs from labor access and customer access in that it focuses more on transportation (of goods or of information) than on people. As a result, reliable access to supplies today emphasizes reliable transportation networks over access to features of urban development, much as it has in the past. However, to the extent that manufacturing processes have come to rely increasingly on just-in-time transportation services, and on truck transportation as the backbone of those services, many logistics service providers, warehouses, and manufacturers now select exurban locations over urban locations because of their superior access to the intercity highway network.

Conclusion

Changes in the definition and characteristics of "access" do not mean that the traditional center will no longer be the locus for a high level of economic activity. Many city centers will continue to be places of concentrated, intense economic activity. These same urban cores, however, are not likely to remain effective economic centers of regions. Changes in the character, quality, and cost of access have unleashed economic forces such that a regional "center" no longer exists as a single, multi-faceted economic nexus. Instead, regions will be defined in terms of multiple sub-centers (some specialized, some not).

The overall message from this first analytical step is that, in many significant ways, there have been dramatic changes in the cost and nature of access. Firms have responded to these changes with rational decisions about the location of business activities in a changed urban environment. And these decisions have undoubtedly had some effect in reinforcing sprawl. Any consideration of policy measures that might alter these decisions must take into account the point that firms have gone through a rational process with results generally beneficial to their customers and employees.

Next Steps

Any transportation policies related to notions of sustainability will have to address the costs and benefits to business of alternative policy options. A more systematic exploration and understanding of business location decision-making is required to begin establishing these benefits and disbenefits. First steps in this direction can be taken through case study analysis of particular business-location decisions that highlight the business location dynamics discussed in this paper and that begin to make quantitative analysis possible.

CONTEXT

Transportation has always had a strong link with economic growth. Indeed, U.S. economic history parallels that of transportation, often complete with dramatic images from the dominant mode of the time. Economic growth, in turn, has fueled demand for transportation. Throughout most of our nation's history, the solution to this growing demand was simply to build new capacity where it was needed – and sometimes in places where it was not yet needed.

Economists have not always measured the connection between transportation and the economy with great precision. In fact they usually err by underestimating the long-term value that transport can provide. Transportation planners, however, know of its importance first hand, since demand for travel is linked directly with land use patterns and business types. Indeed, most planning models rely directly on these connections to forecast demand.[1]

Two broad sets of changes raise questions about the assumptions implicit in these models and indeed in our way of thinking about transportation in general.

- First, business is organized and conducted quite differently now from the manner of forty or even twenty years ago. Are these changes important enough to change our thinking about transportation and urban areas? Or merely an interesting sidelight?

- Second, new issues now shape the debate over transportation policy – phrases such as sustainable development, global warming, brownfields, urban sprawl, and least-cost planning abound. How can we develop policies that address these broad topics and still reflect the underlying economic realities of urban areas?

The forces that shape today's businesses are broad, covering elements that were little noticed fifty years ago. Technology shapes how we work and communicate; changes in family structure and lifestyles change how, where, and when we buy and sell goods and services; the search for productivity places greater emphasis on transport reliability as just-in-time inventories and reduced cycle time become common management techniques; global markets change how we organize and compete.

Similarly, our understanding of transportation and its effects on how well we live and how the world around us lives has changed considerably. We know about the environmental impacts of transport investments, and have changed how we plan new projects and how we manage existing resources in response. We can trace the secondary and tertiary impacts of transportation decisions, even, in some cases, when they cross borders and continents.

[1] It should be noted, however, that this knowledge and experience relates primarily to impacts of regional economies on demand for transportation services and facilities, rather than vice versa.

This white paper aims to provide an economic context for thinking about transportation, urban density, and complex issues such as sustainable development sprawl and brownfields. The underlying focus is the business motivation for locating where they do. The first half provides background on the key forces that influence location. The second half presents an analytic framework for organizing our thoughts about business location in the context of urban form, land use and transportation.

An Old Paradigm

For most of this century, a series of facts and beliefs have shaped much of our urban planning. In more recent years, many of our urban transportation planning models have also reflected these concepts. These facts and beliefs, summarized below may have been true in the 1950s; some are still believed – at least people act as if they still believe them. They are presented here to provide a foil for the rest of the paper and the analytic framework in particular.

Center City (the CBD) was the center for economic activity, often accounting for more than half of the region's economic value and a large proportion of its total jobs. Location choice was defined relative to this economic focus, in large part because the CBD was also the focus for most transportation networks. Today, most major metropolitan areas have multiple centers – what some call Edge Cities.

Home to work trips dominated travel, were the clear source of most urban congestion, and a key issue for modeling and analysis. Today, while work trips still are the primary source of peak-period congestion, trip chaining and off-peak travel are the catch phrases for planning and congestion has spread well beyond the rush hour.

Large businesses were the driving force in economic growth, total activity, and thus in location. Business magazines created lists of the top companies since they were clearly so important. Today, employment in the Fortune 500 is stagnant, large companies improve their bottom line by downsizing, and most jobs are created in small and medium sized firms – long live the *Inc. 500*!

Transportation success was measured in quantity and by narrow engineering standards – ton-miles, passenger miles and VMT. In an age of semi-conductors, ton-miles mean very little. Quality of service is what counts – Did you get to work on time for the nine o'clock meeting? Did you get to the Federal Express office before it closes? Does the engine block meet the chassis on the assembly line during its allotted fifteen minute time frame?

Businesses were hierarchical in structure, with functions vertically integrated within the firm. Today, contracting out and niche markets are buzzwords as well as reality.

The rest of the world was a place to visit, not another market or a fierce competitor or a source of inputs.

The pace of change was slower. Today, technology, competition, and the search for productivity gains mean that new products and new methods of producing goods and services burst on the scene at a steady pace.

The natural environment was something to enjoy not an external impact to be analyzed and ameliorated.

In order to understand the changing rules of business location, we need to start at the beginning: What drives business success today? How do these factors vary by industry? How do they relate to location – particularly by density of development? Answers to these questions, in turn, will support more effective transportation planning.

WHY DOES BUSINESS LOCATION MATTER?

Travel and location choice are linked

Major developments have changed basic patterns of business location from what they were, say, 30 or 40 years ago. General cost reductions and quality improvement in transportation and telecommunications now make it feasible for many activities to disperse away from the dense agglomeration of the center. At the same time, increased urban congestion encourages some business and residential activities to move to lower density areas. This combination of economic forces helps account for the growth of so-called edge cities and the lower density development that some call "sprawl."

Whatever the other causes of sprawl and whatever its costs and benefits, we need to recognize that it reflects business people and their customers making what they perceive as rational economic decisions. In fact, the need for information on urban density and economic activity is about much more than sprawl. Just as sprawl is a relatively new phenomenon, there are likely to have been parallel shifts in the economic forces that drive the location of activities to one part or another in an urban region, to one link or another in the transportation network, or away from the urban region altogether.

Finally, of course, travel and location choice affect each other.[2] An important question is how the new economic structure may have caused shifts in these locational choices. Just as important, however, is how might the economic needs of businesses in this new economy shift the nature of the transportation services they demand. Does the growing emphasis on quality (reliability) imply a need for greater investment? Does the use of the Internet as a marketing tool, mean fewer shopping trips or longer trips to reach more specialized shops?

The stakes are high

Growth in urban travel is substantial

Transportation is simply a more important issue today than it was thirty years ago. Travel continues its post World War II growth, thus raising the stakes in decisions affecting travel. As a result of this growth, both the economic benefits and the environmental and other costs of travel have increased significantly in recent decades.

Furthermore, travel is projected to continue growing rapidly, certainly faster than our recent ability to add capacity. Given the growing importance of reliability and quality in general, what does this imply for our economic competitiveness and for business location? Will firms continue to move to lower density areas, in search of less congested highways? Will technology and telecommunications offset these trends?

Travel and location choices have broad and profound implications

These effects can be both positive – in terms of economic growth and productivity – and negative – in terms of negative impacts on the environment or increases in overall costs.

Transportation continues to be probably the most important single force in shaping the country's economic productivity. Work by Professor Ishaq Nadiri shows that the economic returns to private business from investment in highways exceeds the annual rate of return from private sector investment. Growth in economic productivity is vital to our national competitiveness when we can not depend on growth in natural resources nor population to allow us to outpace our international competitors.

Can we continue to reap these benefits when congestion costs grow each year, and now exceed $40 billion a year? Will our new investments be as productive in an economy with a new structure? Will policy changes aimed at greenhouse gases or controlling sprawl affect these historical returns from transportation?

Building more roads, transit, and infrastructure is also costly. Fiscal pressures will always be with us. What combination of investments is most effective in meeting travel needs and the new economic demands? What are the financial and travel implications of greenfields versus inner city or brownfields investments?

Naïve polices can create real problems

We face a host of complex problems. At the global scale, these include global warming and increases in greenhouse gases in general. At the metropolitan level, concerns continue to be raised about the wisdom of low density economic development. Proposed solutions to both sets of problems may sound simple – a little belt tightening in how we consume fossil fuels or stronger land use regulations. Land use restrictions and enforced higher density as universal solutions – as some have proposed – may end up with unintended negative impacts on our economic effectiveness. We have yet to address the economic and social implications of these policies in any consistent way.

Politics and policies place transportation use in a new spotlight

We once thought of transportation as both a necessity of life and a primary engine for improving our economic well being. Today, transportation -- particularly highways -- is often perceived in ways that are both more complex and less flattering. Many of these new ways emphasize the effects of transportation on environmental quality; many focus on transportation's ability to shape how and where we live; many have little to do with the economic benefits that transportation can generate; and many seem to derive from opinions and personal values about appropriate lifestyles more than hard analysis.

In one sense, however, these new "spotlights" elevate transportation to an even more important place in society than does a pure economic focus. Indeed, many of these new forces emphasize transportation's ability to shape land use and with it our life styles. In a sense, they place an even greater emphasis on transportation and location than the past emphasis on transportation as an economic power. These new ways of thinking, however, raise at least two serious questions:

- What is the likely effect on business efficiency? and
- How hard will it really be to change the current pattern of business location?

NEEDED: A NEW PARADIGM

Perhaps the most important reason to reconsider the relationship between transportation and business location is that it has changed dramatically in recent years, and we do not yet have an adequate understanding of it.

In order to develop public policies that respect economic realities and that are effective in helping solve broader environmental and social objectives, the public and private sectors need to understand the linkages between transportation and business location. Because these relationships have changed radically in recent decades, simply developing a new way of talking about, a new way of thinking about business location and transportation would be very valuable.

The rest of this paper focuses on developing new definitions for two broad dimensions that shape this topic:

- Access and
- Business categories

Redefining access

We suggest that the most basic forces, or factors, considered by businesses in rational location choices have not changed, but how transportation meets these criteria has changed greatly. Put another way, firms still consider the same broad categories in comparing various locations, but not only have all of the prices changed but so have the details that describe each category.

The basic categories of costs, or factors, to consider are:

- Access to labor
- Access to customers
- Access to suppliers
- Costs of land/rent

While firms certainly consider other factors in their location choices, we view these as key in determining financial success.

What has *not* changed is that businesses need *access*, to labor, customers, and suppliers. If this critical access could only be obtained in one location, land prices would not be particularly important – access would be crucial and probably the sole determinant of location. However, when access may be obtained in a variety of locations, as appears to be the case for most types of businesses, then firms may locate more on the basis of land prices. In any case, however, understanding how and where companies can gain these forms of access is the key to understanding business location.

A fundamental point here is that while *access* used to mean *physical proximity*, it now may be obtained through a variety of methods. Access, in turn, has taken on more dimensions than simply the amount of travel time. Physical proximity (location) and transportation play a whole new role in providing access today.

In fact, one can now speak of *modes of access* just as we have traditionally talked about modes of transportation. Where once the only mode of access was traditional transportation, modes of access can now include telephone ordering, express mail delivery to consumers, and just-in-time delivery of supplies.

The body of this paper examines what access used to mean, and what it means today. We also examine how the meaning of access varies widely across specific types of business activities.

Redefining business

In addition to reconsidering the meaning of access, we propose a new way of thinking about transportation and business location: the old business categories are obsolete.

Planners, economists, and policy makers have traditionally assumed that the entities choosing locations are companies, and that *the type of service or product* offered defines them. Increasingly, though, businesses are fragmenting into discernable *activities*. Each activity can be carried out in a different location. It is not an *industry* that needs to be in a certain location, it is an *activity* that is suited for a certain location. It is not as useful to think about where the food industry would locate, for example, as it is to consider where a warehouse, office space, or manufacturing plant would locate. Such activities as warehousing, for example, are common to many industries, and are a much better category for considering location choices.

WHAT ACCESS USED TO MEAN

It is important to consider how businesses traditionally gained access to labor, customers, and suppliers. This is important because these traditional methods of access are often taken for granted and treated as fixed relationships. Too often, we assume that access is still defined by physical proximity and that travel time and cost are good proxies for the economic value that access provides.

In many cases, these assumptions have been built into the current generation of models. They have also been built into the prevailing conventional wisdom, so that when people talk about land use or make transportation policy, they tend to assume that things are what they used to be. This can lead to decisions that fail to consider the new economic realities we face.

Before spelling out what access means today, however, we need to quickly review the assumptions we tend to make, based on what access has traditionally meant. It is useful to review how firms have traditionally gained access to three things:

- Labor
- Customers
- Suppliers

Broadly speaking, access traditionally has been defined by location choice and by transportation. Access was provided largely through proximity allowing pedestrian access in downtown and by roads and rail (or transit to a lesser extent). Of course, over the decades, various other modes have played important roles, including water-borne vessels (intercontinental to canals), airplanes, bicycles, and so on.

In summary, access to labor, customers, and suppliers was traditionally obtained by locating a business relatively near those key players, and by ensuring adequate roads access (or through other traditional modes).

WHAT ACCESS MEANS TODAY

In recent years, a variety of economic, technological, and other changes have redefined how business can gain access to labor, customers, and suppliers. These are outlined here. We discuss how access to labor, customers, and suppliers differs today. First, though, we briefly point out some cross-cutting emerging trends that have helped to redefine what access means in all three of these areas.

Cross-cutting forces redefining access

A variety of political, social, technological, and other changes have occurred in recent decades to help redefine the meaning of access to labor, customers, and suppliers. Some of these broad trends are noted here. They include:

- Splitting up of industries into discrete activities (as discussed earlier)
- Just in time delivery methods
- Direct mail
- Catalog shopping
- Telecommunications, including high-quality phone service, voicemail, conference calling, etc.
- Cable television, including home shopping, infomercials, etc.
- Internet, including email, intranets, and extranets
- Computer software technologies including groupware
- Videoconferencing
- Telecommuting
- Intelligent Transportation Systems

- Various trends (technological and political) affecting gasoline prices and thus transportation costs
- Environmental and other regulations affecting land development costs
- Environmental and other regulations affecting motor vehicle costs

A full discussion of these trends is outside the scope of this paper, but it is clear that the variety and importance of these trends is substantial. It is no wonder that businesses are able to gain the access they need in entirely new ways today.

DEVELOPMENT OF ANALYTIC FRAMEWORK

Firms are in a continual process of choosing sites for business activities. They follow rational processes as they seek locations that will be optimal for their earnings. Their location decisions, in turn, have an effect on the form of urban growth. Our goal here is to analyze the forces that shape these decisions and, in particular, how and whether business activities are driven towards particular districts within urban regions. A parallel question is how and whether activities are drawn to particular links in the transportation network. A third question is whether a firm has any reason to locate an activity in an urban region at all. For some activities, small cities, towns, or rural districts would serve just as well, if not better, from the perspective of a firm's profits.

We focus our attention on location of *activities* rather than of *businesses*. For some kinds of firms, this distinction does not matter. A small, professional-service firm—a law firm or consulting firm—has only one real activity and may well have only one office. Many businesses, however, comprise a set of diverse activities. A super-market chain, for example, has stores, warehouses, and a head office. And it is likely to have different location criteria for each of these activity types.

Some firms have distinct activities within the head office and no strong reason to have them all in the same place. Modern telecommunications and computer systems mean that top management, sales, and back-office functions need not be in close physical proximity. Nor does the firm increase its profits by treating the locational needs of each sub-unit in the same way. These trends are very real, witness the number of back office functions located in Hoboken and other parts of Northern new Jersey while the corporate headquarters remains in Manhattan.

Depending on a firm's size, and the nature of its business, it may make sense to have everything under one roof.[3] But the point we need to keep in mind is that this is often not the case and, it appears, increasingly not the case.

That the activities that make up a business operation can be separated in this way is, of course, one reflection of the major developments that have changed basic patterns of business location from what they were, say, 30 or 40 years ago. Cost reductions and quality improvement in transportation and telecommunications have made it feasible for activities to disperse away from the dense agglomeration of the center. Without doubt, this is one of the major forces driving the phenomenon called "sprawl." Whatever the other causes of sprawl, and whatever its costs and benefits, we need to recognize that

[3] Note the conclusion by some researchers that lower private costs incurred by firms locating in dispersed patterns are offset by higher environmental and public infrastructure costs.

part of what is going on is economic agents making rational decisions in the light of profoundly changed conditions. The purpose of this analysis is to show the ways in which firms' responses to these changes have led to new patterns of location.

A significant consequence of improvements in transportation and telecommunications is the change in the mechanics of access. Economic activities have been able to disperse from the center, not because their requirements for access have changed, but because the cost and the character of access have changed. This may seem an obvious point, but much of the discussion and debate on sprawl suggests that it has been missed. In a sense, there is nothing new here. Access has always been important and has always been affected by transportation costs. Cities grew on navigable rivers, because waterways gave easy access to markets and supplies. The Romans well understood the importance of transportation and communication to running their empire, so they built a first-class highway system, the forerunner, in a way, of the Interstate. Cable and Wireless, Ltd., had the British Empire globally wired with telegraph, telephone, and radio before the end of the last century.

What is different now is the way economic activities at the level of shops and factories have been able to separate spatially from one another, avoiding the high land rents that come with dense agglomeration but maintaining the degree of access they require to be economically viable. Access is maintained in several ways. A good highway network lets a mega-retailer serve an entire urban region from one or two locations. A combination of good highways, sophisticated logistics, and inexpensive telecommunications lets a catalogue house like Land's End or L. L. Bean do a huge volume of national retail business from a single out-of-the-way location.

Some of these changes have brought employment to rural areas or small towns that would not otherwise have been there. They have also redistributed economic activity and employment concentrations within urban regions, and these effects are the particular concern of this paper. A striking structural change in the economy since World War II has been the shift of employment from manufacturing to services. (Services accounted for 59 percent of employment in 1946, 79 percent in 1995.) The net effect of this on access requirements is not necessarily very great however. Services that entail provision of information and do not require face-to-face dealing may be relatively footloose. Services that do require face-to-face dealing or require highly skilled labor, will still have to be near customers, workers, or both.

For many activities, access to customers and labor is better achieved from the urban periphery than from the core, but certainly not for all. The fact that improvements in transportation and communication have made dispersal feasible in a physical sense does not mean that it is economically feasible for all activities to disperse. Such a shift is desirable for some activities but not for others. For some activities, physical proximity to customers or support services, face-to-face dealing with customers and colleagues, and the like are very important. Many (but by no means all) downtowns are bustling and prosperous even while they account for a much smaller fraction of a region's economic activity than they once did. Our goal is to understand better how the changed character of access drives the sites of business activities to one part or another of an urban region, to one link or another in the transportation network, or away from the urban region altogether.

ACTIVITY-LOCATION FACTORS AND URBAN-DISTRICT TYPES

The centerpiece of our analysis is the Activity-location Matrix, presented in the following section. In the matrix, we relate the location factors that matter to businesses to types of urban district and to links in the transportation network.

For simplicity, we limit ourselves to four types of urban district:

- metropolitan center
- metropolitan sub-center
- low-density periphery
- exurbia

When a firm's executives consider a location decision, however, they do not, typically, think in terms of selecting one of kind of district or another. Rather they consider economic factors more directly relevant to them that might, or might not, drive them to choose a particular type of urban district.

We chose to focus on four location factors that are critically important to firms in choosing activity sites and may vary according to type of urban district. These are:

- Access to customers
- Access to labor
- Access to supplies
- Real-estate prices

These activity-location factors were selected on the basis of the literature on firm location. Several other factors are also cited in the literature as important to firms but we chose not to focus on these, largely because they vary *among* metropolitan areas not *within* metropolitan areas. It is useful to review briefly our rationale for identifying these key activity-location factors, while setting some others aside.

The starting point is the summary shown in the following table. These activity-location factors clearly emerge as the dominant group. Their relative weights vary across business sizes and activity types, but each one has some importance for almost all firms.

Summary of Activity-location Factors in the Literature

Vary According to Urban District	Vary Much Less According to Urban District
Access to customers Access to labor Access to supplies Links to transportation network Real estate prices	Taxes Utility quality and prices Cost of living Access to cultural/recreational facilities

This classification requires some discussion. Taxes, for example, may be quite different on either side of a jurisdictional boundary. But that difference is not inherent in urban-district characteristics. The difference in taxes is not necessarily a function of high or low density, as such, or distance from the center, but of where a political boundary happens to lie. It may, indeed, be the case that there are significant differences in income and requirements for government services as between the central city and some of the suburbs and that these differences account for different tax levels. The cost to provide public protection services, for example, may vary on a per capita basis depending on factors related to density and income levels. Public works costs associated with maintenance of water and wastewater infrastructure may also vary on a per capita basis depending on factors related to density. Such patterns, however, would not be consistent across different urban regions for the very reason that they are not directly related to urban-district characteristics.

Utility quality and prices, as well as cost of living, are factors that businesses tend to perceive as varying among urban regions but not within urban regions. To a large degree, this is also true of access to cultural and recreational facilities; many businesses will see this as a matter of comparison among metropolitan areas rather than within them. On the other hand, for certain types of labor, especially high-skill labor, a business location accessible to high-amenity neighborhoods is likely to be very important. In our analysis, we treat access to high-amenity neighborhoods as an important urban-district characteristic regarding labor access for certain types of firms.

The literature shows that access to markets and access to labor are the factors most frequently cited by business executives as major influences in site selection. Access to supplies is frequently cited as an important factor for firms engaged in manufacturing or distribution; it is also important for mega-retailers that strive to hold down logistics costs.

Links to the transportation network are rarely cited specifically as an important factor in location decisions. Part of the reason is that much of the literature is concerned with choices among metropolitan areas rather than choices within metropolitan areas , and metropolitan areas are not perceived as being greatly different in this respect. More importantly, links to the transportation network are implicit in the other factors: access to customers, labor, or supplies. Manufacturing and distribution facilities, for example, must have good access to the inter-city network. Mega-retailers must be on sites with good freeway access.

In our analysis, we treat links to the transportation network as an important characteristic of a potential site, independent of urban-district type. A firm that ships over long distances may not care, as far as access to customers is concerned, what part of a city its warehouse is in. It will care very much about the nature of its links to the intercity highway network and, possibly, rail links.

Real estate prices vary considerably according to urban district. The highest priced land is in the centers or sub-centers, where economies of agglomeration lead to high densities and high land rents. The pattern in the past was generally that land prices were highest in the center, followed by sub-centers, if any. This is not true for all urban regions today; land rents may be higher in some peripheral sub-centers than in the old core. After the centers, land rents are lower in the low-density periphery and, generally, lower still in exurbia.

The effect of land prices is to sway firms' decisions when other factors do not have a strong influence. For instance, some types of firms will choose the low-density periphery, not because it is has an inherent appeal for them, but because it the lowest-cost location from which they can still have adequate access to customers, labor, and supplies in an urban region. Put another way, firms will not locate in high-rent districts without strong reasons to do so. This effect is pervasive, and we do not note it in the matrix unless there is a particular reason to do so.

Another factor discussed in the literature is the "cluster" effect. This is a tendency of some types of activities to want to be near one another. Typically, it occurs because being near other firms of the same kind is important for access to customers or to labor or because a group of similar firms creates a sub-market for other businesses.

In earlier literature, the cluster effect is often cited as an example of the economies of agglomeration at the center. This may have been true before the flexibility provided by widespread use of automobiles. But clustering in current conditions does not necessarily pull firms towards the center. Today, it can pull them towards a sub-center or some part of the low-density periphery.

ACTIVITY-LOCATION MATRIX

The attached matrix draws from the literature in combination with some general observations and common sense extrapolations. The matrix focuses on the fundamental economic forces that shape firm profits in general and location in general.

Transportation is discussed, but only after the fundamental economic implications have been developed. The businesses shown in the matrix were selected as a broad cross section of American industry, largely because they provide useful examples. They also represent a significant parts of the overall economy.

In the matrix, we see how these factors may, or may not, drive firms to certain types of urban districts. The first three columns of the matrix are concerned with the key activity-location factors:

- Access to customers
- Access to labor
- Access to supplies

Table 1
Factors that Affect Firm Location Decisions

Business Activity	Access to: Customers (1)	Access to: Labor (1)	Access to: Supplies (1)	Cluster Effect?	Attracted to Center?	Urban Region Required?
RETAILING						
Mega-retailer (Wal-mart or K-Mart)				Yes, to be near other similar retailers	Maybe, if downtown market is big enough to offset access costs	Urban region not necessary. Could serve a wide rural area.
1. *Relative Importance of Access Factor*	A	B	A			
2. *Type of Urban District Preferred*	Low-density periphery	Periphery or Exurbia	Indifferent			
3. *Transportation Amenity Required*	Good freeway access	Good freeway access	Good freeway access			
High-end retailer (Neiman Marcus)				Yes, to be near other similar retailers	Yes, to center and some subcenters	Yes, essential for market
1. *Importance of Access Factor*	A	C	C			
2. *Type of Urban District Preferred*	Center and subcenters	Indifferent	Indifferent			
3. *Transportation Amenity Required*	Indifferent	Indifferent	Indifferent			
Other-auto sales				Yes, to be near other similar retailers	Yes, to center and some subcenters	Yes, essential for market
1. *Importance of Access Factor*	B	C	C			
2. *Type of Urban District Preferred*	Periphery	Periphery or Exurbia	Indifferent			
3. *Transportation Amenity Required*	Reasonable hwy access	Good hwy access	Indifferent			
MANUFACTURING						
Light (plastics injection molding)				No	No No advantage	No Needs enough population for labor pool. Small cities/rural areas ok
1. *Importance of Access Factor*	A	B	A			
2. *Type of Urban District Preferred*	Indifferent	Periphery or Exurbia	Indifferent			
3. *Transportation Amenity Required*	Inter-city hwys with predictable congestion	Good hwy access	Inter-city hwys with predictable congestion			

Table 1
Factors that Affect Firm Location Decisions

Business Activity	Access to: Customers (1)	Access to: Labor (1)	Access to: Supplies (1)	Activity-Location Factors: Cluster Effect?	Attracted to Center?	Urban Region Required?
Heavy (auto assembly)						
1. *Importance of Access Factor*	A	B	A	No	No	No
2. *Type of Urban District Preferred*	Indifferent	Periphery or Exurbia	Indifferent		No advantage	Needs enough population for labor pool. Small cities/rural areas ok
3. *Transportation Amenity Required*	Inter-city hwys with predictable congestion; good rail access also.	Good hwy access	Inter-city hwys with predictable congestion			
High-tech (software development)						
1. *Importance of Access Factor*	C	A	C	Yes	No	Yes
2. *Type of Urban District Preferred*	Indifferent	High-income, high-amenity neighborhoods	Indifferent	To be near specialized, high-skill labor pool.	But could become new center.	Needed for high-skill labor pool.
3. *Transportation Amenity Required*	Small package service and airports	Good road or transit access	Good highway access			
DISTRIBUTION						
Long-reach (warehouses)						
1. *Importance of Access Factor*	A	B	A	No	No	No
2. *Type of Urban District Preferred*	Indifferent	Periphery or Exurbia	Indifferent		No advantage	Small population needed for labor pool.
3. *Transportation Amenity Required*	Inter-city hwys with predictable congestion; perhaps rail access also.	Good hwy access	Inter-city hwys with predictable congestion			

Table 1
Factors that Affect Firm Location Decisions

Business Activity	Access to: Customers (1)	Access to: Labor (1)	Access to: Supplies (1)	Cluster Effect?	Attracted to Center?	Urban Region Required?
Local (beverage distribution)				No	No No advantage	Yes Essential for market
1. *Importance of Access Factor*	B	C	B			
2. *Type of Urban District Preferred*	Periphery/ low-rent district in older suburb	Indifferent	Indifferent			
3. *Transportation Amenity Required*	Reasonable road access	Reasonable road access	Good hwy access			
SERVICES						
Local--architecture and engineering firm serving developers and builders				Some Need for custom services and teaming	Little Most customers likely to be on periphery	Yes Essential for market
1. *Importance of Access Factor*	A	B	C			
2. *Type of Urban District Preferred*	Periphery	High-income, high-amenity neighborhoods	Periphery			
3. *Transportation Amenity Required*	Reasonable hwy access	Good road or transit access	Reasonable hwy access			
Long-reach--Insurance company headquarters				Yes Investors and deal makers prefer access to colleagues in nearby firms.	Yes Cluster effects and specialized services both pull to center	Yes Need high-skill labor and specialized services (legal, accounting)
1. *Importance of Access Factor*	C	A	C			
2. *Type of Urban District Preferred*	Indifferent	High-income, high-amenity neighborhoods	Indifferent			
3. *Transportation Amenity Required*	Reasonable airport access	Good road or transit access	Indifferent			

Table 1
Factors that Affect Firm Location Decisions

Business Activity	Access to: Customers (1)	Access to: Labor (1)	Access to: Supplies (1)	Activity-Location Factors: Cluster Effect?	Attracted to Center?	Urban Region Required?
Long-reach--Insurance claims processing						
1. *Importance of Access Factor*	C	A	C	No	No	No
2. *Type of Urban District Preferred*	Indifferent	Periphery or exurbia neighborhoods	Indifferent		No advantage	Needs enough population for labor pool. Some small cities/rural areas ok
3. *Transportation Amenity Required*	Indifferent	Reasonable hwy access	Indifferent			
Local--Large Ins. Co. sales						
1. *Importance of Access Factor*	A	B	C	No	Some	Yes
2. *Type of Urban District Preferred*	Center and sub-centers, depending on market	Near high-income, high-amenity neighborhoods	Indifferent		Customers for some insurance lines will be downtown	For most markets
3. *Transportation Amenity Required*	Good highway or transit access (transit for center)	Good road or transit access	Indifferent			

(1) The following terms used in this table require explanation. The term "indifferent" means that firms are not particularly sensitive to variations in this factor by itself. The grades "A", "B", and "C" refer to the relative importance to firms of having access to the applicable business success factor: access to customers, access to lab and access to supplies.
Comments related to the type of urban district preferred refer to the type of urban district that a given business would prefer in order to gain access to the relevant businss success factor.
Comments related to the transportation amenity required refer to the type of transportation amenity that a given business would prefer in order to gain access to the relevant businss success factor.

The fourth column is about whether and why the cluster effect operates for an activity. The fifth column addresses the point of whether the city center has any attraction at all for that type of activity. The last column speaks to the question of whether that type of activity has any need even to be in an urban region. The rows of the matrix are types of activities.

Activity types selected are representative of those likely to be a significant part of the economic life of an urban region. And there is a choice about their locations; they are not neighborhood or community businesses. A neighborhood drug store or dry cleaner is necessarily located in the neighborhood it serves. It has no options. Finally, the activity types selected cover a wide range: manufacturing, distribution, service, and retail.

It is important to note that, under the Service heading, the same kind of firm, a large insurance company, appears in three rows. This is done to illustrate the diverse activities, with diverse location requirements, that may be conducted by a single firm.

Each cell in the first three columns of the matrix contains three pieces of information. The first element is a rank (A, B, or C) that indicates, in descending order, the importance that firms place on the factor of that column when making location choices for the activity of that row. An "A" in Mega-Retail/Access to Customers shows that location is very important for such firms' access to their customers. A "C" for High-tech Manufacturing under Access to Customers shows that access to customers is relatively unimportant to firms when they select a location for that activity within an urban region.

The second element in the cell refers to the kind of urban district such an activity would be drawn to by the factor in question. "Indifferent" means a firm does not care what kind of urban district that activity is in, as far as that factor is concerned. The third element indicates types of links in the transportation network firms want such activities to be close to, as far as that factor is concerned. Again, "indifferent" indicates a firm does not care, with respect to that factor, about that activity's access to the transportation network.

Take, as an example, the cell for Heavy Manufacturing/Access to Supplies. "A" says that access to supplies is an important factor in choosing a location. "Indifferent" means the type of urban district does not matter for access to supplies. The last element tells us how the firm wants to connect its factory to the intercity network in order to receive supplies.

In the column dealing with cluster effects, the information in the cells simply indicates whether the effect operates for that type of activity and, if so, why. The information in the last two columns is presented in a similar way. The question posed in the column heading is answered, and the reason for the answer is given.

Access to Customers

The matrix clearly shows that access to customers does not necessarily mean physical proximity to customers' homes or work places. High-end retailers want to be in a district where high-income customers will come from some distance because there are other attractions for them in the district. This will mean location in the center and/or sub-

centers where there are similar high-end shops and other up-market amenities. A strong cluster effect operates here.

The mega-retailer, on the other hand, will avoid the high rents of the center and sub-centers. It does not need other shops to enhance its pulling power; all it needs is a place with good freeway access so its customers from middle to lower-middle income neighborhoods in the periphery and exurbia can reach it easily. And it needs low land rents for a big, one-story building and a big parking lot.

Auto dealers may be somewhat less sensitive to customer access when they choose a location. For many households, purchase of a car is a relatively infrequent event, and people expect to go some distance to visit a dealer, especially if they want to shop for the best buy.[4] Most auto dealers require a large amount of space, so they will seek sites on the periphery.

For activities serving customers in other metropolitan areas—"long-reach" activities—access to customers may drive them towards certain links in the transportation network but not to any particular type of urban district. This is the case for manufacturing facilities and "long-reach" warehouses shipping in truckload lots or larger. Access to inter-city highways with predictable (preferably low) congestion is key for these activities. Predictability of congestion is important for schedule reliability, a critical factor when shipping to a receiver with a just-in-time operation or to a receiver with a rigid system of arrival-time reservations for the loading dock. For facilities such as motor-vehicle assembly plants that ship high volumes and heavy loads, access to a rail line is likely to be essential.

For managers of a software manufacturing plant shipping boxes of diskettes, on the other hand, the only customer-access concern may be that the plant have access to a high level of service from a small-package carrier, such as UPS or Federal Express. Good access to an airport may also be important for such a facility. For activities of this type, the high quality, variety, and ubiquity of express services make customer access a relatively minor factor in location decisions.

Local distribution is different from long-reach distribution in that the warehouse has to be reasonably close to the customers. For the example we have selected, wholesale beverage distribution, many customers are downtown (hotels and restaurants). Even so, the distributor's warehouse is likely to be in a low-rent section of the periphery.

Firms providing services to the local market will want to be in places where their customers can come to them fairly easily or they can go to their customers. The example in the matrix is architecture and engineering services for local builders and developers. Most developers and builders are on the periphery and firms providing services to them will want to be there as well. For professional services of this character, both marketing

[4] Recent changes in auto retailing characteristics and consumer preferences make this section somewhat speculative. Factors that may make dealers *less* sensitive to customer access (and more sensitive to traffic volume) include the increasing reliability of automobiles and the decreasing frequency required for routine servicing. A factor that may make dealers *more* sensitive to customer access is the increase in dealer service options included in the sales price of new vehicles. These service options tend to increase consumer reliance on dealers as compared with other auto service providers, and thus tend to increase the importance of consumer access as a dealer location factor.

and delivery of services require fairly frequent face-to-face meetings, site visits, and the like. Similarly, law firms serving financial institutions are drawn towards the center or sub-center where their clients are clustered.

The diverse functions in a large insurance company comprise both long-reach and local activities. The matrix shows that customer access hardly matters for the headquarters office or for claims processing. Except where on-site inspection is required, access for claims processing is provided by telephone, fax, and e-mail. The headquarters office is concerned with corporate strategy, investing, and deal-making. The people there need never see a policy holder. A need to be near supplies of specialized services decision-makers at other financial institutions may draw the headquarters to the center, but not access to customers.

It is the sales force of the insurance company whose location will be influenced by customer access. As with other professional services, face-to-face contacts may be very important for marketing. Sales people (or agents) will be drawn to centers and sub-centers according to the markets they serve. Many other types of firms have a similar ability to separate activities spatially. Firms involved in financial services and information processing will often fit this pattern. Beyond that, any firm that has significant analytical or deal-making functions and routine information-processing work can separate these activities.

For customer access, physical proximity appears to matter most for retail firms that sell through stores and for professional-service providers for whom both marketing and delivery of services require a substantial amount of face-to-face interaction. But good highways allow a mega-retailer to serve all, or a large part, of an urban region from one peripheral location. And it should be noted that radial transit links, as well as good highways, can help a service provider work with downtown clients from a peripheral location. In the examples considered in the Activity-location Matrix, customer access draws activities to the center only in the case of high-end retail sales and some insurance sales.

Access to Labor

The influence of access to labor is dependent on the kind of skills required. The matrix shows a clear bifurcation in this regard. Activities that require high-skill, specialized workers, need to be accessible from high-income neighborhoods with good amenities. These include: high-tech manufacturing; architecture and engineering services; insurance company headquarters and insurance company sales.

For most other skill requirements, activities will be drawn to any point on the periphery where they can easily be reached by highway from middle income or lower-middle income neighborhoods. For most activities, being near a labor pool with the right mix of skills and wage requirements is a critical factor in a location decision. Access to labor is a location factor where some degree of physical proximity matters.

Very few activities can operate with an all-telecommuting work force. But the need to be somewhere near workers' dwellings does not, in most cases, pull activities towards the center or even necessarily to an urban region. Ability of some activities to move away from large population centers is related to the phenomenon of spatial separation of different activities of a firm. The senior executives and specialized professionals required for a head office may well pull headquarters to an urban region and possibly to the center. But the manufacturing and distribution activities of the same firm could be a thousand miles away, in a small city or a rural area. The feasibility of this kind of spatial separation is almost entirely due to improved telecommunications.

Access to Supplies

We see that access to supplies, while quite important for some activities, is rarely related to type of urban district but is very much related to access to particular links of the transportation network. Access to supplies matters for: mega-retail stores; manufacturing (but not high-tech manufacturing); and distribution. Need for good supply access, however, does not draw these activities to the center and may well not draw them to an urban region.

Services and high-tech manufacturing are not much affected by the flow of supplies. Once the computers have been delivered, the only inputs required for production of software, for example, is electricity and blank diskettes – and even these can be dispensed with if the software code is shipped electronically to a production site.

Other Factors

The matrix shows that the cluster effect is strong for some businesses, but does not necessarily pull them towards the center. Auto dealers may want to be near one another for customer-access reasons, but they will cluster somewhere on the periphery. Some cluster effects do pull towards the center; that associated with high-end retailing is one example. Activities that require specialized labor or special support services may also cluster.

The fifth column shows us that activities will shy away from the central cities unless very strong factors, generally related either to customer or labor access, draw them there. In part, this reflects that being in the center may not help them with customers or labor. It also reflects the effect of high land rents in the center. The high rents reflect, in turn, the fact that some activities find it immensely valuable to be in the center, so they bid up the rents in the dense core. Activities that do not find location in the center equally valuable are inevitably pushed away.

And, finally, there are some significant types of activity that can do without a city. The last column shows this is particularly true for manufacturing, warehouse, and distribution functions where customers are in other metropolitan areas, and special labor skills are not required. Being in an urban region does nothing for these activities in terms of customer access, and labor access requirements are of lesser relative importance. One key reason for this relative indifference to the customer and labor access attributes of different urban districts is that wherever these businesses locate, their greatest need is the ability to ship long distances quickly and reliably. As a result, an uncongested rural highway (not necessarily an Interstate) may be their optimal location. If their shipments are in small packages, any place in reach of UPS or Federal Express will do. If they do not require highly specialized labor, small towns and rural areas may provide them abundant labor at relatively low cost. The high-tech manufacturing firm, on the other hand, requires specialized labor, and this will drive it to cluster with similar firms in or near an urban region.

SUMMARY AND CONCLUSIONS

We see from this that the distinction between activities that are drawn by type of urban district and those drawn by particular links in the transportation network is an interesting one. This point is illustrated in the Sensitivity Matrix, shown on the following page. The two rows correspond to the A and B sensitivity rankings from the Activity-location Matrix. The matrix is restricted to the top two ranks, because we want to concentrate on the factors that are important to firms' managers. The columns are the same as the first three columns in the Activity-location Matrix. In each cell is the activity type associated with that sensitivity rank and location factor. For example, A/Access to Customers contains those activities where firms are highly sensitive to customer access when they choose locations.

The key information is in the brackets following each activity type. A "D" shows sensitivity to urban-district type; a "T" shows sensitivity to transportation links.

A number of observations may be made about this matrix. For customer access, urban district matters for activities whose customers are in the urban region, but not for activities whose customers are elsewhere. For access to supplies, urban district does not matter much; it is transportation links that count.

For labor, urban district always matters, given that an activity is in an urban region. Indeed, even the footloose manufacturing, warehouse, and distribution activities have to be some place where workers can reach them with a tolerable commute. This reflects the fact that people value their own time. They cannot be shipped long distances every day, and, for these kinds of activities, the work force has to be at the job site. They cannot sit at home and e-mail their output to the work site, as some workers, albeit a limited number, can do. This suggests that improvements in transportation and telecommunications have probably made the least change in access to labor.

The greatest changes are in access to customers. Some activities are free to locate almost anywhere, if they can utilize a non-specialist labor force and ship by small-package express. For those activities that do need the urban region for customer access, locations in sub-centers or the low-density periphery are frequently preferable to the center. Clearly, this is not always true; some activities require a presence in the center for customer access.

It is not clear that access to supplies has changed dramatically in the context of this analysis. It is generally true that the cost of freight transportation has come down and there have been significant quality improvements, in long-haul trucking and in some aspects of rail shipment. These improvements have made possible such developments as just-in-time deliveries; while beneficial to many firms, it is doubtful that this change has had much impact on location decisions. Taking together all improvements in freight movement, there is some effect in terms of shipment over longer distances, allowing some increase in spatial separation of factories and warehouses from suppliers. The greater effect on location of manufacturing and distribution facilities is the telecommunications improvements that have allowed activities in a firm to separate from one another in space.

Perhaps the biggest impact of changes in access is on the role of the traditional center. We have seen that many activities that were once located in the center for access to customers and labor, are now pushed by economic forces to sub-centers or the periphery, if not out of the urban region altogether. In effect, the center has ceased to be the effective nexus of the region in the sense of being the place for maximum access to the region. Indeed, there is no longer a single nexus in this sense. Depending on the nature of the activity, a point of maximum access might be anywhere on the periphery.

In no sense does this mean the traditional center is not the locus for a high level of economic activity. In many metropolitan areas it is and will continue to be; some major activities are attracted to centers and all sorts of support services along with them. But the old center can be a place full of economic activity and still not be the effective center of the region in terms of access to the rest of the region. Changes in the character, quality, and cost of access have unleashed economic forces such that a "center" no longer exists. Any decision-makers contemplating policies for affecting the future form of urban development have to recognize and understand these forces.

Implications of this new paradigm

In preparing this paper, we reviewed the written literature, developed an analytic framework to organize our thoughts, and generally spent time thinking about the topic of location and transportation. In the process we have developed some opinions about concepts which are rarely addressed head-on in the literature. These are not presented here as proven facts, but rather as theories that seem reasonable based on what we know about this complex topic. We hope they will both stimulate reactions and provide insights that might help shape future policies and provide general direction regarding applied research on sustainable development, sprawl, brownfields, and transportation planning in general.

Does location still matter? Yes, but probably less than it used to. This is not because of dramatic stories about Egghead Software closing all their stores and selling from a single website on the Internet or the talk about "virtual" companies with one employee who contract out all their functions and work from home. These businesses still have products that must be manufactured, packaged, and shipped someplace. What is widespread, however, is the much greater flexibility in where businesses locate.

Two powerful forces are at work here. First, technology (telecommunications in particular) makes it possible for different corporate functions to work together but from a longer distance. Second, the pace of change in business – and of course, life in general – means there are fewer rules about how business organizes itself. Management concepts such as just-in-time (JIT) inventories and reduced cycle times, combined with the need to become closer to the customer and to increase productivity, create a more flexible business structure. In this world, location still matters, but exactly how it matters can and does change with little notice. It should be noted that telecommunications improvements and JIT practices are not the only forces at work. However, they are powerful forces and serve to illustrate the point.

The implications for transportation planners and policy makers of these changes is not clear, but it does raise questions about policies based on more simple paradigms and models built on data when location was a more stable concept.[5]

Does access matter? Absolutely, but now it can be provided in several ways. While physical proximity still counts, other modes of access are coming into broad use. Indeed, the functions of transportation and telecommunication often seem to be part of a continuum providing similar services. This means that they both compete with each other as well as stimulate each other. Also, the definition of access is changing. Quality is at least as important as the traditional metrics of travel time and cost. The measures of a successful transportation system now should include quality measures as well as quantity. Indeed, travel time alone may be a misleading measure. Schedule reliability and damage to goods are two other important criteria.

[5] These implications apply primarily to traditional travel models that take land use characteristics as exogenous variables that remain unaffected by transportation network service levels.

SENSITIVITY MATRIX

Sensitivity Rank	Access to Customers	Access to Labor	Access to Supplies
A	Mega-retailers **[D,T]** High-end retailers **[D]** Light manufacturing **[T]** Heavy manufacturing **[T]** Long-reach distribution **[T]** Local high-skill services **[D,T]**	High-tech manufacturing **[D]** Long-reach high-skill services **[D]**	Mega-retailers **[T]** Light manufacturing **[T]** Heavy manufacturing **[T]** Long-reach distribution **[T]**
B	Auto sales **[D,T]** Local distribution **[D,T]**	Mega-retailers **[D,T]** Light manufacturing **[D,T]** Heavy manufacturing **[D,T]** Long-reach distribution **D,T]** Local high-skill services **[D]**	Local distribution **[T]**

LEGEND: Characters in brackets indicate whether sensitivity is to urban-district type [D], access to transportation network [T], or both.

Is transportation still important? Yes, and in many ways it is more important today than when we originally built our networks. But it matters most as a key input into an economy built on services and high-valued goods. Reliability in getting people and goods where they need to be and when they need to be there is key in a world where potential competition – as well as customers -- can appear from anyplace that has a phone connection.

In fact, private sector providers of transportation services are certainly more important than in the past. Just-in-time inventory methods integrate the physical movement of goods into the manufacturing process. When and how goods are delivered is a vital part of an efficient business. In some cases, transportation providers go beyond the mere movement of goods and provide maintenance and logistical services.

Does land use matter? Yes, but as in the discussion of location, in different ways than it did before. As business structures become less hierarchical and location more fluid, density itself has less of a clear economic benefit. Land use is certainly less fluid than business location, except perhaps on the urban fringe where both begin to merge. This raises questions about the power of land use controls as a policy tool and about how best to link land use and transportation.

Do cities matter? Certainly, even though the geographic center of cities matters much less than in the past while the urban fringe has increased in economic importance. Again, our review shows that density remains an important economic benefit for what appears to be a smaller portion of the economy. Brownfields may provide opportunities to revive center cities.

Does business type matter? Of course, but the definition of business needs to focus on activities versus the standard industrial classification (SIC) codes used to assemble most economic data. This is an important point, since much of our analytic work and our intuitive thinking about business may now be a bit off center. This problem is less serious in economic sectors such as agriculture and natural resources, but even heavy manufacturing now contracts out traditional functions. These means that what used to be seen as a single industry (and what much of our economic data still sees that way) is really numerous different businesses, each responding to its own set of market and economic forces. This, in turn, complicates our analytic efforts and is a major reason why location is less important.

Do transportation models still work? Yes, but probably less well than when our urban economies were denominated by the CBD and work trips seemed to be the most important transportation challenge.

Is research useful? Certainly, but a new approach is probably needed in order to develop policies that are effective in meeting some of the large-scale environmental and land use issues that we face – sustainable development, greenhouse gases, etc. – while also continuing to support long-term economic growth in the midst of a business sector in constant change.

Is policy still relevant? Yes, but many of the policy prescriptions that focus on land use as a way to shape demand for transportation should be re-examined in light of new insights regarding access and business activities. Seemingly straight-forward proposals such as changes in land use or urban growth boundaries may have unintended consequences. In sum, if it was ever in doubt before, we clearly live in a non-linear world.

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THE COSTS OF ALTERNATIVE LAND USE PATTERNS

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THE COSTS OF ALTERNATIVE LAND USE PATTERNS

1.0 INTRODUCTION

Transportation planning professionals today are being challenged not only to perfect their transportation plans, but also to put those plans into the larger context of community development. Just as transportation projects are subject to scrutiny for their costs and benefits, so are the community development plans of which these projects are a part.

This paper offers a way for planning professionals to think about this larger context. We introduce an accounting framework, which we believe offers planners and policymakers a summary of the costs and benefits associated with infrastructure investments, including but not limited to transportation. Costs include both public and private costs, and both capital and operating costs. Some of these may be denominated in dollars; others cannot.

In subsequent sections we describe in more detail a simple spreadsheet model which enables planners to estimate, track and summarized these types of costs. The growing interest on the part of planners and policymakers in sustainable development requires this type of accounting. This framework serves as an introduction to the subject.

We are not offering a completed, calibrated model, but rather an accounting framework within which such a model can be developed and calibrated. The spreadsheet software, available through FHWA and cited at the end of this paper, is only a point of departure for analysts; it is not ready to be used without careful review and meaningful enrichment. It does represent, however, a way for planners to understand much more completely the full set of costs and benefits associated with alternative forms of metropolitan development, and this understanding, we believe, will improve substantially the practice of metropolitan planning.

2.0 A FRAMEWORK FOR EVALUATION

Regional transportation and land use planners' get to general goals without much difficulty. Where they have problems is in the plan evaluation stage. They lack a framework for thinking about the impacts of policies.

This paper focuses on such a framework, one that is comprehensive (all significant benefits and costs are counted) and mutually exclusive (they are counted only once). It addresses such questions as: What are the impacts (benefits and costs) of alternative urban forms? What are the causal relationships among those impacts? How do public goals and policies about urban form interact with market forces?

Many of the costs of different urban forms can be measured by adding up the market costs of the resources the different forms of development use up. Supplying sewer and water to new residential development takes labor (planning, design, and construction), concrete, steel, machinery and so on. The costs can be added and expressed in dollars. Many of the benefits and costs of public projects, however, are ones not typically registered through market transactions. Some of these benefits and costs are not internalized in the prices paid for the goods and services needed to build and operate the project - for example, the costs of air pollution on people and property near highways where automobiles generate that pollution. Economists call such costs spill-overs or externalities, and argue that society should consider them in its evaluation of a project since they result in real gains or losses.

Without an acquaintance with the fundamental concepts and methodological issues associated with a full-cost framework, planners and policymakers will be unable to take the first steps towards a more comprehensive evaluation of alternative urban forms, and the policies and investments that cause them to occur. Some of the main concepts and issues include:

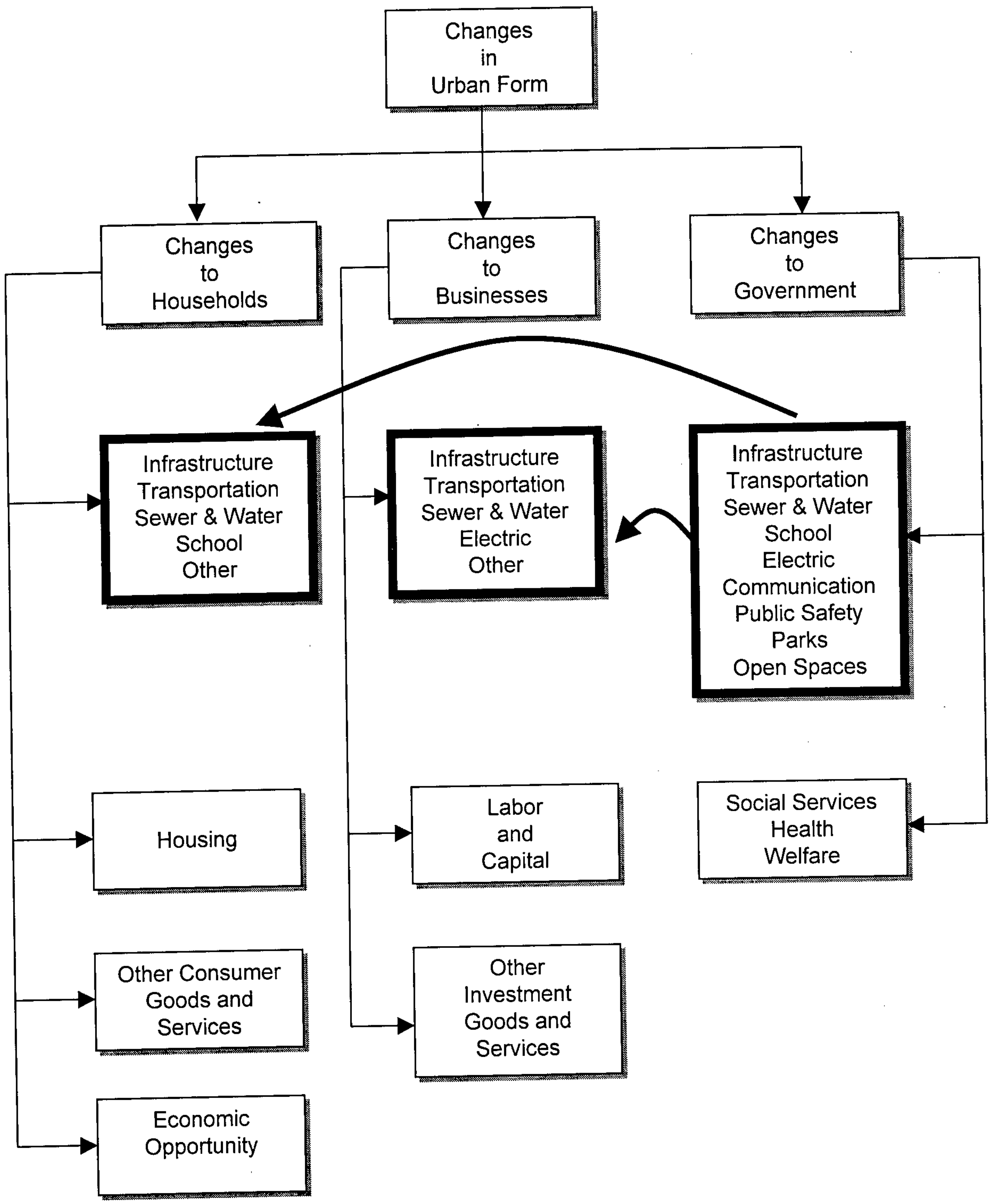
- *Costs are real economic resources used by a policy or project.*
- *Benefits are negative costs; costs are negative benefits.*
- *Benefits and costs must be defined in a way that is both comprehensive and mutually exclusive.*
- *Measuring all benefits and costs means considering some that do not have obvious market prices.*
- *A full-cost accounting framework must look at all impacts, both benefits and costs, that result from a defined change in the state of the world (in the case of this study, either a change in urban form or, more correctly, from a change in policy that attempts to change urban form).*
- *A full-cost accounting framework must consider all the people affected by the change. Many people may feel the change not just as residential consumers, but also in their capacities as employees of businesses and government.*

These points lead to a number of frameworks, including that shown in Figure 1 for analyzing the impacts of alternative development patterns.

Figure 1 shows our assumption that the main effects of a change in form should be captured through changes in the costs of providing infrastructure services. As the title of Figure 1 implies, an important and defensible assumption is that the effect of urban form on households, businesses, and governments occurs mainly through a derived demand for infrastructure, an intermediate good.

Our operating assumption is that the impact of changes in urban form on the cost of infrastructure is probably the single most important impact to evaluate. That approach, with infrastructure as the sole concern, does not cover everything, either technically or politically. However, as a reasonable basis for an accounting framework, Figure 1 is appropriate and useful.

Figure 1: Markets Where Policies to Change Urban Form are Likely to Have Direct (Internalized) Effects on Prices



2.1 *A PROTOTYPE ACCOUNTING MODEL*

How might we convert this framework into a model which planners and policymakers can use in metropolitan planning? The balance of this paper contains the organization and implementation of such a prototype model, for estimating the Full Social Cost of Alternative Land Development Scenarios (SCALDS) at the regional level. The model has been developed by Parsons Brinckerhoff Quade & Douglas, Inc. using software that is commonly available to most Metropolitan Planning Organizations (MPO), the computer spreadsheet (EXCEL). The prototype model consists of 18 interconnected spreadsheets, which produce an aggregate estimate of the full costs of regional land use scenarios.

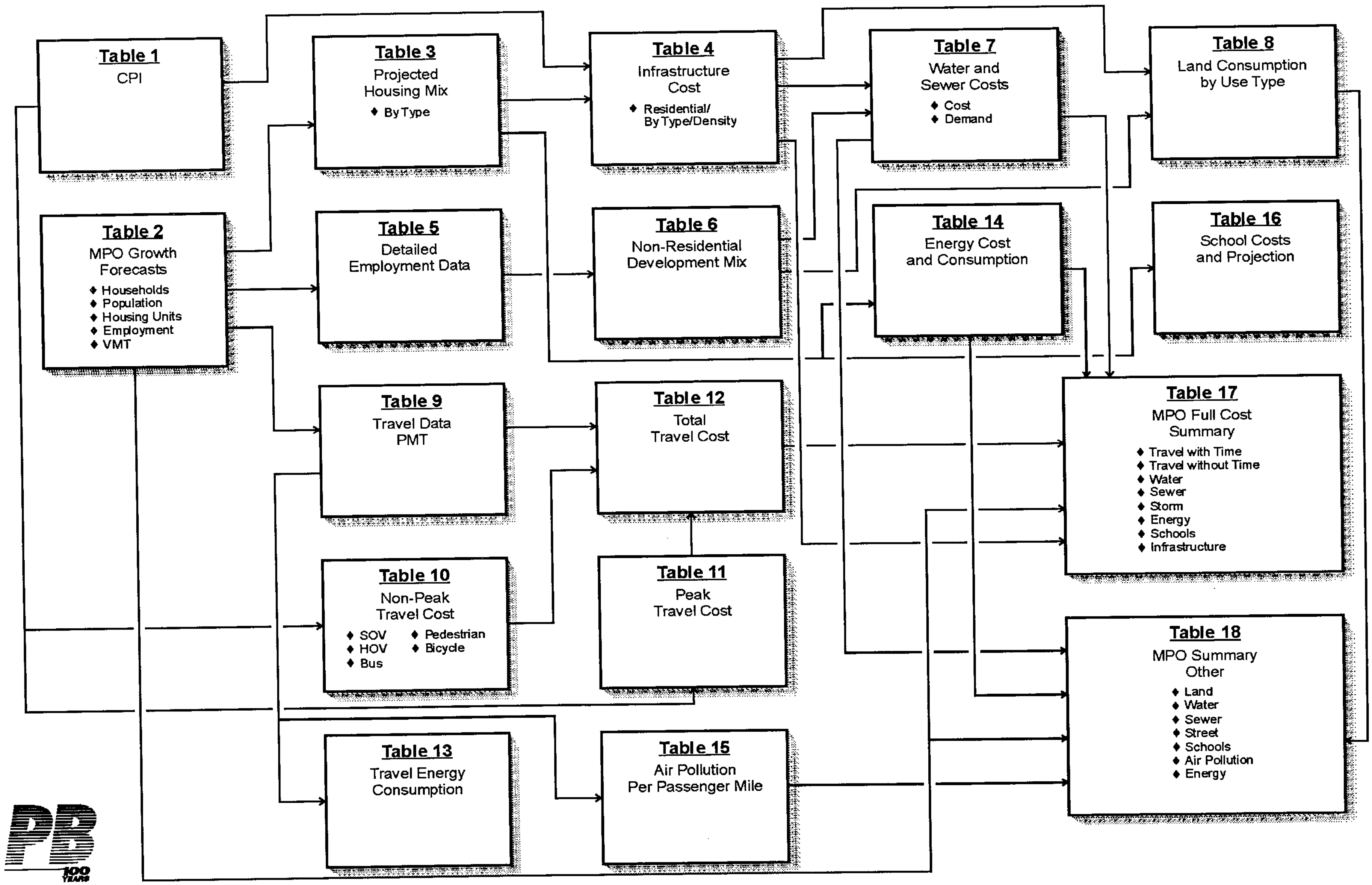
This model builds on three components, which we consider to be essential to a full cost framework that has potential for practical application. First, this model pays particular attention to infrastructure costs, since these are the costs with which many citizens and elected officials are most familiar. Secondly, it acknowledges both public and private costs. (While an ideal framework would further differentiate private costs into those borne by businesses and consumers, this model affords opportunities for further development in these directions at a future date.) Third, it deals with both internal and external costs, with external costs being accounted for through several elements of the model.

The development of alternative land use scenarios requires that the MPO have several copies of the spreadsheet files, each named for the scenario that it estimates. The individual scenario files need to be appropriately modified so that they will calculate the cost of the alternative land use pattern based on the appropriate modifications of model variables. To compare the relative cost of two or more scenarios, it is necessary to summarize the results from these two files outside the model process.

The SCALDS Model is not intended to be the definitive solution or the cookbook for estimating costs, but a guide to how a metropolitan area might approach this project. Additional tables can be added and local cost factors substituted for the national averages used in several situations. One approach to starting the modeling process is to estimate a full cost base scenario using the default national cost estimates. Then additional scenarios can be developed, possibly using selected local costs if available.

The SCALDS Model has three general calculation paths. (See Figure 2) The physical development path (Tables 3 through 8) models the consumption of land, the projected mixture of new housing units, the local infrastructure cost and annual operating cost of services for sewers, water and storm water services. It is also possible to project the average amount of non- residential building space needed to support new development. The total travel cost path (Tables 9 through 12) models the annual operating cost of peak and non-peak travel on a passenger miles traveled (PMT) basis.

Figure 2: Full Cost of Alternative Land Use Model Schematic



The third path (Tables 10 through 16) models the air pollution produced by transport mode, the energy consumption by transportation and the energy consumed by residential land use in non-dollar units. The residential energy consumption contains a factor that approximates the non-residential energy consumption. This path also estimates the cost of the energy consumed by transport and residential land use. However the transport related energy costs are not carried forward to the summary Tables 17 and 18 because this cost has already been included in the model elsewhere.

Finally, the third path has an illustrative table, number 16, that shows a short term projection of the increase in new students from the construction of new housing units. This table estimates the marginal change in the number of school age children and the marginal change in school operating cost. The results from this table are not carried forward to the summary tables because the marginal cost change estimates are only good for the short run. In order to get a good estimate of these projected changes in school age children and school operating cost it will be necessary to undertake a separate modeling process outside of the SCALDS Model framework and then add the results of this process back into the SCALDS Model.

The balance of this paper is devoted principally to an explanation of each of the steps or elements in the model.

2.2 *DEMOGRAPHICS IN THE SCALDS MODEL: SOME CAVEATS*

The SCALDS Model is not designed to show the demographic variations that occur within sub-areas of a metropolitan area and which can produce jurisdictional or sub-area variations in the estimated full cost of development. The estimation of sub-area or jurisdictional marginal costs needs to approached more rigorously than the estimation of MPO level estimates.

The population of a metropolitan area as a whole has distinct age/sex/household size characteristics that do not change in response to policy variables such as the projected mixture of housing unit types. On the contrary, the mixture of new housing units constructed is directly related to the demographics of the population purchasing or renting new housing units.

The model itself does not forecast changing demographic patterns over time. If a metropolitan area expects a major or systematic shift in regional demographic patterns to occur during the forecasting period, exogenous adjustment should be made to the model inputs to reflect the predicted changes, and these adjustments should be well documented. An alternative approach to this problem would be to estimate the full cost of development using constant demographic patterns and then estimate the cost making the anticipated changes in the region's demographic patterns. This will allow the analyst to approximate the impact of the change in cost.

A good population forecast is an invaluable resource for the SCALDS Model. It allows the analyst to make informed adjustments to policy variables, such as the new housing mix, which affect the total cost of development in a metropolitan area. In the same vein, good inventories of the existing developed environment improve the overall operation of the model. However, the analyst should remember that it is possible to make changes in the housing mix that mathematically implies changes to the age structure of the population or the average household size in the region. The demographic pattern of the region is not changed by simply changing the mixture of new housing types built in the region. Therefore the analyst should adjust the mix of new housing units within the context of the expected average household size and projected rate of household formation.

MPO's have a substantial body of research that they can draw on to modify the unit costs used in the SCALDS Model or to enhance the model by adding new cost calculation modules to the Model. MPO's also have access to large amounts of data from the US Census, various state agencies, city and county governments. Data sources are numerous. We have incorporated data from many different sources in the Model. MPOs have the option to carry this process further and adapt the SCALDS Model to more closely match local conditions.

3.0 DESCRIPTION OF MODEL ELEMENTS

All the elements of the SCALDS Model are shown in Figure 2. Further, the links between the different elements are diagrammed. Figure 2 should be a quick guide or "road map" to the discussion, which follows.

3.1 CONSUMER PRICE INDEX - TABLE 1

The starting point for the SCALDS Model is Table 1 – Consumer Price Index (CPI). The Model uses default cost data from a number of different years to estimate the cost of alternative land use patterns. It is, therefore, necessary to adjust the costs used in the model to remove the effects of inflation. This is done by means of an inflator factor or deflator factor, which adjusts the costs taken from different national studies to base year dollars. The Base Year is the year (1995) that is used as the base in the analysis. The default cost in the model has been adjusted to base year of 1995. If an analyst wishes to use a different base year for the value of money, it will be necessary to deflate or inflate the cost in various portions of the spreadsheet model to the new base year.

The CPI used in the model is the Consumer Price Index for All Urban Consumers for All Goods. This index was chosen because it is a general national indicator of inflation and it smoothes out local economic fluctuations. The CPI shown in Table 1 is from January of each year. The CPI contains a unique CPI factor for each month in the year. A CPI for a different month could be substituted if this meets some other MPO criteria. The CPI for All Urban Consumers for all Goods (1982-1984=100) is available from the Bureau of Labor Statistics on their web site *(http://stats.bls.gov/cgi-bin/surveymost - Series ID CUUR0000SA0).* This site contains the CPI on a monthly basis for the time periods from 1913 to present.

Indexing costs from different years to the base year is done using the following equation. In this example the base year is 1995 and the original year or the year of the cost estimate is 1987.

$$\text{Base Year Cost 1995} = \text{Original Year Cost 1987} * \left(\frac{\text{Base Year CPI 1995}}{\text{Original Year CPI 1987}}\right)$$

There are a few options available for adjusting costs to base year values. A metropolitan area could elect to use one of the other forms of the CPI such as the Engineering News Record material price index which is very good for forecasting capital intensive infrastructure cost. Other cost indexes exist but none of them address overall issues of inflation in urban cost as well as the CPI.

The CPI requires very little effort on the part of the MPO in terms of data maintenance. It can be updated as necessary by down loading the newest data from BLS. This is only necessary if the MPO wishes to use a cost data estimated for a year for which the MPO does not currently have a CPI factor. The other possible use of the CPI is to move all of the costs in the Model to a new base year such as 1997. The MPO simply needs to insure that it has adjusted each of the costs described in the following sections from its original year costs to the new base year cost to accomplish this transition.

CPI cost adjustments are not made automatically in the prototype model. It is necessary to apply the cost indices to data from the base year cost used by an MPO.

3.2 MPO GROWTH FORECASTS – TABLE 2

The MPO Growth Forecast is a key portion of the SCALDS Model. All of the remaining spreadsheets in the model are linked directly or indirectly to the data entered into this table and all of the cost estimates flow from these projections.

Table 2 contains much of the basic planning data that a metropolitan area develops during the normal course of creating a transportation-planning model for an urban area. These data are developed exogenously or outside of the SCALDS Model and are brought into the model by the MPO. All of the data are aggregated at the MPO level. This aggregation can mask local or sub-regional demographic changes, trends and differences.

The data needed to fill this table can be divided into the following general categories:

- Total Population and related aggregate factors such as average household size for the MPO.
- Total Number of Housing Units, the MPO average vacancy rate and the MPO multifamily / single family housing split.
- Total MPO employment and the retail / non-retail employment split.
- Total Vehicle Miles Traveled (VMT) – VMT is needed for some portions of the travel costing modules such as the Federal/State Highway Investment portion of total travel cost. Travel costs, however, are modeled on a Passenger Mile Traveled basis in most portions of the model.
- Road system summary data at the MPO level including a factor to estimate the consumption of land for the road right of way.

Housing and population data used by the Model is expected to be at about the same level of generalized detail as the data that is maintained by the MPO. It is particularly important to have an accurate inventory of the existing building stock by type before making projections of future growth. There is little that can be done to substantially change the nature of the existing housing stock in the short run. It is also unlikely that new development will completely change the nature of the housing stock during a twenty-year planning period. The existing housing stock, like existing demographic patterns, is a given in the modeling process. New development and new growth create only marginal changes in both population and housing.

The Model allows the analyst to divide the projected housing stock into several categories by building type. These categories facilitate the estimation of different costs of development associated with different land use patterns. The categories are one of the areas where local government policy can influence the nature of development and the full cost of development. The ability of the model to estimate the cost of development depends in large part on the data supplied to it in these modules.

NOTE: The use of different housing stock types in this model is for convenience in the calculation of aggregate, regional impacts. Because different types of housing stock have been linked with different types of costs, it is convenient and appropriate for use in the aggregate level of analysis. However, use at a sub-regional or local level is likely to be misleading or wrong for several reasons. First, local costs vary within regions. Secondly, since housing stock is a supply variable (not a demand in itself), it is not possible to vary regional costs by varying the regional housing stock. While local policies governing housing type, density and amenities may affect the demographic characteristics of local or neighborhood residents, at the regional level differences disappear; the forces that control regional demographic changes are not influenced (and certainly not influenced easily) by manipulating housing unit size or the number of bedrooms.

It is appropriate to note again that the population forecasts used in the model are summary forecasts that show general trends, such as a decline in average household size. The model assumes that any demographic trends that are occurring in the metropolitan area population are occurring outside the model process and will not be affected by the model's assumptions (e.g., about housing stock).

Data for this model is available from the MPO itself, and from secondary data sources such as the US Census (population and housing), the state employment agency (ES202 files on covered employment), local planning agencies on land areas, housing units, miles of street etc. It is likely that most of this information exists in a metropolitan area. But the MPO may need to invest considerable effort in the process of gathering, inventorying, classifying and organizing the available data, if this process has not already been accomplished. The MPO should establish a standardized set of databases based on relatively stable geographic boundaries such as census tracts. It is important to have agreements with local governments on the continuous collection of the data on new development. While it is a problem to constantly maintain databases, it is harder to rebuild them from scratch whenever it is necessary to undertake a new study. Attention to database design and maintenance is one of the best long-run investments that an agency can make.

3.3 *PROJECTED HOUSING MIX - TABLE 3*

This table contains the detailed housing mix for the region that is the basis for residential infrastructure cost and land consumption. The table is an elaboration of the basic housing data added to the model in Table 2.

The model will work with a housing mix that designates housing units only as single family or multifamily. However, the model will provide a significantly better estimate of the cost of a particular land use pattern if it has a more detailed mixed of housing unit types and densities to work with.

The accurate and detailed inventory of the existing housing stock is also a key component used in several other tables to estimate regional operating costs. If local data on the housing mix in the metropolitan area is not readily available, a good place to start looking for data is the decennial census of housing. Local government building permit data is also a valuable source of data on the changes that have occurred since the last census.

Data on the details of the housing mix can be obtained from the decennial census (1990 Census of Housing) and from city and county building permit data. An additional distribution of housing type has been estimated from the Public Urban Microdata Sample for a metropolitan area. Local homebuilder organizations may be able to provide some additional detailed information on the composition of new single family housing construction trends.

Numerous national studies have reviewed the cost of development by housing type and logically concluded that the cost of development and the infrastructure required to support a particular type of development is directly related to the density of development and the type of unit constructed. The different studies produce different estimates of the cost per unit depending on the assumptions and the details of the cost included in the analysis. The costs used in the SCALDS Model are taken from a study by the Urban Land Institute that is cited in the discussion on Table 4.

There are two elaborations of the SCALDS Model, which could be developed and connected to the model through the housing mix data in Table 3. The first elaboration is the estimation of the cost of new residential construction associated with different land development patterns. To estimate the cost of new construction it would be necessary to develop construction average costs per square foot or per unit for each type of housing. If average cost per square foot is used, then it is necessary to also estimate the average size of the new units constructed.

NOTE: The types of new housing units constructed and their size is going to be driven by the demographics of the purchasers and renters of new housing. For example an urban area which is experiencing a significant in-migration of retired couples will not contain many new single family houses with three or more bedrooms.

A second elaboration could involve estimating the number of housing units needed by number of bedrooms per unit. This is a variation on the cost of housing because the more bedrooms in a housing unit, the larger and more costly the unit. This type of analysis would again be directly linked to a detailed demographic forecast that is exogenous to the SCALDS Model. Such a forecast would provide a more detailed picture of the projected housing need and would be more sensitive to the demographics of the future urban population. But this type of forecast needs to be the subject of additional research before a clear methodology is available to add to this model.

NOTE: The model does not address housing price issues (relationships between supply, demand and price) or any issue related to the income distribution of the existing or future population of a metropolitan area. While these issues are important they are also too complex to be addressed in a basic model like the SCALDS Model.

3.4 *INFRASTRUCTURE COST BY HOUSING TYPE – TABLE 4*

This table estimates the cost of infrastructure associated with residential construction. The construction of new local government infrastructure in most urban areas is focused in developing residential areas. Substantial portions of the annual expenditures for new streets, sewers, water line and storm drainage facilities are made by the development community during the land development process. It is difficult to estimate the average expenditures for infrastructure per new housing unit by structure type using local data because these expenditures are not normally made directly by local governments; but if good local records are available, a metropolitan area may wish to estimate the cost of this infrastructure based on local information. The SCALDS Model uses average costs for infrastructure by housing unit type. Table 4, Columns C and D, contain cost factors that express the differences in development costs associated with compact development and leapfrog development. Columns E and F contain additional costs associated with development located some distance from major infrastructure facilities such as sewer trunk lines or water transmission mains. At the MPO level these variations in cost are difficult to use. They will be more useful in future model extension at the subregional level.

NOTE: The MPO using the SCALDS Model needs to review the infrastructure cost estimates for the low density and very low density single family residential uses. It is not uncommon for these land uses to be developed using septic tank instead of public sewer, and wells instead of public water facilities. The model does not currently contain an estimate of the capital cost of installing these private systems. If this type of development is commonly supported by private infrastructure such as wells or septic tanks, a metropolitan area should obtain estimates of the average cost for the installation of these systems from installers of these systems who work in and around the urban area, and use those estimate for the average capital cost of this form of development. Operational cost of these services (wells and septic tanks) also differs from the operating cost of water service in Table 7, and thus it should be estimated based on local well and septic tank service costs.

The best sources of local data on the cost of infrastructure related to local residential development is city and county planning and engineering offices. These records should provide an estimate of how much infrastructure was installed with each new residential development. If there are large variations in the cost estimates for these improvements, the MPO could collect the data on the quantity of materials used by type and estimate the cost of the infrastructure using the cost factors found in the ENR (Engineering News Record). These cost estimates are updated continually and provide a third party source for determining the cost of infrastructure.

The collection and maintenance of data on infrastructure cost can be a relatively formidable task in an urban area. One method to collect and maintain this type of data is creation of a GIS based facilities management system. The maps and data bases developed as part of such a system are a valuable resource to the local water, sewer and storm water service providers and a good source of basic planning data at the MPO level. The development of a cooperative or intergovernmental GIS system can help spread the cost of developing and maintaining a GIS. The collection of data is not adequate justification by itself for the cost and effort that is required to create a GIS system. It is merely another use of the data that can be developed from this type of system.

3.5 DETAILED EMPLOYMENT DATA – TABLE 5

This table is a more detailed presentation of the regional employment projections, which are the basis for non-residential land consumption and water and sewer demand estimates.

These data are all developed locally by the MPO. The economic growth of the urban area is the driving force behind overall regional growth. Historic data in this table is available from a variety of sources including the US Census, County Business Patterns, and state data on covered employment (ES 202 file). Projected employment is available from the Bureau of Economic Analysis. These data sources are all good starting points for a metropolitan area employment forecast.

This particular data set does not lend itself to local maintenance of data. The one exception is site level data from the ES 202 files. MPO's may be able to obtain these data, subject to agreements on confidentiality. The ES 202 files commonly require some level of data clean up and geocoding before they are usable by a metropolitan area. The ES 202 file commonly has data on about 90 percent of the employment in an urban area. If a MPO decides to use these data it should be updated at regular intervals such as annually, biannually or every 5 years in order to provide time series data for future employment projections.

3.6 NON RESIDENTIAL DEVELOPMENT MIX – TABLE 6

This table converts the employment by sector into building area and land area needed to support development. The conversion factors for this process vary a great deal from industry to industry. There are no definitive national data for these estimated ratios.

The process of converting employment to building area demand and land area demand will benefit from the use of local data. However this information can be difficult to obtain locally. If there is a local GIS system that has building size data by parcel, and parcel data, the MPO could geocode firm-level employment data from the ES 202 file in order to obtain local building and land demand ratios. Time series employment data and building areas would allow the tracking of these demand ratios over time and could show long term change in the demand for land and building space by industry group. The other approach that could be used is a survey of existing employers. The main drawback to the survey approach is the fact that the data is only good for one point in time.

Vacancy rates were not used in the model. They will increase the amount of building space demand and the amount of land consumed. This should be done during any local elaboration of the SCALDS Model.

3.7 WATER AND SEWER COSTS – TABLE 7

This table estimates the demand for water and sewer service and the cost of water, sewer and storm water services for the urban area. A number of the issues related to infrastructure cost and availability were previously discussed during the discussion on Table 4.

NOTE: Water and sewer demand calculations need to be reviewed for very low density and low density residential. These residential areas may not be served by public water and/or sewer systems in the MPO area.

Non-residential water and sewer demand do not include water and sewer demands for industrial processes and as such these estimates are lower than the expected demand from non-residential uses. The industrial process demand for water and sewer services varies greatly for non-residential uses such as food processing, microprocessor manufacturing, restaurants, hotels, offices etc.

3.8 LAND CONSUMPTION BY TYPE – TABLE 8

This table marks the end of the physical development path in the SCALDS Model. From here the Model is linked to Summary Tables 17 and 18. It begins the travel cost path in Table 9.

Land consumption forecasts are based on the data in two tables, Table 3 (Housing Mix) and Table 6 (Non-Residential Development Mix). The calculation of residential land consumption is very simple. The number of units is multiplied by the density of units per acre to estimate the residential land consumption. Table 6 contains a calculation of the number of employees per gross acre. The demand for non-residential land is estimated by dividing the total employment by the number of employees per acre.

Acres are gross acres that include the area for any public rights of way. If a metropolitan area wishes to change the land area basis to net acres (acres less public rights of way) it will be necessary to recalculate the density factors used in the Model.

The one type of land use which is not estimated directly by this model is public land. These lands include schools, parks, public buildings and public open spaces. A place holder number has been put into the model for this type of land use. Private non-profit uses such as churches, private schools, fraternal and civic organizations are not explicitly addressed by the model. They are assumed to be in the non-residential land uses based on the employment, but the Model probably underestimates them. The MPO should develop an estimate of the amount of land consumed by public uses and put it into the Model under the other land category. This process could also include the estimation of the amount of private nonprofit lands consumed in the urban area.

3.9 TRAVEL DATA – PERSON MILES OF TRAVEL - TABLE 9

This table is the beginning of the travel cost path in the SCALDS Model and is linked back to Table 2 in order to estimate the total number of person trips at the regional level.

The total number of person trips is derived from the total number of households and the average number of trips per household. Total number of trips are allocated to individual modes based on the percentage of trips made by vehicle type. Total daily person miles traveled is then calculated by multiplying the total number of trips by their average trip length. Finally, annual personal miles traveled are estimated by multiplying the daily total by 330. The result is a calculated annual and daily estimate of person or passenger miles traveled by mode.

An MPO with an up-to-date travel forecasting model or local travel data will use these local data instead of nationally estimated values. Model runs can produce better estimates of differences in trip lengths and mode shares for alternative land development scenarios. The MPO may wish to use locally derived per-capita and/or per-household trip estimates and local mode split data to derive the data in these tables.

*3.10 TRAVEL COST (NON PEAK) - TABLE 10 [1]
TRAVEL COST (PEAK) - TABLE 11
TOTAL TRAVEL COST - TABLE 12*

These three tables are the heart of the travel cost-estimating path in the SCALDS Model. Tables 10 and 11 contain the estimate of the cost per passenger mile for peak and off-peak travel by all modes except truck. (Truck costs are assumed to be the same as bus cost for this initial analysis). Table 12 is the table in which the number of miles traveled and the cost per mile are combined to produce a total travel cost estimate.

The data used to estimate the cost of transportation is not generally available at the MPO level. MPO's do not need to maintain these data but do need to know where to look for updates of national cost numbers. MPO's do need to maintain information on basic transportation measures such as annual average vehicle miles traveled and average vehicle occupancy at the regional level if they wish to use numbers that reflect local trends rather than national trends.

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[1] All travel costs used by the prototype model were developed for Boulder Colorado. MPOs using the prototype model should consider the appropriateness of these costs for their environment. It is our intent to extend this model in future work to provide a mechanism to calculate local travel costs based in part on the data from local travel demand models.

3.10.1 Depreciation and Financing Costs

Vehicle depreciation was estimated using the following equations.

$$\text{SOV \& HOV Costs} = \frac{\left(\frac{(\text{Annual Finance Cost} + \text{Annual Depreciation Cost})}{\text{Average Annual VMT}}\right)}{\text{Vehicle Occupancy}}$$

$$\text{Bicycle Cost} = \frac{\left(\frac{(\text{Purchase Cost} - \text{Resale Value})}{\text{Vehicle Life}}\right)}{\text{Average Annual VMT}}$$

$$\text{Pedestrian Cost} = \frac{\text{Average Shoe Cost}}{\text{Average Shoe Life in Miles}}$$

3.10.2 Vehicle Insurance Cost

Insurance cost estimates were developed for single occupancy vehicles and high occupancy vehicles. No insurance costs were estimated for bicycle and pedestrian travel because this type of insurance is generally not available. Insurance costs for truck and buses were not estimated.

$$\text{SOV \& HOV Costs} = \frac{\left(\frac{\text{Annual Insurance Cost}}{\text{Average Annual VMT}}\right)}{\text{Vehicle Occupancy}}$$

3.10.3 Registration and Licensing [2]

Registration and licensing costs are expected to vary on a state by state basis. Each MPO needs to determine the registration and licensing cost for its own state. Truck and bus registration and licensing costs should also be estimated and added to the Model. These fees are more complex than auto registration fees and will require more knowledge of the composition of the local truck and bus fleet and their registration costs.

$$\text{SOV \& HOV Costs} = \frac{\left(\frac{\text{Annual Registration Fees}}{\text{Average Annual VMT}}\right)}{\text{Vehicle Occupancy}}$$

$$\text{Bicycle Cost} = \frac{\text{Annual Registration Fee}}{\text{Average Annual VMT}}$$

2 Registration Fees included in this cost factor are the portion of fees not used to fund construction or maintenance projects.

3.10.4 Gasoline Cost

Gasoline costs are among the most visible of the costs paid by the drivers of cars. In addition, these costs can and do change frequently during the course of a year. Differences in fuel economy can produce substantial variation in the cost of fuel consumed by an individual. The gasoline costs used in the model were derived from national average costs in order to represent an overall average. If local gasoline prices are consistently higher or lower than the national average cost for gasoline, the MPO may wish to adjust this cost estimate.

$$\text{SOV \& HOV Costs} = \frac{\left(\left(\frac{1}{\text{Fuel Economy MPG}}\right) * \text{Fuel Cost per Gallon}\right)}{\text{Vehicle Occupancy}}$$

3.10.5 Maintenance Cost

Vehicle maintenance costs are subject to considerable variation in a metropolitan area. Some of this variance is the result of personal preferences and some of it is the result of the characteristics of the vehicles in the urban area. Accordingly, national cost estimates were used for this variable. Truck and bus maintenance costs were not estimated or included in the Model.

$$\text{SOV \& HOV Costs} = \frac{\left(\frac{\text{Annual Maintenance Costs}}{\text{Average Annual VMT}}\right)}{\text{Vehicle Occupancy}}$$

$$\text{Bicycle Cost} = \frac{\text{Annual Maintenance Cost}}{\text{Average Annual VMT}}$$

3.10.6 Transit Fares

Transit fares are set by local governing bodies and are normally set at a level that is intended to provide the transit provider with a percentage of the total transit operating budget. The amount of the transit system budget that is collected from the fare box varies substantially from urban area to urban area. This cost should be revised by the MPO to account for local conditions. The local transit agency should be able to provide the other necessary data needed to estimate this cost.

$$\text{Transit Fare} = \frac{\text{Total Annual Fares}}{\text{Total Annual Passenger Miles}}$$

3.10.7 Residential Parking Cost [3]

The estimation of residential parking cost will require the collection of a large amount of local data. These data also are sensitive to fluctuations in the type and amount of local development and local cost variations. Several alternative cost estimation methodologies are possible. A more complex formulation of this methodology would estimate these costs using an arithmetic moving average of costs to allow for year to year variations. However, all of the alternative methodologies substantially increase the complexity of the cost estimation process with no assurances of a better estimate of the costs. MPOs will need to work with city and county building departments and with county assessors to estimate this cost locally.

$$\text{SOV \& HOV Costs} = \frac{\left(\dfrac{\left(\left(\begin{matrix}\text{Number}\\ \text{Garages}\\ \text{Constructed}\end{matrix}\right) * \left(\left(\begin{matrix}\text{Land}\\ \text{Value}\end{matrix}\right) + \left(\begin{matrix}\text{Construction}\\ \text{Cost}\end{matrix}\right)\right)\right) * \left(\left(\begin{matrix}\text{Number}\\ \text{Surface}\\ \text{Parking}\\ \text{Spaces}\end{matrix}\right) * \left(\left(\begin{matrix}\text{Land}\\ \text{Value}\end{matrix}\right) + \left(\begin{matrix}\text{Construction}\\ \text{Cost}\end{matrix}\right)\right)\right)}{\text{Annual VMT}}\right)}{\text{Vehicle Occupancy}}$$

3.10.8 Non-Residential Parking Cost User Paid

Non-residential parking costs that are paid by the user are out-of-pocket costs. These costs are normally paid by users that park in a small portion of an urban area. Parking costs are most common in central business districts. There are no good national sources for these data. The data must be developed locally. There will be variations in the cost of on-street paid parking and off-street paid parking depending on variations in public policy and local market conditions. An MPO will need to develop a methodology for collecting and maintaining these data. The cost estimated by the following equation will produce a regional average cost. This will however understate the cost for those individuals actually paying for parking and overstate the cost for those individuals who never pay for parking.

$$\text{SOV \& HOV Costs} = \frac{\left(\dfrac{\text{Annual User Parking Cost}}{\text{Annual VMT}}\right)}{\text{Vehicle Occupancy}}$$

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[3] Parking costs are derived for Boulder Colorado using local data. Future extensions of the prototype model will provide a method for calculating these cost directly. This may result in the creation of a single parking cost category to replace the three cost categories presently used in the prototype model. Users of the model should carefully evaluate the parking cost estimates produced by different land use scenarios.

3.10.9 Non-Residential Parking Cost – Societal Costs

This cost includes the cost of all of the non-residential "free" off street parking spaces in an urban area. This cost estimate adds the average cost paid by business and industry to provide free parking to their customers and employees. The methodology used in this calculation might be improved through the use of an arithmetic moving average, but this type of a process would require substantially more data collection and maintenance.

$$\text{SOV \& HOV Costs} = \frac{\left(\dfrac{\left(\text{New Non Residential Spaces Constructed}\right) * \left(\left(\text{Land Value}\right) + \left(\text{Construction Cost}\right)\right) + \left(\text{Number Existing Non Residential Parking Spaces}\right) * \left(\text{Annual Maintenance Costs}\right)}{\text{Annual VMT}}\right)}{\text{Vehicle Occupancy}}$$

3.10.10 Accident Costs Not Covered by Insurance

Estimating accident cost from local data is a difficult process at best. Our SCALDS Model uses national data to estimate these costs and MPO's should consider sticking with the national and state level data when estimating these costs. The costs estimated by this formula do not include the costs previously attributed to insurance (3.10.2).

$$\text{All Modes} = \left(\left(\left(\text{Fatal Accident Rate}\right) * \text{PMT}\right) * \left(\text{Fatal Accident Cost}\right) + \left(\left(\text{Injury Accident Rate}\right) * \text{PMT}\right) * \left(\text{Injury Accident Cost}\right) + \left(\left(\text{Property Damage Only Accident Rate}\right) * \text{PMT}\right) * \left(\text{Property Damage Only Accident Cost}\right)\right) * \left(\text{Share of Accident Cost Burden}\right)$$

3.10.11 Travel Time

The key element in estimating the cost of travel is determining the value of time. This cost is normally assumed to be a percentage of the average wage in an urban area. If local data is not available, the US Bureau of Labor Statistics has an average for most urban areas. Average costs are calculated for each mode using the mode's individual travel speed and the value of time.

$$\text{All Mode Costs} = \left(\frac{1}{\text{Speed MPH}}\right) * \text{Value of Time}$$

3.10.12 Federal /State Highway Investment

Federal and state capital cost and operating expenditures per VMT are estimated at the state level due to limitations of the available data. In our model the amount of state and federal gas taxes is deducted from the total expenditures because gas taxes are included in the model under the section on gasoline costs. This deduction removes a potential double counting of costs.

Cost factors are used for each mode to reflect the magnitude of the damage done to the transportation infrastructure by each of the travel modes. The result is a weighted estimate of the highway operating and capital cost by mode.

$$\text{All Mode Cost} = \frac{\left(\left(\frac{\text{Fed State Capital Costs}}{\text{VMT}}\right) * \left(\text{Vehicle Cost Factor}\right)\right) + \left(\left(\frac{\text{Fed State Operating Costs}}{\text{VMT}}\right) * \left(\text{Vehicle Cost Factor}\right)\right) - \left(\text{Federal State Gas Tax}\right)}{\text{Vehicle Occupancy}}$$

The vehicle cost factors used in this process, representing the relative damage caused by individual vehicle by mode, are as follows:

Mode	Capital Expenditures	Maintenance
SOV/HOV	0.683	0.719
Transit Bus	1.810	3.420
Bicycle	0.034	0.014

3.10.13 Municipal Services

There are a few municipal development costs that have not already be accounted for directly or indirectly in previous tables. Public safety is one of these costs. In Boulder, the portion of the public safety budget that was directly related to traffic and travel was estimated using the following equation.

$$\text{SOV \& HOV Costs} = \frac{\left(\frac{\begin{pmatrix}\text{Annual}\\\text{Police}\\\text{Budget}\end{pmatrix} * \begin{pmatrix}\%\\\text{Trans}\\\text{Calls}\end{pmatrix}}{\text{Annual VMT}}\right) + \left(\frac{\begin{pmatrix}\text{Annual}\\\text{EMS}\\\text{Budget}\end{pmatrix} * \begin{pmatrix}\%\\\text{Trans}\\\text{Calls}\end{pmatrix}}{\text{Annual VMT}}\right) + \left(\frac{\begin{pmatrix}\text{Annual}\\\text{Court}\\\text{Budget}\end{pmatrix} * \begin{pmatrix}\%\\\text{Trans}\\\text{Cases}\end{pmatrix}}{\text{Annual VMT}}\right)}{\text{Vehicle Occupancy}}$$

MPO's will need to work with local governments to obtain the cost estimates included in this equation. Once a budget allocation process has been developed, it should be relatively easy for the MPO update this information as needed. Additional research into local, state and federal expenditures should be undertaken to insure that all of the appropriate governmental costs have been include in this model.

3.10.14 Government Net Transit Costs (Total Cost – Fare Box Revenues)

This cost variable was developed to estimate the transit costs that are not paid for by transit fares. The methodology for estimating this cost is relatively simple. However, depending on the source of the revenue that supports these operational costs, additional analysis may be required to insure that no double counting of cost has occurred.

The estimation of this operational cost leaves only one transit cost that may not have been included in the SCALDS Model - transit capital cost. Transit capital cost can vary greatly from year to year and the normal problems related to the timing of construction. These capital costs are a candidate for the use of an arithmetic moving average methodology or some other methodology that explicitly works with variations in expenditures / cost over time.

$$\text{Net Transit Cost} = \left(\frac{\left(\begin{pmatrix}\text{Total}\\\text{Transit}\\\text{Costs}\end{pmatrix} - \begin{pmatrix}\text{Transit}\\\text{Fares}\end{pmatrix}\right)}{\text{Annual Transit Passenger Miles}}\right) * \begin{pmatrix}\text{Peak}\\\text{NonPeak}\\\text{Adjustment}\\\text{Factor}\end{pmatrix}$$

3.10.15 Deferred Maintenance Cost [4]

This estimated cost is an attempt to capture an often hidden cost associated with development. State and local infrastructure maintenance often does not keep up with growth. It is not uncommon in an urban area to find places where development has occurred and existing infrastructure is not maintained to standards, due to the demands placed on state and local governments to expand facilities rather than facilities maintenance. Most urban areas have an estimate of the order of magnitude of this deferred maintenance cost.

The data needed to estimate these costs are normally available from local governments and normally include estimates of the number of years that maintenance is expected to remain unfunded given the current level of available resources. A cost allocation factor is used to allocate the unfunded need to individual modes This methodology provides a minimum estimate of the deferred cost. MPOs should estimate this cost for the local urban area when implementing the SCALDS Model.

$$\text{Total Vehicle Cost} = \frac{\left(\left(\frac{\left(\frac{\text{Local Unfunded Maintenance Need}}{\text{Years of Need}}\right)}{\text{Local Annual VMT}}\right) + \left(\frac{\left(\frac{\text{State Unfunded Maintenance Need}}{\text{Years of Need}}\right)}{\text{State Annual VMT}}\right)\right) * \left(\text{Cost Allocation Factor}\right)}{\text{Average Vehicle Occupancy}}$$

4 The authors recommend that the MPO estimate the deferred maintenance cost of the existing road system and substitute this cost for the 1to 2 cents per passenger mile included in the model to avoid any double counting of costs. This estimate should not include capital costs of projects, since cost of delay associated with congestion are already included in Tables 10 and 11.

$$\text{Pedestrian Cost} = \frac{\left(\frac{\text{Unfunded Need}}{\text{Years of Need}}\right)}{\text{Pedestrian VMT}}$$

3.10.16 Air Pollution Cost

Air pollution costs are one of several transportation externalities that have been studied extensively during the last two decades. Substantial data on the cost of air and other forms of pollution can be obtained from separate work recently completed by Litman (1995) and Mark Delucchi (1996) on the social costs of transportation. The methodology used in the SCALDS Model is expressed in the following equation.

$$\text{Vehicle Cost} = \frac{(\text{Emissions Per Vehicle Mile} * \text{Cost of Pollutant Per Gram})}{\text{Vehicle Occupancy}}$$

A metropolitan area can use a different formulation of this equation but it will still need to rely on the various national estimates of the external cost of pollution in order to calculate the costs.

3.11 TRAVEL ENERGY CONSUMPTION – TABLE 13

The cost of energy is included in the estimates of peak and non-peak travel cost in Tables 10 and 11. The non-dollar-denominated estimates of energy consumed directly by transportation are estimated in this table. The energy consumption data is derived from the information in National Transportation Statistics, 1996, Tables 105, 106, and 107. The total annual energy usage is calculated in a straightforward manner using the estimated total passenger miles by vehicle type as derived in Table 9. Estimated energy consumption can be converted into gallons of fuel consumed by using the factor in the table if a metropolitan area needs this information.

The total energy consumption is calculated in this table; it accounts for approximately 7 percent of total travel cost excluding the value of time. However, while the total energy consumption is calculated here for illustrative purposes, they are not passed on to the cost summary in Table 17 in order to avoid double counting of costs.

3.12 ENERGY COST AND CONSUMPTION – TABLE 14

Table 14 estimates the cost of energy and the amount of energy consumed by urban land uses. The energy consumption estimates include all the energy consumed by all land uses in an urban area. These estimates do not include any industrial process energy used by large energy consumptive industries such as aluminum smelters.

The energy consumption estimates in this table are derived from an approach used in the "Place^{3}s" model the US Department of Energy. The energy consumption numbers are derived by modifying the values presented in the report, The Energy Yardstick, Allen (1996). The energy consumption values in the DOE report were modified to remove energy consumption associated with transportation. The result is an approximation of the energy consumed by various residential land use types.

The Place^{3}s energy consumption methodology is a first generation effort. It is probable a more complete integration of the Place^{3}s methodology and the SCALDS Model could be accomplished after some additional study of the operational details of the two models.

It is possible for a metropolitan area to use the Place^{3}s model to develop estimates of energy consumption at a regional level. These estimates can be maintained over time and entered into the SCALDS Model exogenously. Cost estimates can be converted to the base year for the SCALDS Model using the CPI factors.

The Place^{3}s data was derived from the report by Allen, Elliot, Michael McKeever and Jeff Mithcum, (1996) The Energy Yardstick: Using Place^{3}s to Create More Sustainable Communities, DE-FG49-94R900027, Salem, Oregon, Oregon Department of Energy.

3.13 AIR POLLUTION PER PASSENGER MILE - TABLE 15 [5]

The cost of air pollution is included in the estimates of peak and non-peak travel cost in Tables 10 and 11. The non-dollar cost estimates of air pollution produced directly by transportation is estimated in this table. The pollution estimates are denoted in tons of pollutant per year.

There are other models that can be used by a metropolitan area to estimate the amount of air pollution produced by traffic in an urban area outside the SCALDS Model framework. If the MPO wishes to use one of these models, the resulting estimates can be entered into the SCALDS Model exogenously. The alternative is to use the average air pollution per passenger mile figures from this table to estimate the total level of air pollution.

3.14 SCHOOLS COSTS AND PROJECTION – TABLE 16

Table 16 is included in the SCALDS Model as a placeholder. At this point in time, the cost estimates and estimates of the number of new students produced in this table is not connected to the cost and non cost summaries in Table 17 and 18. Table 16 estimates average number of new pupils and average education costs.

NOTE: This type of estimate performs well only for short term, local projections of growth because it is based on two assumptions. First, the demographics of an urban area will not change very much in the short term (less than 5 years). Second, the

5 The air pollution production rates used in this table are taken from a study by the Greater Vancouver (BC) Regional Council. In subsequent enhancements, we will replace this data with other values.

number of students that will be generated from a particular type of housing unit will be the same as recently generated from existing housing units of the same type.

Over time it is necessary to use a different model - cohort survival - to estimate the number of school children at a regional level. This model takes into account changes in the demographic patterns of the region and provides better long-term estimates of the number of students that are expected regionally.

MPO analysts need to take care when using new households to estimate the number of school age children. It is possible for the analyst to make changes in the housing mix that mathematically would appear to change the number of school age children. However this is not the case in reality. The demographics of the region are not changed by changing the housing mix. The analyst should adjust the mix of new housing units within the context of the expected average household size and projected rate of household formation.

The MPO needs to adjust these figures to match local conditions. The cost factors used in this prototype model are the average cost for students in the State of Oregon in 1995. The number of school age children per unit is taken from Burchell (1997a), page IV – 2, estimated from 1990 US Census PUMS data for new non-central city housing in Michigan. While these numbers are a starting point for the SCALDS Model they cannot be expected to produce good estimates when applied to demographically different situations. A metropolitan area can choose to use projections from a local school district, instead of using this type of projection factor, to develop the data exogenously and then enter it into the Model.

One area of further analysis that would improve the operation of this model would be an estimation of the number of school age children by housing unit type by number of bedrooms. These ratios should perform better in the short term than a simple number of students per household. However, to use these data it is necessary to have better data on the composition of the housing stock. These data will require more effort to collect and more effort to maintain. If this type of data is available, the SCALDS Model can be easily be modified to allow the estimations to be made by using these more detailed data.

4.0 SAMPLE MODEL APPLICATION

In the previous section we have explained the elements of our SCALDS Model, their relationships, the sources of data on which they are based and in some cases the limitations of application. In this section and the associated tables we present the results of several sample applications of the SCALDS Model.

Because this model is in the very preliminary stages of development, the results of the simulations presented below are merely illustrations of order of magnitude impact estimates. They indicate the general direction and magnitude of changes that can be expected in various costs, and the distribution of these costs.

Since the sources of data used in this sample application come from a variety of national as well as local sources, they represent in many cases "placeholders" for more accurate parameters, to be furnished by metropolitan area planners.

4.1 SUMMARY TABLES – TABLE 17 AND 18

Tables 17 and 18 contain the summaries of the cost and non-cost estimates developed in the preceding sixteen tables of the SCALDS Model. These two tables can be used to develop scenario comparisons such as the ones contained in the following examples. The scenarios are intended to be illustrative and not a definitive analysis of the cost of alternative land use patterns in any one metropolitan area.

The two scenarios presented are identified as Metro Regional Plan and Metro Sprawl. The only differences in these two spreadsheets are the number of single family housing units assigned to the Conventional SFD / Small Lot SFD and a small difference in the average trip length for auto trips to reflect the differing densities of the new single family housing areas.

The creation of these scenarios began with two copies of the same set of spreadsheets containing the data for the Metro Regional Plan scenario. The spreadsheet for the Metro Sprawl Scenario was then modified by shifting single family residences from the small lot single family land use type to the conventional single family land use type and by making a small increase in average trip length for the SOV and HOV vehicle types. The scenario costs were then compared and are shown in the Table below.

Total Annual Scenario Cost by Year

Year 1990 Base Year	**Metro Regional Plan**	**Metro Sprawl**	**Difference (Sprawl – Plan)**
1995 5 Model Years	$7,833,550,569	$9,010,519,641	***$1,176,969,073***
2005 15 Model Years	$9,594,617,050	$11,069,634,947	***$1,475,017,897***
2015 25 Model Years	$11,540,873,445	$13,322,601,691	***$1,781,728,246***
Change 1995 to 2015	***$3,707,322,876***	***$4,312,082,050***	

It is apparent that the lower density development pattern has higher operating costs, in excess of $1 Billion per year, after the first five year time period. These cost differences increase to nearly $2 Billion per year by 2015. A more complete comparison of the cost estimates for the scenarios are presented in the following Figures 3 and 4, for three illustrative years.

4.2 ADAPTING THE PROTOTYPE MODEL FOR YOUR MPO

For this model to be useful to an MPO it must be adapted to reflect the conditions in the local urban area. The process is straightforward for experienced spreadsheet users. The first step is to make a copy of the spreadsheet and enter the basic data needed by the prototype model. These data include historic and projected values at the MPO level for population, number of households, single family / multifamily household split, total employment, retail / non-retail employment split and projected travel (Table 2). It also includes detailed housing mix (Table 3) and employment at the two digit SIC level (Table 5). When these data are entered, an analyst is ready to begin the cost estimation process.

The next step is to determine the base year for the analysis and to manually adjust all cost variables to the new base year cost. Policy variables that are adjustable in the prototype model are identified by the gray shading in a cell. These cells should be adjusted to reflect the present conditions in the MPO. All other cells are protected and cannot be changed. Constructing scenarios from existing conditions is a matter of making a copy of the existing condition file and then making adjustments to the policy variable cells. By comparing the results of the two spreadsheets, as depicted in Tables 17 and 18, the analyst will be able to examine the relative costs of the two scenarios that have been created.

Figure 3: Annual Cost Summary: Metro Regional Plan Scenario

COST SUMARY	1995	2005	2015
Annual Full Cost of Transportation - Without the Value of Time	$4,357,448,808	$5,373,106,876	$6,563,069,023
Total Annual Water Costs	$543,776,669	$669,106,720	$799,205,555
Total Annual Sewer Costs	$551,749,657	$679,942,299	$813,527,620
Total Annual Storm Water Costs	$55,174,766	$67,994,029	$81,352,561
Annual Non-Transportation Energy Cost	$2,325,400,669	$2,804,467,127	$3,283,718,686
Total Annual Costs	**$7,833,550,569**	**$9,594,617,050**	**$11,540,873,445**

NON COST SUMMARY	1995	2005	2015
Population	1,596,100	1,920,264	2,205,800
Households	627,937	774,300	917,000
Housing Units	642,380	792,109	938,091
Total Employment	988,915	1,228,500	1,486,600
Total Developed Land in Acres	299,842	340,398	382,841
Water Demand - Gallons / Day	129,470,160	159,310,646	190,286,557
Sewer Demand - Gallons per Day	99,621,106	122,766,997	146,886,568

Figure 4: Summary: Metro Sprawl Scenario

COST SUMMARY	1995	2005	2015
Annual Full Cost of Transportation - Without the Value of Time	$5,520,271,497	$6,806,966,654	$8,272,657,946
Total Annual Water Costs	$543,776,669	$669,106,720	$799,205,555
Total Annual Sewer Costs	$551,749,657	$679,942,299	$813,527,620
Total Annual Storm Water Costs	$55,174,766	$67,994,029	$81,352,561
Annual Non-Transportation Energy Cost	$2,339,547,053	$2,845,625,245	$3,355,858,010
Total Annual Costs	**$9,010,519,641**	**$11,069,634,947**	**$13,322,601,691**

NON COST SUMMARY	1995	2005	2015
Population	1,596,100	1,920,264	2,205,800
Households	627,937	774,300	917,000
Housing Units	642,380	792,109	938,091
Total Employment	988,915	1,228,500	1,486,600
Total Developed Urban Land in Acres	307,779	361,789	419,091
Water Demand - Gallons / Day	129,470,160	159,310,646	190,286,557
Sewer Demand - Gallons per Day	99,621,106	122,766,997	146,886,568

5.0 SUMMARY AND CONCLUSIONS

In this paper we describe in some detail a set of costs (and, by definition, benefits) associated with alternative forms of metropolitan development. We suggest that planners engaged in infrastructure evaluation view public (and private) infrastructure investments in a context which enables them to examine not only the capital, but also the operating costs; not only costs faced by government but also the costs paid by others; not only today's costs but also long run costs, including those external costs which must be accounted for in any comprehensive evaluation.

Those wishing more information on the methods for estimating costs in these spreadsheets should consult the full report from which this summary is taken. Entitled "The Full Social Costs of Alternative Land Use Patterns," the report can be found on the Internet at http://www.ota.fhwa.dot.gov/scalds/. In addition the user may obtain there a copy of the spreadsheets, as well as instructions for their calibration.

For further information on related work sponsored by FHWA, readers may contact: Patrick DeCorla-Souza of the Federal Highway Administration, Metropolitan Planning Division, 400 Seventh Street SW, Washington, D.C., (202) 366-4076.

Those seeking to apply this accounting framework must review carefully the assumptions contained in it. For results to be useful, planners must commit to a process of data collection and model calibration, using local inputs rather than relying on generalized estimates such those embedded in the spreadsheets in their current form.

FHWA is proposing to support additional modifications and refinements to this framework. These enhancements may focus on improving estimation of costs related to transportation and making them consistent with procedures used in FHWA's STEAM software. (For more information on STEAM, see the STEAM web site at http://www.ota.fhwa.dot.gov/steam/). Also, the calculation paths for other utilities, energy and land consumption are rudimentary. In addition, since successful use of this framework requires additional instructional material, FHWA may support the development of a user's handbook. Lastly, since many citizens, elected officials and staff are looking to apply these concepts at a smaller geographic scale than that developed to date, FHWA may support enhancements for that purpose as well.

The authors hope through this paper to contribute to the ongoing dialogue concerning the best ways to plan for the communities in which we live, and the costs and benefits that define quality of life there.

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Using *STEAM* For Benefit-Cost Analysis Of Transportation Alternatives

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1.0 INTRODUCTION

The Intermodal Surface Transportation Efficiency Act (ISTEA) emphasizes assessment of multimodal alternatives and demand management strategies. This emphasis has increased the need for planners to provide useful comparative information to decision makers with regard to proposed alternative transportation solutions. Benefit-cost analysis is a useful tool to compare the economic worth of alternatives and evaluate trade-offs between economic benefits and non-monetizable social and environmental impacts.

In 1995, the Federal Highway Administration (FHWA) developed a corridor sketch planning tool called the Sketch Planning Analysis Spreadsheet Model (SPASM) to assist planners in developing the type of economic efficiency and other evaluative information needed for comparing cross-modal and demand management strategies (1). When more detailed analysis is required, however, SPASM cannot be used directly, owing to several simplifying assumptions. For example, all trips are assumed to be of an average trip length, made between the two ends of the corridor. Also, it is difficult to use SPASM for systemwide analysis. To allow more *detailed* corridor analysis and to facilitate systemwide analysis, FHWA has developed an enhanced version of SPASM, called the Surface Transportation Efficiency Analysis Model (STEAM).

2.0 OVERVIEW OF STEAM

There are several significant improvements in STEAM. First, the software accepts input directly from the four-step travel demand modeling process or from off-model software such as FHWA's Travel Demand Management (TDM) software (2). Second, it post-processes traffic assignment outputs from conventional four-step planning models in order to more accurately estimate highway travel speeds under congested conditions. Third, it performs risk analysis to clearly describe the level of uncertainty in the analysis results, thereby minimizing the potential for unproductive technical controversy over unit monetary values or impact estimates. Finally, STEAM produces estimates of *systemwide* impact; i.e, impact estimation is not limited to the improvement corridor.

The software is based on the principles of economic analysis, and allows development of monetized impact estimates for a wide range of transportation investments and policies, including major capital projects, pricing, and travel demand management (TDM). Impact measures are monetized to the extent feasible, and quantitative estimates of natural resource usage (e.g., energy consumption) and environmental impacts (e.g., pollutant emissions) are also provided. Decision makers can then use net monetary benefits (or costs) of alternatives as computed by STEAM to evaluate trade-offs against non-monetizable impacts.

STEAM is highly flexible in terms of the transportation modes, trip purposes, and time periods analyzed. It provides default analysis parameters for seven modes (auto, truck, carpool, local bus, express bus, light rail, and heavy rail) and allows the user to accomodate special circumstances or new modes by modifying these parameters. Different trip purposes can be analyzed separately by the model. Also, STEAM can be applied using average weekday travel inputs or, alternatively, using separate peak and off-peak travel inputs.

As shown on the right side of Figure 1, STEAM consists of four modules:

1. A *User Interface Module*, which includes on-line help files.

2. A *Network Analysis Module*, which reads a file containing highway traffic volumes, segment lengths, capacities, and other link data and produces zone-to-zone travel times and distances based on minimum time paths through the highway network.

3. A *Trip Table Analysis Module*, which produces estimates of user benefits based on a comparison of Base Case and Improvement Case travel times and out-of-pocket costs for each zone-to-zone trip interchange for a given forecast year. It also produces estimates of pollutant emissions, noise costs, accident costs, energy consumption, and other external costs associated with highway use.

4. An *Evaluation Summary Module*, which calculates net present worth and a benefit-cost ratio for the improvement under consideration. It also provides summary information on individual benefit and cost items, and probability distributions of several performance measures based on a risk analysis.

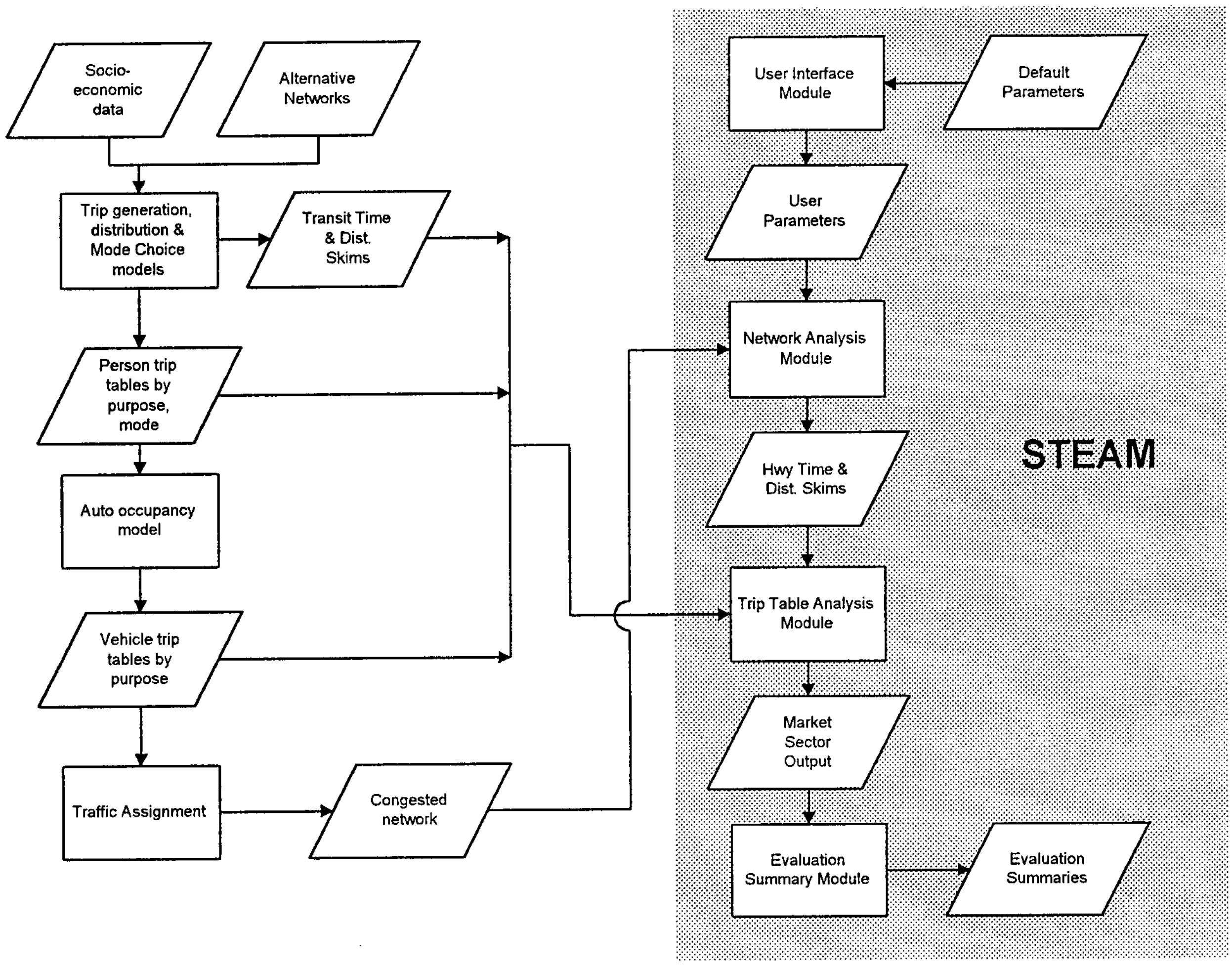
3.0 CASE STUDY ANALYSIS

A real-world test of the software was performed using case study data from a western U.S. urban area, which is being called Any City in this paper to maintain its anonymity. An evaluation of transportation alternatives was performed for the Central Freeway corridor in Any City. In this section, the alternatives and procedures used to develop the needed input data for STEAM are described. In section 4.0, impact analysis procedures embedded in the software are discussed, and results of STEAM's impact analysis are presented. In section 5.0, STEAM's economic efficiency analysis procedures are discussed, and results from the economic efficiency analysis are presented. Section 6.0 discusses current limitations of the software and planned enhancements.

3.1 Corridor Alternatives

The limits of the case study corridor were defined by the interchanges of Central Freeway with the beltway loop north and south of the city. The corridor is about 12 miles in length. Currently, traffic in the corridor exceeds capacities in many locations, causing significant peak period delays. Significant growth is expected in the Any City region, and in the corridor in particular. Population in the corridor is anticipated to increase by more than 100% while employment is estimated to increase by more than 140% over the next 20 years. Traffic on Central Freeway in the southern portion of the corridor is expected to double.

Figure 1. Overview of Analysis Procedures



For the purpose of demonstrating the application of the software, three corridor alternatives were analyzed:

- *"No-Build" alternative*: This alternative included all new capacity projects in the region's Long Range Transportation Plan, except for Central Freeway improvements. A planned light rail line in the Central Freeway corridor was included.

- *"Build" alternative*: This alternative involved the widening of Central Freeway to include two additional mixed-flow travel lanes in each direction. The section of Central Freeway to be expanded currently has 6 lanes, 3 in each direction.

- *"TDM/Tolls" alternative*: This alternative primarily involved introduction of a $1.00 toll to be collected on Central Freeway through automated collection techniques at both ends of the corridor (i.e., at each of the two beltway interchanges), and at all entrance ramps within the corridor. No highway capacity improvements were included. A 25% increase in both bus and light rail service was included, to handle increases in transit demand due to auto users "tolled off" the freeway.

3.2 Developing STEAM Inputs from Demand Models

STEAM accepts as input the following output from the four-step travel demand modeling process: (1) person trip tables for passenger travel and vehicle trip tables for truck travel; (2) travel time and cost matrices skimmed from transit networks and (optionally) from highway networks; and (3) loaded highway network output from traffic assignment.

Travel demand model outputs for the two action alternatives and the No-Build alternative were obtained from runs of the four-step travel demand models developed by Any City planners. The models were run using Any City's 2015 Transportation Plan and its 2015 socio-economic forecasts for the region. For the TDM alternative, the No-Build highway network was re-coded to reflect an in-vehicle time penalty equivalent to the toll. The demand modeling procedures are presented graphically on the left side of Figure 1. Both trip table and loaded highway network outputs were obtained for a 24-hour time period. The transit time and cost skims reflected peak period service.

3.3 Defining Market Sectors

Market sectors for use in STEAM analysis may be defined by trip mode, purpose, and time of day. Since the Any City models produced daily demand estimates, market sectors were defined only by trip mode and purpose. The travel demand models provided *person trip tables by mode* (auto, bus, walk-accessed light rail and drive-accessed light rail) for the following four internal trip purposes: Home-based (HB) work, HB non-work, HB college, and Non-HB. For HB work person trips, an additional mode, i.e. "Carpool" was estimated by the models. Additionally, *vehicle trip tables* were provided by the models for the following three trip purposes: internal truck, internal-external, and through. Since internal-external and through trips include both passenger and truck travel, the first step would be to break down trip tables for each of these two purposes into auto and truck modes. For Any City, the truck share of these trips was unknown, so all trips were assumed to be auto mode trips.

Executing STEAM using Any City trip tables could potentially require running (for the "daily" time period) each of 22 purpose/mode market sectors identified by an "X" in the upper part of Table 1. To reduce the number of market sectors to be analyzed, the seven trip purposes (shown in the first column of the table) were collapsed into two: (1) a passenger travel purpose and (2) a commercial (truck) purpose; i.e., all non-truck trip purposes were combined into a single "passenger travel" category, for which the same values of time and other STEAM parameters could be applied irrespective of the actual trip purpose. The resulting market sectors are indicated by an "X" in the lower part of Table 1.

TABLE 1 Market Sectors for Any City

A. Potential Market Sectors

Trip Purpose	Auto mode	Carpool	Bus	Walk-to-Light Rail	Drive-to-Light Rail	Truck
HB work	X	X	X	X	X	
HB college	X		X	X	X	
HB non-work	X		X	X	X	
NHB	X		X	X	X	
Internal truck						X
Internal-external	X					potential
Through	X					potential

B. Combined Market Sectors

Trip Category	Auto mode	Carpool	Bus	Walk-to-Light Rail	Drive-to-Light Rail	Truck
Personal travel	X	X	X	X	X	
Internal truck						X

3.4 Developing Market Sector Inputs

Highway Mode Inputs: Auto-occupancies needed as input into STEAM for the passenger travel auto and carpool modes were obtained by dividing the sum of regionwide person trips by the sum of vehicle trips for each mode (using output from the four-step demand models). While STEAM can estimate vehicle operating costs based on internally generated zone-to-zone highway distance skims, the user must provide "out-of-pocket cost" skims reflecting tolls for zone-to-zone travel. For the TDM alternative, toll skims were obtained using the demand modeling software. First, a select-link analysis was done to identify zone-to-zone vehicle trip interchanges subjected to tolls, and the number of vehicle trips for each zone-to-zone interchange actually choosing the toll route. For each trip interchange, these trips were divided by trips from the total vehicle trip table to get the proportion of zone-to-zone vehicle trips actually paying tolls. Average out-of-pocket cost per vehicle for each zone-to-zone interchange was obtained by multiplying the vehicle toll by the proportion of vehicle trips paying the toll. The average out-of-pocket cost per vehicle was then divided by auto-occupancy in order to generate a skim table of average out-of-pocket cost per person for input into STEAM.

Non-Highway Mode Inputs: For the non-highway passenger travel modes (bus and rail), STEAM inputs for average occupancies were estimated from passenger count data. STEAM cannot generate travel time skims for non-highway modes. Travel time "skim" tables as well as out-of-pocket cost tables must be obtained for input into STEAM using output from the demand models. For Any City, the in-vehicle travel time skims generated by the demand models were used directly as input into STEAM. The Any City models also generated walk time skims and wait time skims. These were summed by origin-destination pair to get "out-of-vehicle" travel time skims needed for input into STEAM. Additionally, the Any City models generated out-of-pocket cost skims (in cents) based on transit fares. These were directly input into STEAM.

4.0 IMPACT ANALYSIS PROCEDURES

This section discusses the speed estimation procedures used in the Network Analysis Module, procedures used in the Trip Table Analysis Module to estimate emissions and energy consumption impacts, and the analysis results produced by STEAM for the Central Freeway corridor in Any City.

4.1 Estimating Travel Speed

Users can format input network files to include link speeds which STEAM can use directly. As an option, STEAM can estimate travel speeds based on procedures which relate average weekday traffic-to-capacity ratios (AWDT/C) to average hourly delay and speed (3). The procedures incorporate the dynamic effects of queuing and peak-spreading which are not considered when conventional Highway Capacity Manual (HCM) procedures are used with assigned traffic volumes. Additionally, the procedures account for day-to-day variations in traffic. The relationship between delays due to congestion and traffic volumes are highly non-linear, especially when demand volume-to-capacity is close to 1.0. Hence, by explicitly accounting for day-to-day variations in traffic volumes, the model estimates speeds more accurately than if uniform daily volumes are assumed. The procedures also take into account delays due to incidents, using data on the frequency, severity, and duration of incidents compiled by Ball State

Engineering (4). Accounting for incident delays in economic analysis of transportation actions is important because incidents account for a large share of total travel delays due to congestion, especially on freeways. Failure to include the effects of incidents could grossly understate the benefits of transportation actions that reduce congestion.

To develop these speed relationships, hour-by-hour traffic for typical facilities was first estimated based on the flattening of the diurnal distribution of traffic that occurs in response to increasing levels of congestion at higher AWDT/C ratios. Monte Carlo simulation of traffic volumes was used to reflect day-to-day variations in traffic volumes. The hour-by-hour traffic estimates were then used to obtain hour-by-hour estimates of congestion delay using the traffic microsimulation models FRESIM and NETSIM (5). The speed relationships thus account for spreading of traffic from congested time periods to uncongested time periods, queuing impacts on traffic speeds in succesive hours, day-to-day variations in traffic volumes, and incidents.

4.2 Emissions Analysis

The conventional link-based emissions analysis approach cannot easily be used to estimate the changes in cold start emissions that may result from demand management actions. STEAM therefore uses a trip based approach to estimate emissions (6). In STEAM, emissions for autos, trucks and carpools are calculated as the sum of: (1) emissions due to vehicle miles of travel (VMT), calculated under the assumption that vehicles are already warmed up, i.e., in either the hot-start mode or hot-stabilized mode; and (2) added emissions due to cold starts. Non-cold start emissions are calculated using emission rates as a function of speed. The added emissions due to cold starts are calculated on a per vehicle trip basis. STEAM allows the user to specify the fraction of vehicle trips starting cold; national defaults are provided from recent research (7).

Default emission rates in STEAM for non-cold-start operations were calculated using MOBILE5A by setting the cold start VMT fraction equal to zero, the hot start VMT fraction equal to 0.479 and the stabilized VMT fraction equal to 0.521. The default emission rate due to each cold start in STEAM was calculated by subtracting the gram per mile value (at 26 mph) under hot start conditions from the gram per mile value (also at 26 mph) under cold start conditions, and multiplying the result by 3.59 miles.

4.3 Fuel Consumption and Greenhouse Gas Emissions

Increases or decreases in use of motor fuel are estimated by STEAM by vehicle type (auto and truck) as a function of average speed for each trip interchange, using fleet average fuel consumption rates (8). STEAM calculates changes in greenhouse gas emissions using carbon dioxide (CO_2) emission rates per gallon of motor fuel consumed (9).

4.4 Impacts of Case Study Alternatives

Table 2 summarizes travel demand estimates by mode for the entire region, obtained from Any City travel demand models. Auto person trips include both solo-driver and carpool trips; and transit person trips include both bus and light rail trips. The analysis used STEAM-estimated speeds rather than travel model output speeds. Table 2 provides estimates from STEAM of resulting average regionwide vehicular travel speeds, and total regionwide emissions and fuel consumption. Note that average speeds estimated by STEAM are lower than those typically estimated by travel demand models or even by HCM procedures. This is because, as discussed in Section 4.1, STEAM's speed relationships take into account delays due to queues carried over from one hour to the next, as well as delays due to incidents and the effects of day-to-day variations in traffic when volume-to-capacity ratios are close to 1.0.

5.0 ECONOMIC ANALYSIS PROCEDURES

All benefits are computed by STEAM's Trip Table Analysis Module based on weekday travel estimates by market sector for a specific analysis year. Weekday benefits for each market sector are annualized assuming a default value of 250 working days per year. This annualization factor may be modified by the user. The analysis year may be selected by the user to be representative of benefits over the analysis period, which is normally the life of the investment. Alternatively, the user may run STEAM separately with data for several different analysis years, and estimate the stream of benefits over the analysis period.

5.1 User Benefits

User benefits are calculated for each zone-to-zone trip interchange. Benefits include savings in user costs such as travel time costs, vehicle operating costs and out-of-pocket costs for fares, parking (if paid by the user), fuel taxes, and tolls. User benefits also include the portion of accident costs that are perceived by the traveler and taken into account in travel decisions. As discussed in Section 5.3 below, a substantial portion of accident costs are not perceived by travelers. STEAM treats the portion of accident cost savings not perceived by travelers as "external" costs, i.e., costs not considered in the decision to drive. The user may specify the breakdown between "internal" (i.e., perceived) and "external" (i.e., unperceived) accident costs. User benefits estimated by STEAM may differ depending on the extent to which such costs are considered to be perceived.

User-perceived benefits are reduced as a result of increases in user costs. Since user payments for fares, fuel taxes and tolls represent monetary transfers to the government (i.e., not a net increase in the resource cost of transportation to society as a whole), it is necessary to account for these revenue transfers as "benefits" to government agencies in the estimation of total societal benefits of the actions under consideration.

Travel cost changes for vehicle operation are computed by STEAM based on VMT changes and on fuel consumption changes. At the user's option, vehicle operating and fuel cost changes can be treated by STEAM as "external" costs, i.e., costs not perceived by travelers and therefore not taken into consideration in travel decisions. STEAM uses a defaults for variable vehicle operating cost (excluding fuel costs) amounting to 3.4 cents per mile for autos (10) and 10 cents per mile for trucks. It is assumed that fixed costs such as vehicle depreciation or garaging costs will not vary by alternative, but if they do, the differences with respect to the No-Build can be provided as an input to STEAM in the "non-mileage costs" category discussed in Section 5.3. The defaults for fuel cost are $1.21 per gallon of auto fuel and $1.15 per gallon of truck fuel *inclusive of fuel taxes*. Therefore, changes in fuel tax revenues resulting from changes in fuel consumption need to be considered as benefits or losses to public agencies in the accounting for total societal benefits.

TABLE 2 Impacts Of Alternatives: Year 2015

	No-Build	Build	TDM/Tolls
Weekday Person Trips (in millions)			
Auto	5.719	5.721	5.708
Transit	0.091	0.090	0.102
Truck	0.018	0.018	0.018
Total	**5.828**	**5.828**	**5.828**
Weekday Vehicle Trips (in millions)			
Auto	4.231	4.231	4.224
Truck	0.018	0.018	0.018
Total	**4.249**	**4.248**	**4.242**
Weekday Vehicle Miles (in millio	**27.767**	**27.958**	**27.452**
Avg. Auto Speed (mph)	18.24	18.98	18.32
Annual Emissions (tons)			
Hydrocarbons (HC)	7,723	7,622	7,578
Carbon Monoxide (CO)	166,075	162,417	162,662
Nitrogen Oxides (NOx)	8,853	8,913	8,743
PM 10	310.0	312.0	305.6
Annual Fuel Use (million gallons	246.06	241.72	241.29

Travel time savings for personal travel (i.e., autos, HOV and transit) are monetized by STEAM using a value of passenger travel time per hour provided by the user. STEAM's default is \$8.90 per person hour for in-vehicle time (11). The default value for out-of-vehicle travel time is \$17.00 (9). For commercial truck traffic, STEAM's default is \$16.50 per hour for in-vehicle time (11), and \$17.00 for out-of-vehicle travel time.

For *new* users of a mode (for each trip interchange), savings are valued by STEAM at one-half the rate used for former users, as suggested by consumer surplus theory (12), since new users do not really save the full amount saved by former users, but approximately half. Former users are those users who used the specified mode under the base case (i.e., No-Build scenario). New users are those users attracted to the mode, or to a new destination, due to facility or service improvements. For users who shift *away* from a mode or destination, disbenefits are computed similarly.

5.2 Revenue Transfers

Fares, tolls and taxes are transfers from users to the government, and are not normally relevant in evaluation of economic costs and benefits for society as a whole, even though they are extremely important in demand estimation. However, as discussed in Section 5.1, since the imposition of fares, tolls and taxes causes a reduction in the user-perceived benefit estimates computed by STEAM, any changes in these revenues to public agencies must be added back into the computation of total benefits to society.

STEAM calculates changes in revenues occurring as a result of *changes* in fares, tolls and other out-of-pocket costs paid by transportation system users. The transfers are calculated at the zonal interchange level. Revenue increases due to increased transit ridership or revenue losses due to a decrease in ridership must be computed by the user off-line, and combined appropriately with estimates of changes in revenues estimated by STEAM.

If additional motor fuel is consumed in an improvement case, the additional user costs for the motor fuel include fuel taxes which are simply a revenue transfer from users to the government. STEAM calculates the amount of revenue transfer based on an average combined State and Federal fuel tax rate of 37.48 cents/gallon for gasoline and 42.6 cents/gallon for diesel. The user will need to make appropriate adjustments to STEAM's estimates of fuel tax revenue changes if actual combined fuel tax rates differ from these averages.

5.3 External Cost Changes

Many social and environmental impacts (i.e., both benefits and costs) cannot be monetized or even quantified, and must be described qualitatively for consideration by decision makers. For example, it is difficult to monetize benefits such as community livability, and it is difficult to monetize costs such as loss of historical resources. Four types of external costs which *can* be quantified by STEAM are: accident costs, noise damage, pollution, and greenhouse gas emissions.

Accidents: Accidents cause many costs which are not borne by system users directly (e.g., costs for public services such as police, fire and court systems, health insurance coverage which may be paid by employers, and pain and suffering caused to non-users). Moreover, even the portion of accident costs that are actually incident upon drivers may not be taken into account by them in making a decision to drive. In STEAM, these unperceived portions of accident costs may be treated as external costs. STEAM provides default estimates of fatality, injury and property damage only (PDO) accident rates by facility class. (The rates do not vary by congestion levels or speed.) Also, STEAM provides default estimates of the breakdown between "internal" (i.e., user-perceived) and "external" accident costs per accident (13), based on the assumption that all costs *borne* by the highway user are taken into consideration in the decision to drive. Therefore, the STEAM user may wish to adjust the breakdown of costs if the urban area's travel models reveal that accident costs borne by highway users are underestimated by them and are not fully taken into account in driving decisions.

Air pollutant emissions, greenhouse gas (CO_2) emissions, and noise: STEAM permits the user to specify emission costs per ton of pollutant and per ton of CO_2, and noise costs per VMT. STEAM provides default monetary values for HC, NOx and CO emission costs per ton based on Denver (14), PM 10 costs per ton based on nationwide estimates (15), and noise damage cost per VMT and global warming cost per ton of CO_2 based on an FHWA study (11,16).

Other external costs: These include other external costs which are not *specifically* computed by STEAM. The user may provide estimates of these costs per VMT by facility class and mode for mileage-based external costs (e.g., indirectly borne highway patrol and safety costs). Annual non-mileage based external costs (e.g., indirectly borne parking cost changes) can be provided by mode as a lump-sum user input. Any changes in vehicle fixed costs may be included here. External costs during construction (such as travel delay and environmental impacts) may also be provided separately as a user input.

5.4 Public Agency Costs

Included in this category are all costs borne by highway and transit agencies. Capital costs and annual highway operation and maintenance (O&M) costs must be input directly by the user. For construction costs, STEAM projects out to the year of opening of the facility the value of capital costs assumed to be incurred at the mid-point of construction, and then annualizes this cost based on the facility life. A default discount rate of 7%, as recommended by the Federal Office of Management & Budget (OMB) is used to annualize capital costs (17). STEAM permits the use of alternative discount rates.

Transit operating costs are calculated by STEAM by applying cost per vehicle mile, cost per vehicle hour and cost per peak vehicle (input by the user) to the changes in transit vehicle miles, vehicle hours and peak vehicles, which the user provides as input to STEAM.

5.5 Net Annual Worth

Net annual worth is calculated by STEAM by subtracting annualized costs to public agencies from the total annual benefits (i.e., the sum of user benefits, revenue transfers, and changes in external costs). Benefit/cost ratios are also calculated. The numerator of this ratio is the total benefits. The denominator is annualized costs to public agencies. Net worth and benefit-cost ratios are indicators of the economic efficiency of the alternatives.

5.6 Risk Analysis

STEAM includes a risk analysis component. There will always be considerable uncertainty about appropriate values for unit costs or impact rates used as input. For parameters subject to uncertainty, the risk analysis feature in STEAM allows the user to input the median value and the upper limit of a 90% confidence interval. STEAM uses these values to generate a statistical probability distribution. STEAM then uses Monte Carlo simulation techniques to calculate probability distributions for each result metric such as the benefit-cost ratio. Such estimates are useful to decision-makers in selecting the level of risk within which they are willing to make commitments. The results are also useful in forging consensus among diverse groups, each desiring that their own values of input parameters be used in the analysis (18).

5.7 Case Study Benefits and Costs

User Benefits: Table 3 summarizes the annualized costs and benefits of the two action alternatives. User cost savings of $191 million make up most of the benefits for the Build alternative. For the TDM alternative, the large user disbenefits perceived -- $31 million -- reflect a combination of the monetary "losses" to users who continue to use Central Freeway and pay tolls, travel time benefits to these users due to reduced congestion, the consumer surplus losses of former Central Freeway users who are disinduced from using Central Freeway, and the travel time disbenefits to other travelers who are faced with increased congestion when former Central Freeway users who are disinduced from using Central Freeway divert to other facilities.

Transfers: STEAM estimated the fuel tax revenue reductions (due to reduced fuel consumption as a result of average speed improvements) at $1.6 million for the Build and $1.8 million for the TDM alternative. STEAM does not currently estimate fare revenue changes due to changes in transit ridership. Fare revenue changes were estimated "off-line" as a $0.25 million loss for the Build and a $2.75 million gain for the TDM alternative, based on transit ridership changes. Toll revenues for the TDM alternative were estimated at $75.5 million by STEAM based on input out-of-pocket cost changes for auto, carpool and truck trips as discussed in Section 3.4. The tolls paid are more than total losses suffered by users because of travel time savings due to faster speeds on Central Freeway.

External costs and benefits: The increase in VMT in the Build alternative causes external accident and noise disbenefits. In the case of the TDM alternative, reductions in VMT reduce noise costs, but not accident costs, because a significant amount of VMT shifts to arterials, which have higher accident rates.

For the Build alternative, higher speeds result in net cost reductions of $14 million in emissions costs and $0.15 million in global warming costs. For the TDM alternative, cost reductions are similar, but result from both speed improvements as well as VMT reductions. Emission reduction estimates and resulting monetatry benefit estimates by STEAM tend to be higher than conventional approaches because the average speeds estimated by STEAM tend to be lower than those estimated by conventional approaches (as discussed in Section 4.4), and tend to be in the range where emission rates are much more sensitive to differences in speed (i.e., below 25 mph).

For the Build alternative, an increase in other non-mileage based external costs amounting to $0.16 was estimated (off-line) and was provided as an input to STEAM. The cost changes were based on parking cost increases as a result of the higher number of vehicle trips. For the TDM alternative, there are parking cost savings (i.e., non-mileage based cost savings) due to reductions in vehicle trips. When the need for parking spaces at business locations is reduced, there is a saving in resource costs in the long term, because fewer new spaces will need to be provided to accomodate growth, or existing spaces can be redeveloped for other uses.

TABLE 3 Annualized Benefits And Costs

	Build	TDM
Annual Benefits		
User Benefits:	191.40	(30.92
Revenues to Public Agency (change):		
Fuel taxes	(1.64)	(1.80
Fares	(0.25)	2.75
Tolls	0.00	75.50
Sub-total	(1.89)	76.45
External Benefits/Disbenefits:		
Accidents	(0.22)	(0.58
Noise	(0.06)	0.06
Emissions	14.16	13.85
Global warming	0.15	0.01
Other non-mileage	(0.16)	2.01
Sub-total	13.87	15.35
TOTAL ANNUAL BENEFITS	203.38	60.88
Total Annual Public Agency Costs		
Capital	73.74	0.04
Operating	0.89	14.53
TOTAL ANNUALIZED COSTS	74.63	14.57
Economic Efficiency Measures		
Net Annual Worth	128.76	46.31
Benefit/Cost Ratio	2.73	4.18

Public agency costs: Agency cost estimates are presented in Table 3 as differences with respect to the No-Build alternative. Capital costs include costs borne by transportation agencies for construction, engineering and rights-of-way (R-O-W). Opportunity costs of R-O-W already owned by the public agency were included in total R-O-W capital costs. A discount rate of 7% was used to annualize capital costs. Costs for operation and maintenance of added freeway mixed-flow lanes were estimated based on national data (10). Transit operating cost increases (above the No-Build) were also estimated based on average costs per vehicle mile from national data (10).

Economic Efficiency: Table 3 also presents estimates of net annual worth (i.e., benefits minus costs) and benefit/cost (B/C) ratios. B/C ratios are useful in prioritizing investments from a list of candidates for a limited budget. However, in comparing mutually exclusive alternative investments, (i.e., alternatives proposed to address the same problem), *net worth* should be the criterion used in economic comparisons.

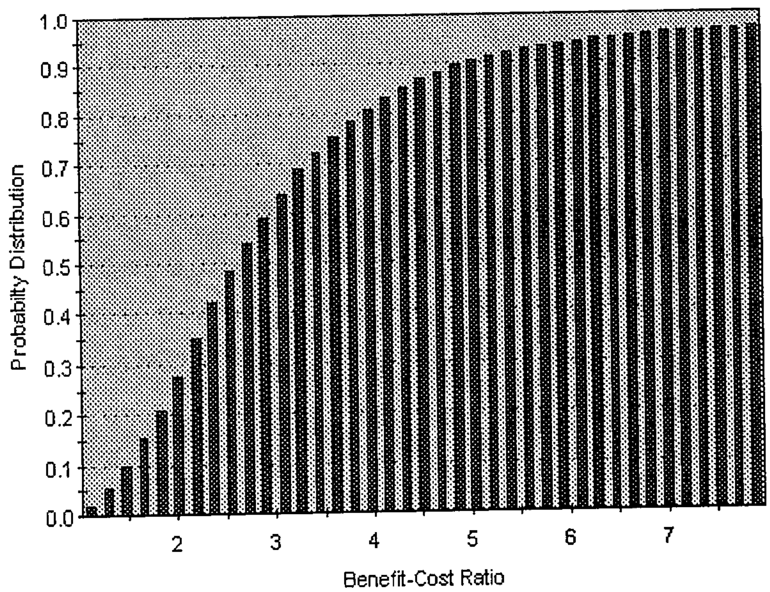
The Build alternative shows a net annual worth of $129 million, while the TDM alternative shows a net annual worth of only $46 million. The Build alternative is therefore superior when only monetized benefits are considered. These net worth estimates provide the decision maker with useful measures for comparative evaluation of alternatives, *along with measures or clear descriptions of non-monetized social and environmental impacts,* such as community livability and pride, neighborhood cohesion, aesthetics, energy security, social equity and environmental justice. The net worth of an alternative can be used by decision makers to assess whether other non-monetized disbenefits (or benefits) are worth the estimated net *monetized* gain (or loss) to society for the alternative under consideration. If net worth is negative, it provides "scale" as to how large non-monetized benefits should be in order to move a project alternative into the acceptable range.

Risk Analysis: STEAM's default 90% confidence intervals for the various input impact rates and monetary values were used to generate probability distributions of benefits, costs and the benefit-cost ratio. Figure 2 provides STEAM's output cumulative probability distributions for the B/C ratios of the Build and TDM alternatives respectively. The probability distributions suggest that there is a 10% probability that the Build's B/C ratio will be less than 1.0, while there is a 27% probability that the B/C ratio of the TDM alternative will be below 1.0 (i.e., that the net worth will be $0.0). In other words, the TDM alternative is "riskier". These risks can be used by decision makers along with median (i.e., 50% probability) estimates of net worth shown in Table 3 and other non-monetized impacts to judge acceptability of risks relative to potential rewards.

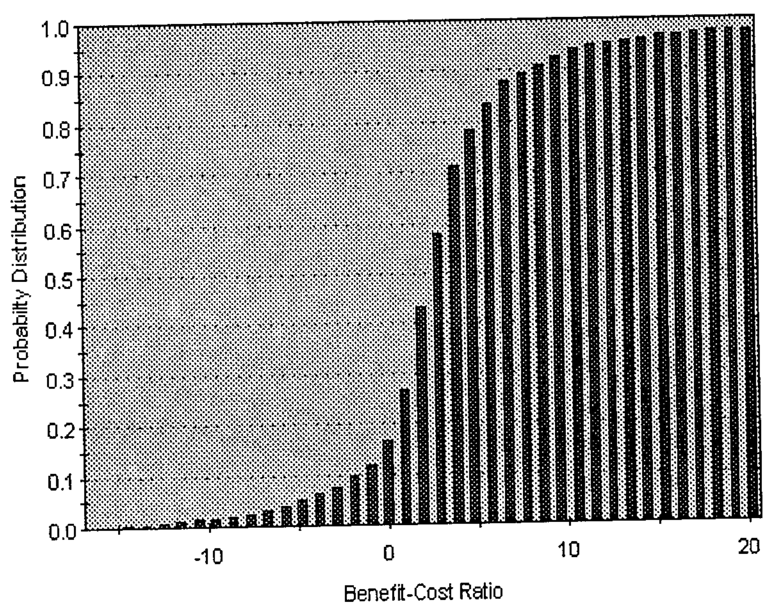
6.0 CONCLUSIONS AND FURTHER RESEARCH

This paper has demonstrated a benefit-cost assessment at a detailed level of analysis for two action alternatives in a major travel corridor of a case study urban area, using FHWA's new software STEAM. Benefit-cost assessment was done on a multi-modal basis using output from the four-step travel demand modeling process. The case study demonstration shows that STEAM can be a useful tool for system planning and corridor planning in metropolitan areas. However, the current version of STEAM has some limitations. These are discussed below, along with FHWA plans to enhance STEAM to address them.

FIGURE 2 Cumulative Probability Distributions of Benefit-Cost Ratios



A. Build Alternative



B. TDM/Tolls Alternative

Benefit Streams: Currently, travel related benefits and costs computed by STEAM are provided for a single forecast year. It is difficult to account for the effects of varying rates of growth in travel demand over time, unless the forecast year chosen for providing input demand estimates is representative of the entire analysis period. A multi-year analysis capability will be developed for the enhanced STEAM, so that the stream of benefits over the life of the investment may be more precisely computed. The STEAM user will be able to provide as input travel demand model outputs for several analysis years to account for the change in demand over time.

Revenue Transfers: STEAM currently calculates the amount of revenue transfer based on an average combined State and Federal fuel tax rate of 37.48 cents/gallon for gasoline and 42.6 cents/gallon for diesel. The user cannot change these default inputs, which are embedded in the software. In the enhanced STEAM, fuel tax rates will be allowed as a separate user input, so that transfers can be properly calculated by STEAM for different metropolitan areas. Also, transit fare revenue changes resulting from changes in transit ridership will be computed directly by STEAM, instead of requiring off-line analysis.

Emissions analysis: Currently, STEAM users are permitted to provide only a single breakdown of cold vs. hot start trips for all market sectors, irrespective of mode, purpose, and time-of-day. To improve emissions estimates, the enhancements will allow users to specify the percentage of trips that occur in the cold start mode *by market sector* (e.g., work trip percentages and peak period percentages for cold starts would typically be higher than non-work and off-peak percentages). Also, currently STEAM users must estimate composite emission rates for an "auto" and "truck" mode, and these rates cannot vary by market sector. For example, a solo-driver market sector and a carpool market sector must both use the same composite "auto" emission rates, although the carpool market sector may include heavier vehicles such as vans. The enhanced STEAM will allow a market sector to have as many vehicle types as MOBILE5A, so that the user simply provides a percentage breakdown by vehicle type for each mode. For example, carpools may be 80% light duty gasoline (LDG) and 20% light duty truck (LDT).

Risk Analysis: Currently, probability distribution inputs can only be provided for monetary values and impact rates. Proposed STEAM enhancements will extend risk/uncertainty analysis to include uncertainty of travel demand inputs.

Monetary Values: Currently, all monetary values must be updated manually in order to ensure that they reflect current year dollars. The enhanced STEAM will provide capability for input of inflation adjustment factors, so that all monetary values can be updated automatically to current year dollars by the software. Also, STEAM currently assumes carpool and solo-driver values of time are the same, and they cannot be differentiated. The enhanced STEAM will allow value of time to differ for different categories of auto and transit travel.

Access VMT: STEAM currently ignores the access portion of transit and carpool trips, with consequent underestimation of vehicle miles and other impacts from park-and-ride or kiss-and-ride operations. The enhanced STEAM will allow for estimation of access mileage and impacts.

Interface with Demand Models: Perhaps the greatest effort in using the current version of STEAM involves converting the networks and matrices produced by travel demand modeling software packages to input formats required by STEAM. An automated process will be developed to allow STEAM to accept and directly convert data from the most commonly used travel modeling packages

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IMPROVED SPEED ESTIMATION PROCEDURES FOR USE IN *STEAM* AND IN AIR QUALITY PLANNING

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ABBREVIATIONS

AADT/C	Average annual daily traffic-to-capacity
AHDT	Average weekend/holiday daily traffic
ATR	Automatic traffic recorder
AWDT	Average weekday daily traffic
AWEDT	Average weekend/holiday daily traffic
BPR	Bureau of Public Roads
FFS	Free-flow speed
FHWA	Federal Highway Administration
gpm	Grams per mile
GT	Greater than
HCM	Highway Capacity Manual
HPMS	Highway Performance Monitoring System
LE	Less than or equal to
mph	Miles per hour
pcphpl	Passenger cars per hour per lane
PCT	Percent
V/C	Volume-to-capacity ratio
VMT	Vehicle-miles of travel
VOL	Volume
vphpl	Vehicles per hour per lane

1. INTRODUCTION

Background

Public concern over health problems associated with air pollution, coupled with the legislative mandate of the Clean Air Act Amendments of 1990, has made air quality an issue of national significance. As part of the process of developing emission control and abatement strategies, a complex modeling process is used to estimate and forecast air quality in urban areas. At the core of the modeling process is the MOBILE5a model, which produces emission factors for various pollutants (grams per mile [gpm]) from which total emissions--and ultimately emission concentrations--can be estimated.

The MOBILE5a model requires users to provide a variety of inputs, including vehicle speeds for the particular time period being analyzed. The research undertaken here focuses on one of these inputs: vehicle speeds due to recurring congestion. Recent research activities by others have used the post-processor approach, i.e., refining the speeds that are used to make assignments in travel forecasting models. However, current techniques suffer from a major shortcoming: speeds in traffic-saturated (congested) conditions are difficult to capture with existing procedures (e.g., the *Highway Capacity Manual* [HCM]).[1] The problem relates to the failure to account for the effects of queues in hours after the queue has formed. For example, when the volume-to-capacity (V/C) ratio (an hourly concept) exceeds 1.0, most methods will make speed estimates in that hour but will not consider what happens in the next hour--the queue is still present at the end of the first hour and will take some time to dissipate.

In addition to the recurring congestion problem, the effect of incidents on speeds has not been addressed in the preparation of emissions inventories. Nonrecurring congestion accounts for 40 to 70 percent of all congestion in urban areas (Ref. 1). However, no methods have been developed to estimate what effect nonrecurring congestion has on speeds for air quality purposes. Addressing nonrecurring congestion's effects on speeds is not within the scope of the current research.

The Federally-mandated transportation process in urban areas must deal constantly with air quality concerns. Since mobile sources are a major contributor to urban air pollution, transportation improvements can have a major impact on area wide emissions. In the course of identifying needed improvements, transportation planning generates much data that are directly applicable to air quality. Specifically, the travel forecasting process provides a base for estimating some of the transportation data needed by air quality models. This process is almost always based on forecasting travel on a network representation of the area's highway system, and thus can provide information on area wide VMT. Also, network assignments can be used to estimate vehicle speeds, but it is generally held that the speeds used to assign traffic are too crude for air quality purposes, especially under congested

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[1] Congestion caused by over-saturated traffic conditions in the absence of incidents in referred to as "recurring" congestion because it will routinely appear in the same times and locations. Incident- caused congestion is referred to as "nonrecurring" because the times and locations cannot be predicted with regularity.

flow (Refs. 2 and 3). There has been some discussion about integrating traffic simulation models with travel forecasting models to provide the desired level of precision, but this integration is hampered by the intensive data requirements of the simulation models and the limitations of computers to simulate entire urban networks. (Simulation models are generally applied to small subnetworks.)

Methodology

The research presented here is an extension of two recently completed Federal Highway Administration (FHWA) projects: *Speed Determination Models for the Highway Performance Monitoring System (HPMS)* and *Roadway Usage Patterns: Urban Case Studies* (Refs. 4 and 5). These studies were concerned with estimating the cumulative effects of congestion on vehicle speeds over the course of an entire day. Because most analytical methods consider only the effects of peak hour congestion (such as the *HCM's* volume-to-capacity [V/C] ratio), a new measurement of daily congestion was developed: the Average Annual Daily Traffic-to-Capacity (AADT/C) ratio, where capacity is the two-way capacity. For reference, the AADT values that result from various AADT/C ratios for typical situations are provided in Table 1.

Table 1. AADT/C Levels and Corresponding AADT Values

	Freeways (10% Trucks)		
	4-Lanes[1]	6-Lanes[2]	4-Lane Signalized Arterials (8% Trucks)[3]
AADT/C	AADT[4]	AADT[4]	AADT[4]
9	72,000	113,000	30,000
10	80,000	126,000	33,000
11	88,000	138,000	37,000
12	96,000	151,000	40,000
13	104,000	163,000	43,000
14	112,000	176,000	47,000
15	120,000	188,000	50,000

[1]Ideal Capacity = 2,200 passenger cars per hour per lane (pcphpl)
[2]Ideal Capacity = 2,300 pcphpl
[3]Ideal Capacity = 900 pcphpl (based on a saturation flow rate of 1,800 pcphpl and 50% green time)
[4]Rounded to nearest 1,000

As part of the aforementioned studies, a simple macroscopic simulation model was developed to study the effects of queuing on speeds. This model, named QSIM, was developed to integrate results obtained from simulation runs for congested and uncongested conditions and to produce estimates of the overall effect of AADT/C on average delays due to congestion over the course of a year. QSIM analyzes the effects of temporal variations in traffic and queuing on an hour-by-hour basis for weekdays and for weekends/holidays. Weekday travel is analyzed separately in each direction--the "home-to-work" peak direction, for which the peak occurs in the morning, and the "work-to-home" direction, for which the peak occurs in the afternoon. Both freeways and signalized arterials are considered by QSIM. Unsignalized streets were also considered by the study, but were not modeled with QSIM. Figure 1 shows the operation of QSIM and the subsequent analysis that was performed.

Set Test Section Capacity

The procedure starts by defining a test section for QSIM to analyze. The capacity of the section is determined using *HCM* procedures. For the research reported herein, the following basic capacity values were used:

- Freeways--2,300 pcphpl, based on the 1994 *HCM*;
- Signalized Arterials--900 pcphpl, based on the *HCM's* saturation flow rate of 1,800 pcphpl and a 50 percent green time;
- Unsignalized Arterials--600 pcphpl.

The test section length is also set at this time; this is a key factor in QSIM as the speed and delay of vehicles are measured over the length of the section. For this study, segment length was fixed at 1.5 miles (7,920 feet) for freeways. For arterials, the length of the segment is equal to the signal spacing. QSIM cycles through AADT/C levels from one to 24. Note that an AADT/C value of 24 indicates that the facility operates at or above capacity for every hour of the day and is thus considered to be the theoretical maximum AADT/C level.

Temporal Distributions and Peak Spreading

Once the AADT/C level is set, AADT is determined by multiplying AADT/C by the (two-way) capacity. Average Weekday Daily Traffic (AWDT) and Average Weekend/Holiday Daily Traffic (AWEDT) are determined by applying factors to AADT: 1.0757 for AWDT and 0.8393 for AWEDT (Ref. 5). From these daily volumes, temporal distributions are used to determine "target" volumes by hour (Table 2). Separate distributions exist for freeways and nonfreeways; three AADT/C ratios (AADT/C less than or equal to 7, AADT/C between 7 and 11, and AADT/C greater than 11); and peak direction (morning and afternoon). Direct application of these distributions would lead to problems for AADT/C ratios on the boundary values. For example, the high AADT/C range's distribution is flatter than the middle range; this could possibly lead to predicting congestion in an hour for the middle range while not predicting congestion in the same hour for the high range. Therefore, a smoothing procedure was used as described in Table 3. This procedure accounted for problems at the boundary values and further spread out traffic throughout the day as AADT/C ratios

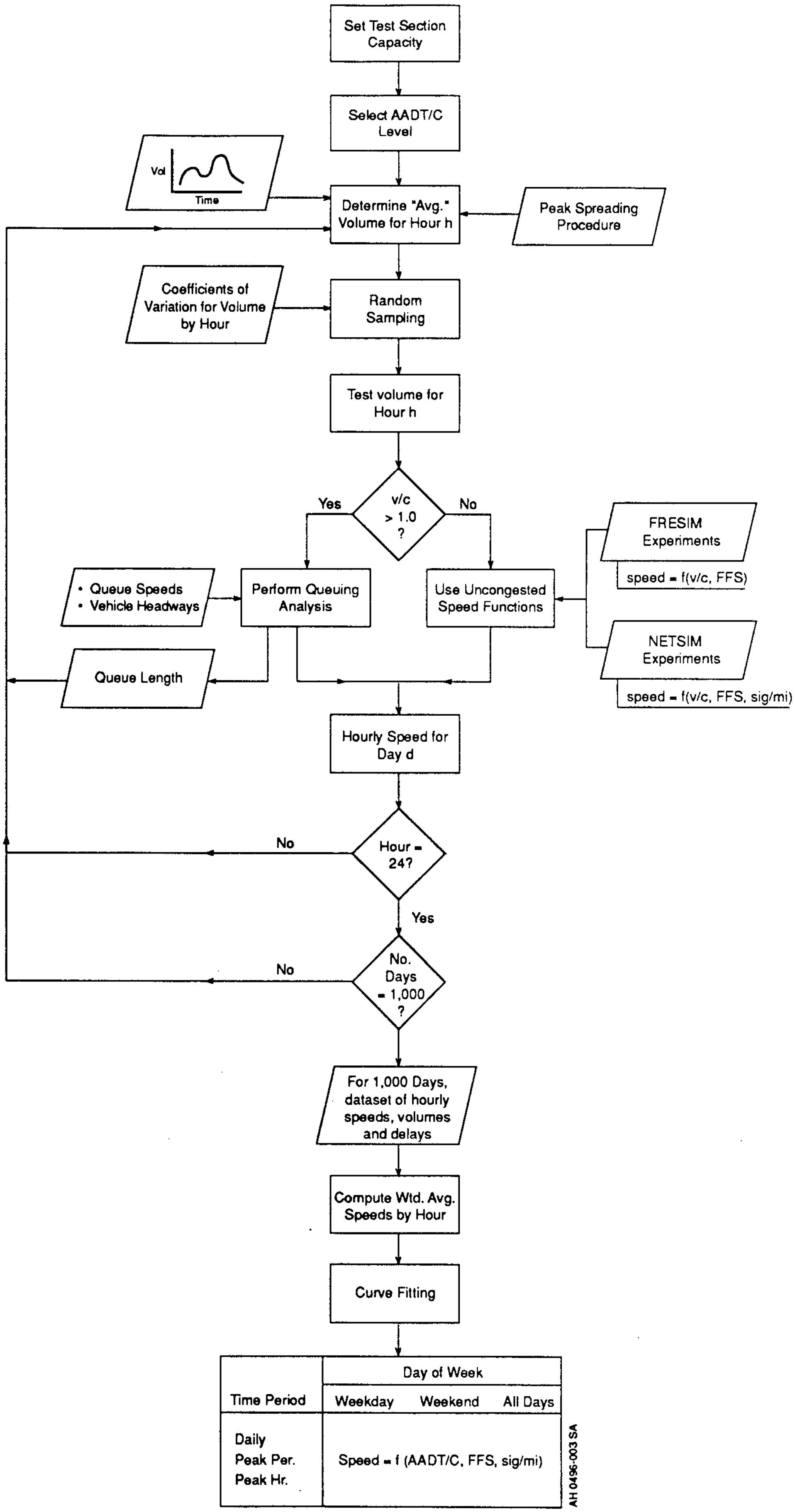


Figure 1. Overview of Speed Model Methodology

Table 2. Weekday Temporal Distributions

TYPE OF FACILITY: FREEWAY

	AADT/C					
	LE 7.0		7.1 -- 11.0		GT 11.0	
	PEAK DIRECTION		PEAK DIRECTION		PEAK DIRECTION	
	AM	PM	AM	PM	AM	PM
	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.
HOUR						
1	0.42	0.58	0.44	0.57	0.47	0.54
2	0.27	0.33	0.27	0.34	0.27	0.32
3	0.23	0.25	0.22	0.26	0.20	0.24
4	0.23	0.22	0.21	0.21	0.18	0.18
5	0.38	0.29	0.36	0.28	0.31	0.25
6	1.17	0.68	1.12	0.69	1.06	0.72
7	3.26	1.75	3.16	1.90	2.86	2.18
8	4.83	2.90	4.59	3.05	3.90	3.27
9	3.56	2.57	3.80	2.76	3.66	3.04
10	2.58	2.24	2.75	2.30	2.94	2.53
11	2.46	2.33	2.50	2.34	2.68	2.49
12	2.56	2.56	2.61	2.61	2.73	2.69
13	2.65	2.71	2.68	2.75	2.75	2.78
14	2.70	2.77	2.75	2.81	2.82	2.86
15	2.93	3.12	2.93	3.15	2.97	3.15
16	3.26	4.01	3.21	3.87	3.21	3.60
17	3.47	4.81	3.38	4.43	3.28	3.82
18	3.42	4.85	3.32	4.39	3.29	3.77
19	2.66	3.23	2.66	3.20	2.82	3.22
20	1.95	2.23	1.97	2.25	2.12	2.36
21	1.54	1.78	1.54	1.79	1.62	1.86
22	1.40	1.63	1.44	1.69	1.54	1.74
23	1.14	1.30	1.19	1.39	1.27	1.46
24	0.79	0.98	0.83	1.05	0.89	1.07
TOTAL	49.87	50.13	49.92	50.08	49.84	50.16

Source: Ref. 5.

Table 2. (Continued)

TYPE OF FACILITY: NONFREEWAY

	AADT/C					
	LE 7.0		7.1 -- 11.0		GT 11.0	
	PEAK DIRECTION		PEAK DIRECTION		PEAK DIRECTION	
	AM	PM	AM	PM	AM	PM
	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.	PCT. OF DAILY VOL.
HOUR						
1	0.34	0.47	0.37	0.47	0.41	0.49
2	0.21	0.28	0.23	0.27	0.24	0.28
3	0.15	0.18	0.17	0.18	0.18	0.20
4	0.14	0.14	0.16	0.15	0.17	0.18
5	0.24	0.18	0.28	0.20	0.33	0.27
6	0.74	0.42	0.81	0.48	1.03	0.67
7	2.23	1.19	2.35	1.27	2.55	1.72
8	4.11	2.28	3.85	2.39	3.57	2.79
9	3.45	2.33	3.42	2.39	3.09	2.78
10	2.64	2.29	2.69	2.31	2.58	2.47
11	2.64	2.56	2.65	2.54	2.62	2.57
12	2.90	3.02	2.90	2.98	2.83	2.89
13	3.20	3.35	3.17	3.30	3.04	3.13
14	3.14	3.24	3.14	3.22	3.06	3.13
15	3.18	3.44	3.16	3.37	3.21	3.34
16	3.40	4.13	3.35	3.93	3.41	3.78
17	3.46	4.78	3.49	4.49	3.47	3.92
18	3.31	4.83	3.45	4.55	3.39	3.86
19	2.68	3.23	2.75	3.31	2.82	3.12
20	2.14	2.41	2.18	2.53	2.28	2.53
21	1.73	1.97	1.75	2.07	1.83	2.09
22	1.49	1.71	1.50	1.77	1.55	1.80
23	1.10	1.26	1.11	1.25	1.22	1.29
24	0.74	0.94	0.75	0.90	0.83	0.97
TOTAL	49.36	50.64	49.67	50.33	49.71	50.29

Source: Ref. (5).

Table 3. Peak Spreading Modification Procedures for Temporal Distributions

AADT/C Range	Modifications
1-7	None; low range used
8	(1/3 of low range) + (2/3 of middle range)
9	None; middle range used
10	(2/3 of middle range) + (1/3 of high range)
11	(1/3 of middle range) + (2/3 of high range)
12	None; high range used
13+	[{pct * (24 - AADT/C)} + {(1/48) * (AADT/C - 12)}]/12 where: pct = hourly distribution of traffic from (5)

increased above 13. This additional peak spreading feature was deemed necessary since the data for developing the distributions (713 urban ATRs [Ref. 5]) did not have a large number of sites where AADT/C was greater than 13. The formula for smoothing the distributions of AADT/C ratios greater than or equal to 13 is basically a weighted average computation between the actual hourly percentage derived in Ref. 5 and a perfectly flat daily temporal distribution. The first term in the equation represents the weight applied to the actual percentage. The second term is the weight applied to a perfectly flat distribution, which has an hourly percentage equal to (1/48), since there are two directions being considered. An example will clarify the process. For an AADT/C of 14, the "weight" on the actual percentage is 10 and the weight on the "flat" percentage (1/48) is 2. For an AADT/C of 16, these weights are 8 and 4, respectively. Note that the procedure adds volumes to offpeak hours as it subtracts from peak hours. It should be pointed out that this procedure is not based on observed data but has been instituted as a purely mechanical procedure to account for two conditions: (1) counterintuitive results at the AADT/C boundaries of the original temporal distributions and (2) excessive queuing that would result at very high AADT/C ratios if the temporal distributions were unaltered. This second condition is really the phenomenon of peak spreading.

Stochastic Variation in Traffic Volumes

In order to account for day-to-day variability in traffic flows, QSIM stochastically determines what the test volume in a given hour should be from the "target" hourly volume (determined above) and information on hourly variability (Table 4), where the "target" volumes are the mean of normal distribution and the variance is defined as:

$$\text{Variance} = (\text{Coeff. of Variation} * \text{Mean})^2. \qquad (1)$$

Random sampling is then used to select the test volume from this distribution. The test volume is then compared to the test section's capacity.

Table 4. Average Coefficients of Variation from Urban ATR Sites

	FUNCTIONAL CLASS													
	URBAN INTERSTATE		URBAN FREEWAY		URBAN PRINC. ARTERIAL		URBAN MINOR ARTERIAL		URBAN COLLECTOR		URBAN LOCAL		TOTAL	
	DAY OF WEEK		DAY OF WEEK		DAY OF WEEK		DAY OF WEEK		DAY OF WEEK		DAY OF WEEK		DAY OF WEEK	
	WEEKEND	WEEKDAY	WEEKEND	WEEKDAY	WEEKEND	WEEKDAY	WEEKEND	WEEKDAY	WEEKEND	WEEKDAY	WEEKEND	WEEKDAY	WEEKEND	WEEKDAY
	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR	COEFF VAR
HOUR														
1	26.83	26.78	27.93	32.68	28.59	33.37	31.14	41.35	34.23	44.64	44.31	42.09	28.62	32.47
2	27.32	27.34	31.75	37.96	31.79	39.77	36.31	54.02	42.98	58.60	55.91	57.32	31.47	37.79
3	26.82	25.63	33.57	39.46	33.95	42.66	41.45	60.29	49.32	69.27	59.72	59.29	33.18	39.52
4	28.59	23.29	36.12	37.59	37.59	41.05	49.38	60.63	56.22	76.76	65.85	61.68	36.76	38.33
5	34.54	22.01	39.88	32.32	42.47	34.57	55.14	48.94	62.72	64.03	53.70	38.82	41.93	32.83
6	44.64	19.12	47.09	22.82	47.37	25.77	55.21	32.96	59.83	37.26	49.28	27.29	48.02	24.36
7	51.23	14.59	52.74	16.43	50.03	17.42	55.22	20.70	55.02	21.68	40.53	20.27	51.78	16.88
8	54.66	11.85	55.98	13.72	53.36	14.42	57.31	16.62	57.79	18.12	52.71	14.88	55.02	13.81
9	41.18	11.37	41.54	13.27	41.54	13.12	42.01	15.52	43.89	16.90	38.30	14.07	41.54	12.99
10	29.77	11.71	29.97	12.87	31.63	13.08	32.06	15.30	31.76	16.74	30.17	14.21	30.72	13.02
11	25.05	12.69	25.93	13.70	28.80	13.86	28.44	15.34	29.92	16.63	27.23	14.16	26.90	13.73
12	22.18	13.14	23.11	13.76	26.52	13.74	27.05	14.54	28.85	15.52	26.16	13.75	24.52	13.71
13	18.56	13.07	18.78	13.27	21.27	13.40	21.58	13.73	22.33	15.22	20.24	13.12	19.94	13.38
14	17.47	13.05	17.69	13.15	20.23	13.62	21.30	13.94	21.20	15.41	19.60	13.22	18.99	13.45
15	17.68	12.69	18.10	13.12	20.01	13.34	21.05	13.45	20.98	14.85	19.41	12.97	19.02	13.13
16	18.89	11.75	19.26	12.59	21.01	12.62	22.16	13.13	22.23	14.63	21.17	11.72	20.16	12.43
17	20.40	11.44	20.67	12.41	21.89	12.28	23.38	13.15	22.38	13.33	23.81	11.60	21.40	12.13
18	21.20	12.48	21.29	13.33	22.62	13.35	23.82	14.09	22.59	13.71	24.91	12.67	22.08	13.12
19	21.01	16.15	21.60	16.78	23.74	16.79	24.58	16.87	23.57	16.15	23.38	15.61	22.48	16.50
20	22.29	19.66	23.75	20.57	25.78	20.32	26.59	20.72	25.65	19.87	25.45	18.67	24.23	20.11
21	23.96	20.05	25.15	21.98	28.19	22.55	29.63	23.74	28.22	23.20	27.56	21.00	26.31	21.67
22	25.38	19.94	27.36	22.02	31.49	24.18	33.26	25.68	30.60	24.32	31.05	21.83	28.73	22.41
23	29.58	23.96	32.43	26.26	36.04	29.40	39.20	32.47	36.03	30.32	31.36	22.68	33.41	27.25
24	36.33	29.32	39.64	33.18	43.51	36.35	46.68	40.46	42.81	39.38	39.15	27.98	40.54	33.80

Uncongested Speed Functions

If the test volume is less than the section's capacity, newly developed uncongested speed functions are applied. The uncongested speed functions were determined by running FRESIM and NETSIM in a series of experiments to gauge the effects of various highway and traffic conditions (Ref. 4). The results were then analyzed with multiple and nonlinear regression analysis to develop equations that first predict delay. (Speed was calculated as a function of delay, as described below.) The relationships used were as follows:

Freeways

$$d_{vc} = 4.46\ V/C - 1.55\ (V/C)^2 - 0.05\ s_{ff}\ V/C + 0.044\ s_{ff}\ (V/C)^2 \quad (2)$$

Where:

- d_{vc} is delay due to congestion in vehicle-hours per 1,000 vehicle-miles.
- s_{ff} is free-flow speed in miles per hour.
- V/C is volume-to-capacity ratio (based on an assumed capacity of 2,200 pcphpl).

Signalized Arterials

$$d_{sig} = (32.6 + 30.0\ (V/C)^2)\ (1 - e^{-.3n}) \quad (3)$$

Where:

- d_{sig} is delay in vehicle-hours per 1,000 vehicle-miles.
- V/C is volume-to-capacity ratio.
- n is the number of signals per mile, assuming an "intermediate" signal progression case (see below).

Here, delay is additional travel time beyond that which would result if all vehicles could traverse the section at the free-flow speed. Delay includes not only the time spent sitting at red lights, but also the time lost while decelerating to a stop and then accelerating back to the free-flow speed. The second term of the equation varies between 0 and 1 and is essentially an adjustment factor for the delay due to the V/C ratio; for high values of signals per mile the term is close to 1.

The NETSIM experiments conducted to produce Eq. (3) were based on assuming a "fixed time" scenario in a simple network of multiple signals where zero offsets in the signal timing were used. (All signals in the test network were also assumed to have the same volumes and capacities.) Since the signals were closely spaced, a degree of progression existed within the system. To gauge the effect of progression, a second set of NETSIM runs was made with the same network and data, but this time with "ideal" progression in the study direction. The results show that progression can have a substantial improvement in arterial speeds (Table 5). A method for incorporating progression effects into Eq. (3) is discussed in a later section.

Table 5. Effect of Progression on Vehicle Speeds

Signals per Mile	Signalization	V/C					
		0.2	0.4	0.6	0.75	0.85	0.95
6	Progression	28.8	29.7	28.8	28.5	27.3	24.2
	Limited Progression	22.2	20.2	18.6	17.4	16.5	14.8
10	Progression	24.5	25.2	24.1	23.2	22.6	17.4
	Limited Progression	20.0	18.4	17.0	15.9	17.4	12.5

Unsignalized Streets

$$d_{ss} = n \left\{ 1.9 + 0.067\, s_{ff} + \frac{1000\,V}{C\,(C - V)} \right\} \quad (4)$$

Where:

- d_{ss} is delay in vehicle-hours per 1,000 vehicle-miles.
- s_{ff} is free-flow speed.
- V is the volume.
- C is the unsignalized intersection capacity.
- n is the number of stop signs per mile.

Queuing Analysis

If the V/C ratio is greater than 1.0, queuing is assumed to take place. Queuing will also affect traffic if there is a standing queue at the end of the preceding hour. If travel in the hour under consideration is affected by queuing, the program analyzes the growth (or decline) in queue length over the hour. Vehicle-hours of travel are estimated separately for those portions of the segment that are affected by queuing and those that are not. The approach developed by Dowling and Skabardonis is used to combine speeds for queued and unqueued conditions (Ref. 3):

Link Speed = [Queue Speed * (Queue Length/Link Length)]
\+
[Nonqueue Speed * (1 - Queue Length/Link Length)] (5)

Where:

- Queue Speed = Capacity/Lane (vehicles per hour) * Spacing (feet per vehicle)

- Queue Length = Average Queue (vehicles) * Spacing (feet per vehicle)
- Average Queue = (Q1 + Q2)/2
  Q1 = Queue at the start of the hour
  Q2 = Queue at the end of the hour
  = [Q1 + (Demand Volume * One Hour)] - [Capacity * One Hour]
- Nonqueue Speed is determined from the uncongested speed functions.

Since queue speed is a function of capacity, speeds can drop dramatically as capacity is reduced, as is the case when a number of lanes are closed. Q2--the queue at the end of the hour--is a function of the queue left over from the previous hour, the demand volume that arrived during the hour, and the discharge capacity of the link. Queue speed may be calculated using the above relationship or it may be "hardcoded." For freeways, examination of data from the Orlando (I-4) and Denver (I-25) indicated that the average speed in queues caused by recurring congestion is roughly 15.5 mph; this is the value used by QSIM for freeways. A queue spacing value (front-bumper-to-front-bumper) of 43 feet is based on assumed values of 18 feet per vehicle and a 25-foot gap.

In addition to the new uncongested speed functions and the freeway queue speed, a significant departure from the Dowling and Skabardonis procedure is the addition of a queue discharge (dissipation) rate: with the onset of congestion, vehicles are assumed to move through the bottleneck point at a flow rate less than capacity. For freeways, the basic capacity of 2,300 pcphpl is lowered to a queue discharge rate of 2,000 pcphpl once queuing begins. (That is, in Eq. [5], 2,000 pcphpl is used as the capacity for determining queue speed and Q2 on freeways since it is assumed that once queues begin, the capacity of the freeway drops to its discharge rate.) Since arterials are interrupted flow facilities, their queue discharge rate is the same as their capacity.

For simplicity, the program assumes that the bottleneck point from which the queue builds is at the downstream end of the segment. The program accumulates total travel time on the segment. If the length of the queue exceeds the length of the segment, total delay due to the bottleneck will naturally exceed total delay on the segment itself. This additional delay can be estimated by rerunning the program with an increased segment length.

Hourly Speed Estimates

The strategy of predicting delay rather than speed was taken for two reasons. First, it is computationally more efficient because it avoids the calculation of average speeds weighted by volumes. Second, it allows the inclusion of multiple sources of delay (such as delay attributable to grades and curves) in the final speed estimation. Since delay is defined as the time that is experienced by vehicles in excess of what it would have been at the free flow speed, the final speed on the segment can be computed as:

$$S = \frac{1}{\frac{1}{S_{ff}} + \frac{Delay}{1000}} \qquad (6)$$

Where:

- S is overall average speed, reflecting the combined effects of all sources of delay.

- S_{ff} is free-flow speed.

- Delay is the sum of delay from all sources (including congestion) in hours per 1,000 vehicle-miles, as computed above.

QSIM Output Data Set

QSIM completes its analysis for each of 24 hours in a day for the weekday/inbound direction, weekday/outbound direction, and weekend/holiday with both directions combined. The results are stored in a data set and the process is repeated by again randomly determining test volumes for another "day." A total of 1,000 "days" were so treated. From these 1,000 observations, delays and volume-weighted speeds were computed for each hour and test direction. For some AADT/C levels, the speeds in a particular hour represent a combination of "days" when queuing did and did not occur due to the stochastic determination of test volumes. The QSIM output tables are included in the Appendix to this document.

Curve Fitting

The data in the tables may be used directly by analysts if desired. However, equations were developed from the data in the tables to facilitate application of the procedure. The curve fitting process was as follows. First, three separate time periods were defined: peak hour, peak period, and daily. Second, three analysis periods were defined: weekday, weekend/holiday, and combined. All hours of a day were used in the daily analyses. The peak period for both freeways and arterials included three hours in the morning (7-10 a.m.) and three hours in the afternoon (4-7 p.m.). This choice is something of a compromise since for high AADT/C levels all six hours will be congested while for low AADT/C levels fewer hours will be congested. Consideration was given to varying the length of the peak period as a function of AADT/C but was dismissed in favor of consistency. From the QSIM output, the peak hour for freeways was between 4 p.m. and 5 p.m. for AADT/C <= 10 and between 5 p.m. and 6 p.m. for AADT/C > 10. For arterials, the peak hour was between 4 p.m. and 5 p.m.. ***The equations are valid for AADT/C levels up to 18; higher AADT/C levels are very unlikely to occur in practice.***

2. STUDY RESULTS

Final Speed Equations

Freeways

Curve fitting for freeways was straightforward. Plots of the data indicated that polynomial forms of AADT/C could be easily fit to the data. The results appear in Table 6 and Figure 2 provided at the end of this Section. The dependent variable in these equations is weighted average hourly delay measured in hours per 1,000 vehicle-miles. For example, consider the Peak Period. The equation for predicting weekday delay (in hours per 1,000 vehicle-miles) is:

$$\text{Delay} = 0.0001732632 * (\text{AADT/C})^5 - 0.0000116968 * (\text{AADT/C})^6 + 0.0000001974 * (\text{AADT/C})^7.$$

Speed is calculated by using the formula:

$$\text{Speed} = \frac{1}{1/\text{FFS} + \text{Delay}/1000}$$

Where: FFS is the free flow speed.

As a complete example, assume a 6-lane freeway with a calculated one-way (*HCM*) capacity (based on 3-lanes in one direction) of 6,600 vphpl and a free-flow speed of 60 mph. Its AADT is 158,400 vpd; therefore, its AADT/C is: 158,400/(2 * 6,600) = 12.0. Delay for Weekday Peak Period is calculated using the above formula and is 15.2602 hours per 1,000 vehicle miles. Weekday Peak Period Speed (i.e., the weighted average speed for the 6-hour period defined as the Peak Period) is:

$$\text{Speed} = \frac{1}{1/60 + 15.2602/1000}$$

$$= 31.32 \text{ mph.}$$

Signalized Arterials

Curve fitting for arterials was far more complex due to the extra influence of signal density, in addition to AADT/C. The same basic functional form was assumed as for the uncongested delay function as described previously. Two separate models were fit from the data with the cutoff point being an AADT/C value of seven (Table 7 and Figure 3).

<u>AADT/C <= 7 (Arterials)</u>

$$\text{Delay} = (1 - e^{-.3n}) * (\text{NOQ} + \text{Q})$$

where:
- n = signals per mile,
- NOQ = predicted value from the "no queue equations",
- Q = predicted value from the "queue equations".

For example, consider the Peak Period. The equation for predicting weekday delay for an AADT/C value of 5, free-flow speed of 40 mph, and 3 signals per mile is:

$$\text{Delay} = (1 - e^{-.3*3}) * \{32.6326 + (0.27187282 * 5^2) - (0.01054104 * 5^3) + (0.0000288004 * 5^6) - (0.0000013948 * 5^7)$$

$$= (0.59343) * (38.4530)$$

$$= 22.819 \text{ hours per 1000 vehicle-miles.}$$

Speed is calculated by using the same formula as for freeways above, except that a different free-flow speed is used:

$$\text{Speed} = \frac{1}{1/40 + 22.819/1000}$$

$$= 20.9 \text{ mph.}$$

<u>AADT/C > 7 (Arterials)</u>

$$\text{Delay} = (EQ_{>7}) + \{(1 - e^{-.3n}) * (NOQ)\}$$

Where: $EQ_{>7}$ is the predicted value from the "AADT/C > 7" Equations.

For example, consider a segment where AADT/C = 12, free-flow speed = 40 mph, and signals per mile = 4. Delay for the peak period on weekdays is calculated as:

$$EQ_{>7} = \{2.789265513 * (12 - 7)\} + \{0.259827 * (12 - 7)^2 * (1 - e^{-.3*4})\}$$

$$= 13.9463 + 4.5392$$

$$= 18.4855$$

$$NOQ = 32.6326 + (0.27187282 * 12^2) - (0.01054104 * 12^3)$$

$$= 53.5667$$

Therefore:

$$\text{Delay} = 18.4855 + \{(1 - e^{-.3*4}) * 53.5667\}$$

$$= 55.9182.$$

Speed is then calculated as:

$$\text{Speed} = \frac{1}{1/40 + 55.9182/1000}$$

$$= 12.4 \text{ mph.}$$

Adjustments for the Effects of Progression

All of the QSIM analysis--including its uncongested delay function and the final equations--are based on the NETSIM results for the no-progression case. (This was defined as zero offsets in the timing of the signals in the test networks.) However, as shown in Table 5, progression results in significantly higher arterial speeds. Based on these data, it was observed that progression effectively acts to "reduce" the signal density. That is, with signal progression, the system behaves as if signal density was actually lower. Therefore, the problem was to develop an adjustment factor to reduce signals per mile in the delay prediction equations. The first step in estimating the adjustment factor was to examine the data in Table 5. For each level of signals per mile (6 and 10) and V/C ratio (0.2, 0.4, 0.6, 0.75, 0.85, and 0.95), the uncongested delay function was used to predict speeds. The next step was to add a factor to the signals per mile variable in the $(1 - e^{-.3n})$ term of the delay function to see how close the predicted speed could get to the actual speed under progression. The adjustment factor was varied iteratively until the average percent error was minimized; the factor was found to be approximately 0.167. This value implies that with progression the signal density can be thought of as 1/6 the signal density for no progression. For the high signal densities on which the factor was developed (Table 5), this ratio makes sense. However, for lower signal densities, the authors thought that the ratio was too high. To compensate for this, several mathematical functions were tested to see if the ratio could be lowered for low signal densities while still using the empirical information tested above. The form finally selected was:

$$n' = \frac{2n}{n + 2}$$

Where:

n' = signals per mile, adjusted for ideal progression

n = actual number of signals per mile.

This functional form produces more reasonable results. For example, at a signal density of 10 per mile, n' is 1.67 which corresponds to the empirical information and at low signal densities n' is also low. However, note that the NETSIM experiments on which the adjustment factor is based (Table 5) are for ideal progression conditions. Also, the original (fixed time) case assumes some degree of progression since signal spacing is relatively small and the timing offsets are zero. One way to think of the situation is to consider that the base models (fixed time) assume intersection arrival flows similar to the *HCM* Arrival Type 3 and the progression case arrival flows similar to Arrival Type 6. It is left up to the analyst to decide which case is most appropriate for the particular situation being studied. If the analyst believes the progression situation to be less than the pure ideal, but more favorable than the base case, an intermediate value can be chosen. **Therefore, the recommendation is to consider progression in some fashion when using any of the delay equations.**

Table 6. Coefficients for Freeway Delay Equations

PEAK PERIOD

	Weekday	Weekend	Combined
AADT/C			
AADT/C^2			
AADT/C^3			0.0347966374
AADT/C^4			-.0122499794
AADT/C^5	0.0001732632	0.0000253342	0.0016577982
AADT/C^6	-.0000116968		-.0000862934
AADT/C^7	0.0000001974	-.0000000318	0.0000015096

PEAK HOUR

	Weekday	Weekend	Combined
AADT/C			
AADT/C^2			
AADT/C^3	0.1055828979		0.0824450974
AADT/C^4	-.0417711090		-.0316382045
AADT/C^5	0.0059009773	0.0000256501	0.0043851790
AADT/C^6	-.0003319769		-.0002436727
AADT/C^7	0.0000064684		0.0000047234

DAILY

	Weekday	Weekend	Combined
AADT/C			
AADT/C^2			
AADT/C^3	0.0551483782	0.0096559689	0.0461854203
AADT/C^4	-.0189486676	-.0023347525	-.0154380323
AADT/C^5	0.0023287974	0.0001925990	0.0018559670
AADT/C^6	-.0001133801	-.0000044347	-.0000887095
AADT/C^7	0.0000018954		0.0000014614

Note: The equations should be applied up to an AADT/C value of 18.

Figure 2.
Speed Curves for Freeways
Weekdays

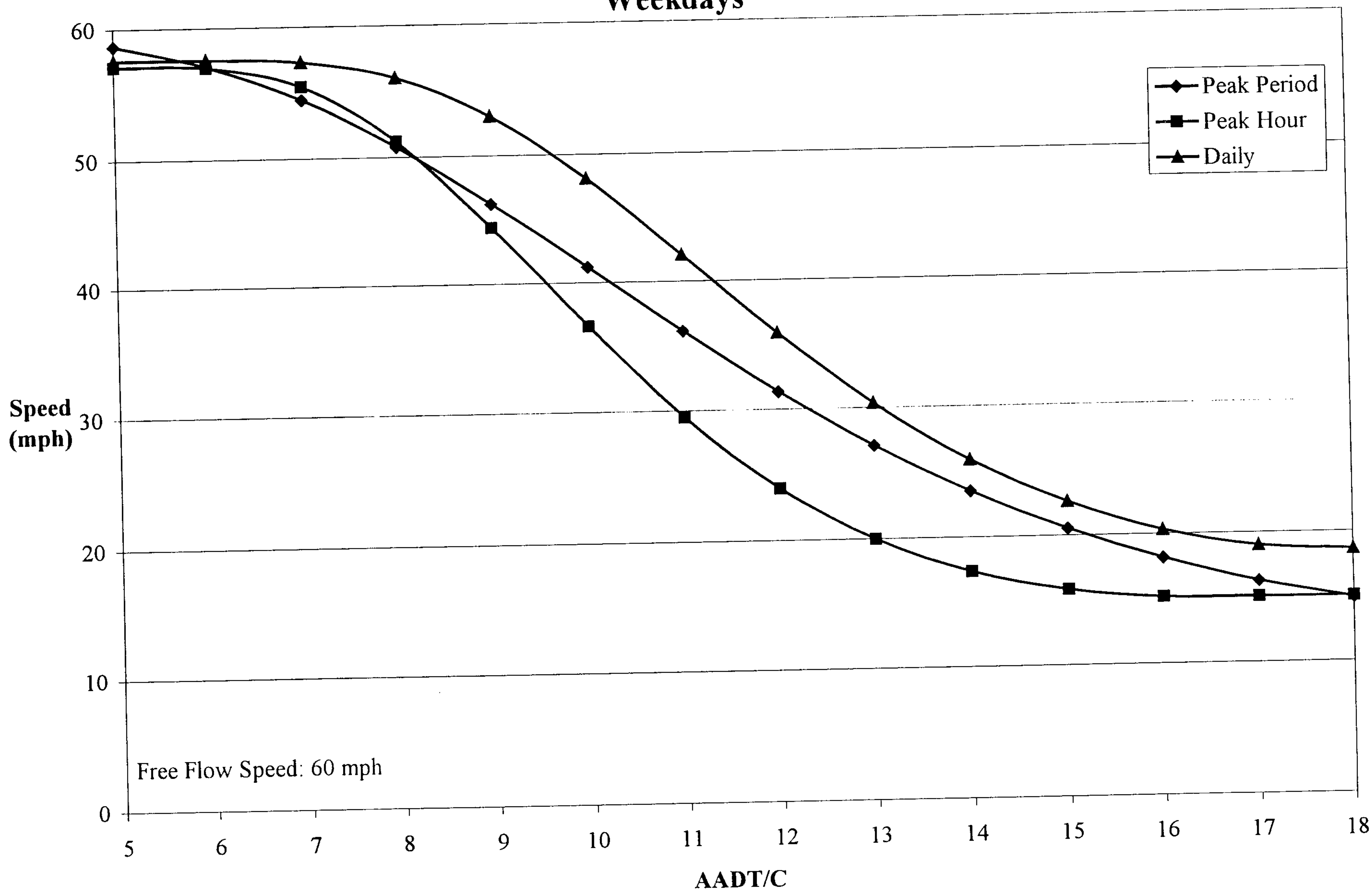


Table 7. Coefficients for Arterial Delay Equations

PEAK PERIOD

NO QUEUE EQUATIONS

	Weekday	Weekend	Combined
INTERCEPT	32.6326	32.8082	32.6270
AADT/C			
$AADT/C^2$	0.27187282	0.10420309	0.23911219
$AADT/C^3$	-0.01054104		-0.00898736
$AADT/C^4$		-0.00012311	
$AADT/C^5$			
$AADT/C^6$			
$AADT/C^7$			

QUEUE EQUATIONS

	Weekday	Weekend	Combined
AADT/C			
$AADT/C^2$			
$AADT/C^3$			
$AADT/C^4$			
$AADT/C^5$			
$AADT/C^6$	0.0000288004	0.0000025067	0.0000225491
$AADT/C^7$	-0.0000013948		-0.0000010684

AADT/C > 7 EQUATIONS

	Weekday	Weekend	Combined
(AADT/C - 7)	2.789265513		
$(AADT/C - 7)^2$			0.265213232
$(AADT/C - 7)^3$		0.0142379985	
$(AADT/C - 7)(1 - e^{-.3n})$			1.445427904
$(AADT/C - 7)^2(1 - e^{-.3n})$	0.259827162	0.1060087507	
$(AADT/C - 7)^3(1 - e^{-.3n})$			

Note: n = signals per mile. The equations should be applied up to an AADT/C value of 18.

Table 7. (Continued)

PEAK HOUR

NO QUEUE EQUATIONS

	Weekday	**Weekend**	**Combined**
INTERCEPT	32.9859	32.6524	32.8591
AADT/C			
$AADT/C^2$	0.36235337	0.13826170	0.31492585
$AADT/C^3$	-0.01545356		-0.01297063
$AADT/C^4$		-0.00019683	
$AADT/C^5$			
$AADT/C^6$			
$AADT/C^7$			

QUEUE EQUATIONS

	Weekday	**Weekend**	**Combined**
AADT/C			
$AADT/C^2$			
$AADT/C^3$			
$AADT/C^4$			
$AADT/C^5$	0.0004278173	0.0000639922	0.0003209231
$AADT/C^6$	-0.0000010179		
$AADT/C^7$			-0.0000007210

AADT/C > 7 EQUATIONS

	Weekday	**Weekend**	**Combined**
(AADT/C - 7)	4.935624291		
$(AADT/C - 7)^2$			0.430066318
$(AADT/C - 7)^3$		0.0213118297	
$(AADT/C - 7)(1 - e^{-.3n})$			1.916741055
$(AADT/C - 7)^2(1 - e^{-.3n})$	0.191184548	0.1612475797	
$(AADT/C - 7)^3(1 - e^{-.3n})$			

Note: n = signals per mile. The equations should be applied up to an AADT/C value of 18.

Table 7. (Continued)

DAILY

NO QUEUE EQUATIONS

	Weekday	Weekend	Combined
INTERCEPT	32.9015	32.8089	32.5177
AADT/C			
$AADT/C^2$	0.15119788	0.10661207	0.19583856
$AADT/C^3$			-0.00728030
$AADT/C^4$		-0.00015241	
$AADT/C^5$			
$AADT/C^6$	-0.00000333		
$AADT/C^7$	0.00000014		

QUEUE EQUATIONS

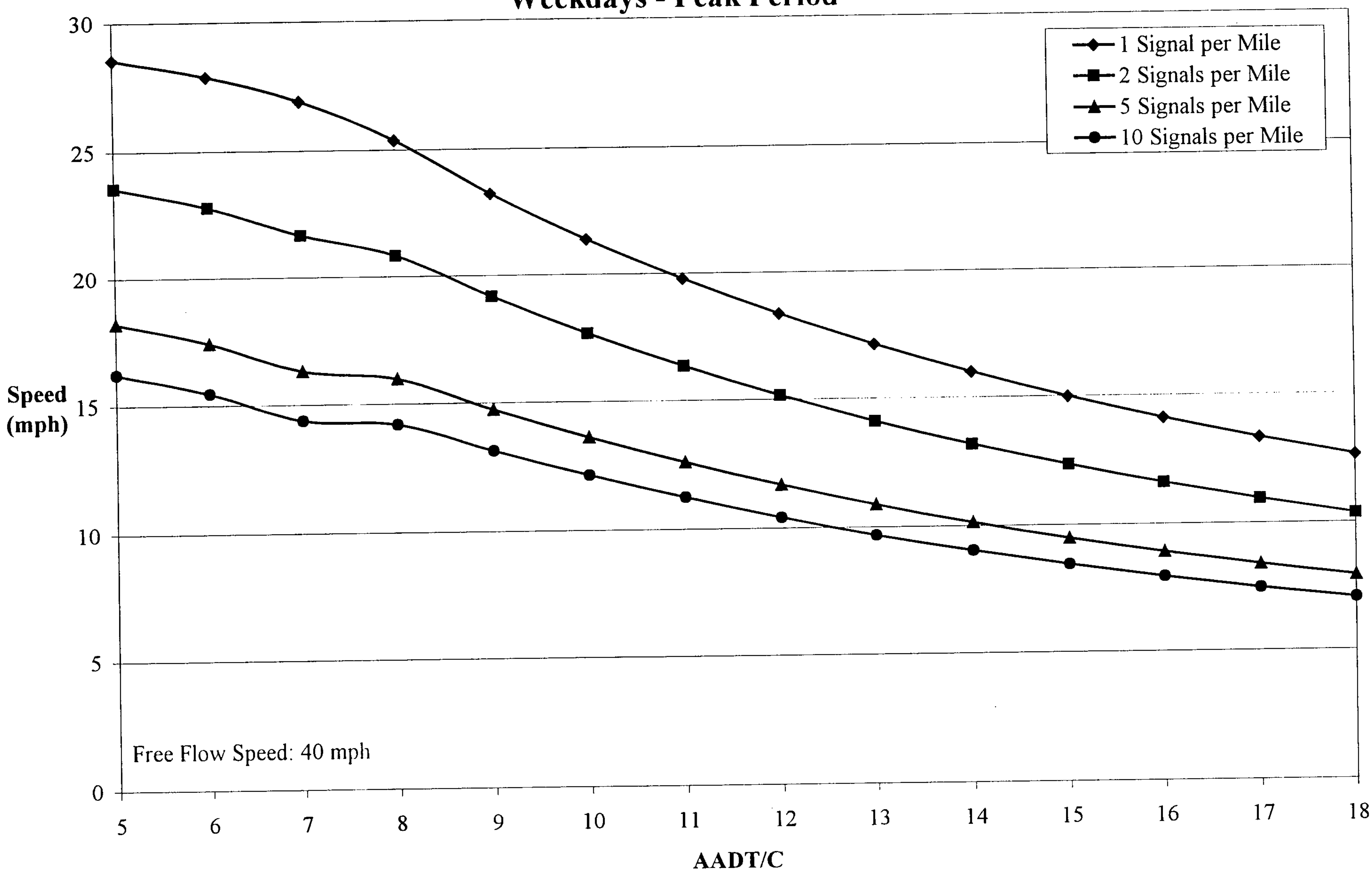
	Weekday	Weekend	Combined
AADT/C			
$AADT/C^2$			
$AADT/C^3$			
$AADT/C^4$			0.0007935231
$AADT/C^5$		0.0000325589	
$AADT/C^6$	0.0000144058		
$AADT/C^7$	-0.0000006601		

AADT/C > 7 EQUATIONS

	Weekday	Weekend	Combined
(AADT/C - 7)			
$(AADT/C - 7)^2$	0.1852764500		0.1586415772
$(AADT/C - 7)^3$		0.0102536589	
$(AADT/C - 7)(1 - e^{-.3n})$			
$(AADT/C - 7)^2(1 - e^{-.3n})$	0.1346060360		0.1211710141
$(AADT/C - 7)^3(1 - e^{-.3n})$		0.0097281924	

Note: n = signals per mile. The equations should be applied up to an AADT/C value of 18.

Figure 3.
Speed Curves for Arterials
Weekdays - Peak Period



3. APPLICATION OF THE NEW SPEED ESTIMATION METHODOLOGY

Introduction

The new speed estimation methodology is based on previous work for the HPMS models. These models use the HPMS data base, a statistical sample of highway segments that can be expanded to represent state and national highway conditions. The speed models are applied to each segment individually. By comparison, transportation-related air quality planning analysis is typically based on network (travel forecasting) models where many hundreds, sometimes thousands, of individual links exist. Speeds on these individual links are estimated during the traffic assignment process, usually with some variant of the Bureau of Public Roads (BPR) function. It is believed by many analysts that the speeds resulting from the final assignment are too crude for use in air quality analysis; speeds are used to achieve realistic traffic assignments (link volumes) rather than to match any observed or theoretical norms. Therefore, many urban areas use a "post-processing" approach where the final assignments and basic link data are used to estimate speeds external to the travel forecasting process. Most areas base their post-processors on standard and well-known procedures, such as the *HCM*, and estimate speeds link-by-link. The purpose of this Section is to show how the new speed equations may be used as the basis for such post-processing of network model output.

Comparisons to Standard Practice

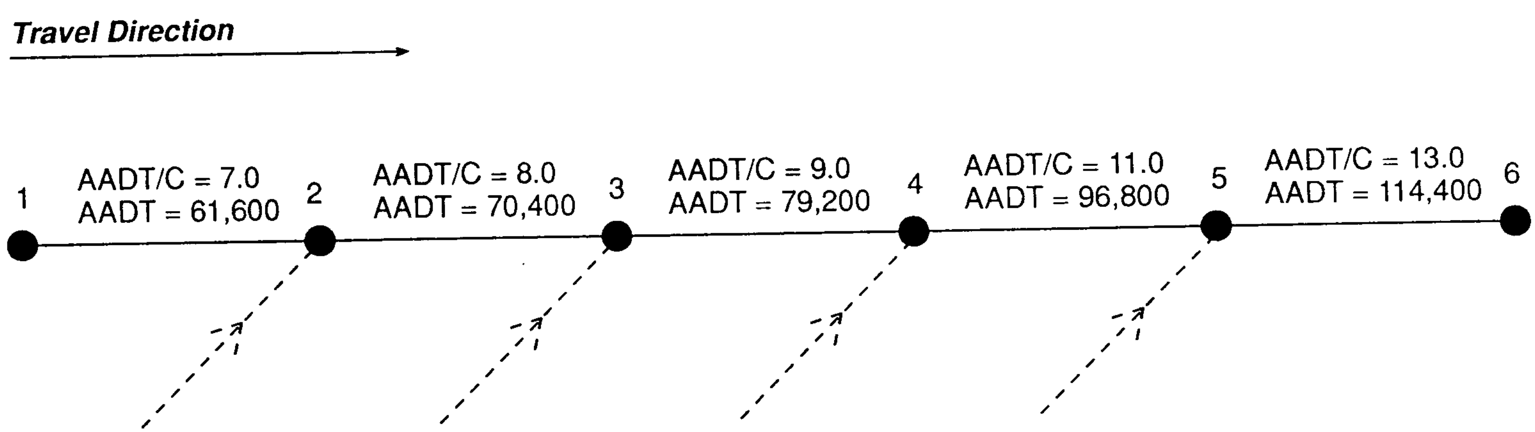
The new speed equations are based on roadway AADT because of its availability in HPMS. When the QSIM model is applied, AADT is converted to AWDT and Average Weekend/Holiday Daily Traffic (AHDT) depending on the case being studied. The final equations, however, relate AADT/C to speed so the effect of varying traffic on weekdays and weekends/holidays is automatically considered. Output from traffic forecasting models is almost always considered to be AWDT due to the way in which trip generation procedures are constructed. **Therefore, analysts should first convert the models' predicted volumes (AWDT) to AADT values.** The adjustment factor reported in Section 1 (i.e., the inverse of 1.0757) provides a default value in lieu of locally developed factors.

Freeways

Comparisons were made for both congested and uncongested links on a hypothetical urban freeway section as presented in Figure 4 and Table 8. The so-called "standard practice" scenario is based on applying the original BPR function for $V/C < 1.0$ and the modified BPR4 function for $V/C >= 1.0$ as post-processors to travel forecasting network data.[1] The reasons for these choices are that the original BPR function closely follows the latest freeway speed/flow curves from the 1994 *HCM*, and the BPR4 curve shows a reasonable degradation of speeds for V/C ratios over 1.0. In practice, most agencies would probably use a single function so that the comparison is geared towards what is felt

[1] Original BPR equation speed = $FFS/(1 + (0.15 * (V/C)^4))$
Modified BPR4 equation speed = $FFS/(1 + (V/C)^4)$

Where: FFS = free flow speed
V/C = volume-to-capacity ratio.



- Capacity = 4,400 vphpl

AADT/C	K[1]	D[1]
<11.0	9.8%	56.1%
≥11.0	8.4%	54.6%

- FFS = 60 mph

[1] *Average values from 1993 HPMS Data for 4/6-lane urban freeways with AADT/C between 9 and 13.*

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Figure 4. Base Data for Freeway Comparison

Table 8. Comparison of New Speed Equations to Standard Practice, Freeways

		Standard Practice: Weekday Peak Hour								New Equations[1] (Weekday)		
		Peak Direction			Offpeak Direction			Combined Directions		Peak Hour	Peak Period	Peak Period
Link	AADT/C	Volume	V/C	Speed[2]	Volume	V/C	Speed[2]	Volume	Speed	Speed	Speed	Volume[3]
(1,2)	7.0	3,390	0.77	57.0	2,650	0.60	58.9	6,040	57.8	55.4	54.5	26,830
(2,3)	8.0	3,870	0.88	55.0	3,030	0.69	58.0	6,900	56.3	51.2	50.8	29,980
(3,4)	9.0	4,355	0.99	52.4	3,410	0.78	56.8	7,765	54.3	44.4	46.2	33,920
(4,5)	11.0	4,440	1.01	29.4	3,690	0.84	55.8	8,130	41.4	29.5	36.1	42,280
(5,6)	13.0	5,250	1.19	20.0	4,360	0.99	52.4	9,610	34.7	20.0	27.1	51,500

AADT/C	K-factor[4]	D-Factor[4]
< 11	10.4%	58.7%
>= 11	8.1%	56.1%

[1]The new equations predict speeds for both directions simultaneously.
[2]Calculated using the original BPR function for V/C < 1.0; modified BPR4 for V/C >= 1.0 (see previous footnote)
[3]The peak period is from 7-10 a.m. and 4-7 p.m.; volumes are from the Appendix.
[4]K- and D-factors developed from 1993 HPMS data.

to be the best procedure.[1] The BPR functions and *HCM* procedures are applied on a hourly basis, usually the "peak hour for the peak direction." Because the new speed equations consider both directions simultaneously, the offpeak direction must be estimated separately for the standard practice case. Note that the hourly V/C ratio used for standard practice is based on the K- and D-factors rather than the temporal distributions on which the new speed equations are based. Note also that the volume differences along the hypothetical segment are large and probably would not be found in the field; the authors are using these for example purposes only. Because of the volume difference, two sets of K- and D-factors (derived from HPMS data) are used. The smaller K- and D-factors for the higher congestion case indicates that at least a small degree of peak spreading is accounted for, something that may not normally be done in practice unless states or local agencies also differentiate these factors as a function of volume/congestion.

The results, as presented in Table 8, demonstrate the implications of using standard practice versus the new speed equations. Considering only the peak hour, the new equations predict lower speeds with the gap between the procedures widening as congestion builds. Additionally, the effect of stochastic variation in traffic from day-to-day is also apparent: for an AADT/C of 9.0, the standard practice peak direction has a V/C ratio of 0.99, right at the boundary between stable and forced flow. The BPR function predicts relatively high speeds because the V/C ratio indicates that speeds are **always** in the stable regime. In contrast, the new equations do not assume that volumes will be constant from day-to-day for the peak hour, but on some days volumes will be high enough to kick flow over into the unstable regime.

Although not directly compared, the peak period speeds predicted using the new equations are likely to be a lot lower than those predicted using standard practice, depending on how local agencies address other hours around the peak hour. If they assume that the peak period is 6 hours per day (as assumed by the new equations) **and** if they also assume that speeds in all of these 6 hours are equivalent to speeds in the peak hour, then their BPR-predicted peak period speeds will be close, but still consistently higher, than those predicted by the new equations. If they assume a shorter peak period, then the volume (VMT) "exposed" to low speeds is decreased, a potentially important fact for air quality analyses. If they assume lower volumes in hours around the peak, then predicted speeds will increase. Overall, even if state and local planners followed the absolute best practices, they would still predict higher speeds than speeds predicted by the new equations developed by this research.

Signalized Arterials

A similar comparison was conducted for signalized arterials (Table 9). Because the current research verified that signal density is an extremely important factor in determining arterial speeds, the *HCM* (Chapter 11) methodology was considered to be the most desirable "standard practice" for post-processing speeds from network model output. (The BPR4 equation was also applied since it

[1]Even if local agencies choose not to apply the new speed equations developed in this research, they should consider using these two post-processor functions for saturated and unsaturated conditions rather than a single function.

Table 9. Comparison of New Speed Equations to Standard Practice, Signalized Arterials

AADT/C	AADT	HCM Methodology								BPR Speed	New Equations		
		Peak Direction			Offpeak Direction			Total Volume	Wtd Avg Speed		Peak Hour Speed	Peak Period Speed	Peak Period Volume
		Volume	V/C	Speed	Volume	V/C	Speed						
8.0	28,800	1,622	0.90	24.6	1,229	0.68	28.0	2,851	26.1	30.2	19.3	21.2	11,220
9.0	32,400	1,825	1.01	19.1	1,382	0.77	27.1	3,208	22.6	26.6	17.2	20.0	12,630
11.0	39,600	1,942	1.08	14.7	1,582	0.88	25.2	3,524	19.4	22.5	14.0	16.8	15,230
13.0	46,800	2,295	1.20	8.7	1,870	1.04	17.4	4,165	12.6	16.8	11.8	11.8	17,820

Arrival Type = 3 (minimal progression)
m = 16 (incremental delay factor)
C = 90 sec
g/C = 0.5
FFS = 40 mph
Sig/Mile = 2.0
Capacity = 1,800 (4-lane arterial)

AADT/C	K-factor	D-factor
< 11	9.9%	56.9%
>= 11	8.9%	55.1%

Note: K- and D-factors developed from 1993 HPMS data.

depends solely on V/C ratio and is easier to apply on a network basis.) For the peak hour (both directions), both the *HCM* and the BPR4 equation predict higher speeds than the new equations, although the *HCM* results are closer to the new equation results. At the highest congestion level compared (AADT/C = 13), the predicted speeds for the *HCM* and the new equations are closer due to the nonlinear nature of the *HCM* delay equations. The 6-hour peak period speeds predicted by the new equations are very close to those of the (single) peak hour, indicating that speeds are relatively insensitive to signal V/C ratio for the ranges studied. The same observations made for freeways regarding speed prediction for hours around the peak also apply to arterials.

A More Detailed Freeway Comparison

The comparisons presented in Tables 8 and 9 show the advantage of using the new speed equations to account for the temporal effects of congestion. However, the spatial effects of congestion on freeways, i.e., the spillback of queues from one link onto another, are not considered directly by the freeway equations. For consistency, the QSIM model tabulates speeds over a constant freeway link length (1.5 miles[1]), although it does keep track of the actual queue length even if it extends beyond the link over which speeds are tabulated. If a longer link length is used, the average speed on the link will be higher (even with the same input volume) because queues will be present over a smaller proportion of the total link length. If queues are allowed to extend back beyond the length of a congested link onto an uncongested link, predicted speeds will be lower on the (previously) uncongested link. In contrast, the lengths over which arterial speeds are computed vary with signal density. The effect of spillbacks are considered from signal to signal **within** the section being studied-- the effect of the queue spilling back behind the first signal in the segment is not considered. Therefore, the arterial equations account for some, but not all, of the spillback phenomenon.

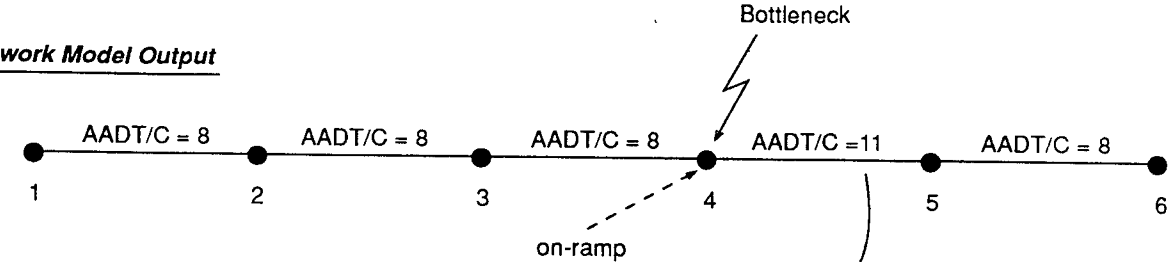
To address the issue of spillbacks, a methodology was developed for applying the equations on a freeway segment (multiple links) rather than on an individual link-by-link basis (as was done in Table 8). Figure 5 displays the procedure that first starts by addressing the "queue mislocation" in travel forecasting networks. Due to the way in which traffic is loaded onto networks, volumes well in excess of capacity can be assigned to links. In reality, these "congested" links never experience the assigned volume because a bottleneck will exist at the upstream node, and queues will form upstream from this point. Consider the network in Figure 5. Link (4,5) has an AADT/C value high enough that peak hour volumes exceed capacity. The reason for this occurrence is that extra volume is entering at node 4; thus, it is the bottleneck point. From here, the following steps are taken:

- Step 1: Adjust the Network for the Bottleneck Location. The simplest way of handling the misplaced queue is to move the volume from the link downstream of the bottleneck to the link immediately upstream, modify the conditions on the downstream link, and conduct the analysis from there. For hours when queuing is present, the downstream link is then treated as being influenced directly by the upstream queue: the link volume is the discharge volume from the queue, the speed at the start of the link is the queue speed from the upstream link, the speed at the end of the link is the speed predicted by the uncongested speed function using V/C = 1.0 from Eq. (6) (52.0 mph), and the overall link speed is the average of these

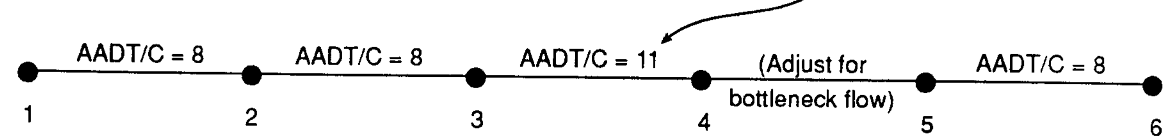
[1]The 1.5-mile link length was thought to be representative of average interchange spacing on typical urban freeways.

Travel Direction →

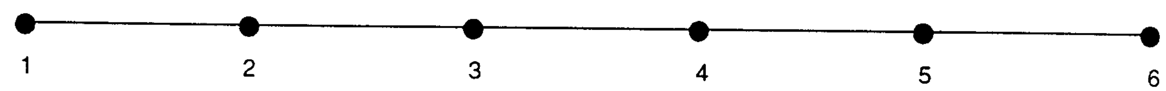
Step 0: Network Model Output



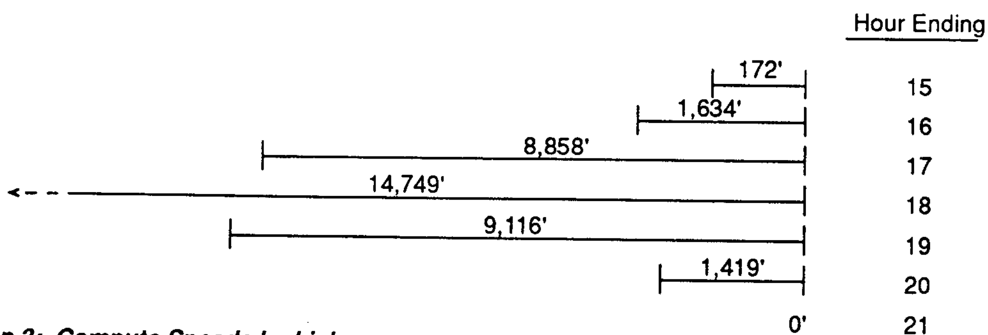
Step 1: Adjust for Bottleneck Location



Step 2: Build Queues by Hour



Note: Link length = 1.0 mile



Step 3: Compute Speeds by Link

			Queue Pct of Link			Queued Vehicles		Nonqueued (processed) Vehicles		Total	
Orientation	Hour	Link	Beginning	Ending	Average	Volume	Speed[1]	Volume[2]	Speed[2]	Volume	Speed
Weekday, OB	17	(3, 4)	31%	100%	66%	81	15.50	1,884	—	2,090	28.65[3]
		(2, 3)	0%	68%	34%	42	15.50	1,684	51.77	1,726	39.27[4]
		(1, 2)	0%	0%	0%	0	—	1,684	51.77	1,684	51.77[4]
		(4, 5)	—	—	—	—	—	—	—	1,884	40.33[5]
	18	(3, 4)	100%	100%	100%	123	15.50	1,864	48.41	1,987	22.32[3]
		(2, 3)	68%	100%	84%	103	15.50	1,668	48.41	1,771	20.77[4]
		(1, 2)	0%	100%	50%	61	15.50	1,668	48.41	1,729	31.98[4]
		(4, 5)	—	—	—	—	—	—	—	1,864	37.16[5]

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[1] As determined from the Orlando and Denver field data, the average speed in queues is 15.5 mph.

[2] Taken from QSIM output using the original AADT/C of the link.

[3] Computed using AADT/C = 11.

[4] Computed using Equation (6): Link Speed = [Queue Speed * (Queue Length/Link Length)] + [Nonqueue Speed * (1 - Queue Length/Link Length)].

[5] Average of speed at V/C = 1.0 and upstream speed.

NOTE: ALL VOLUMES ARE ON A PER LANE BASIS.

Figure 5. Application of the Speed Methodology to Consider Queue Spillbacks

two speeds, assuming it will take the full length of the link for vehicles to come up to final speed.

- Step 2: Build Queues by Hour. For this step, the data on queue lengths (measured in total vehicles) from the QSIM output must be used along with an assumed queue spacing.[1] With this information, it is then possible to build and dissipate queue distances by hour over the network.

- Step 3: Compute Speeds by Link. The queue length information is then used as shown in Figure 5 to compute link speeds. For the link immediately upstream of the bottleneck, the overall speed is taken directly from the QSIM output. For the remaining links, Equation (6) is used after the proportion of the link with a queue is determined.

The result of applying this process is to lower speeds on links that otherwise would have had higher (uncongested) speeds. In Figure 5, link (2,3) would have had a speed of 51.77 mph during the 4-5 p.m. hour (based on its AADT/C value of 8) if it were considered in isolation. However, since the queue has spread to include part of it, the modified procedure predicts a speed of 39.27 mph. Higher congestion levels would lead to queues influencing even more links; the maximum queue length for AADT/C = 13 is 840 vehicles per lane (almost seven miles).

The example provided above is for a simple case with a single bottleneck. Highway sections with multiple bottlenecks present a more difficult situation to model. One way to approach the problem of multiple bottlenecks is to locate the first bottleneck encountered by traffic and proceed as above. The downstream flows from the first bottleneck will have to be adjusted to account for the "gateway" effect of the first bottleneck. In some cases, this will remove some downstream bottlenecks because of the gated flow from the first bottleneck. If not, then queues should be built behind any downstream bottlenecks that still exist based on the revised flow. If the queues from the downstream bottlenecks build back past the first bottleneck, the queues should be added together.

Summary of the Research

This research has developed a new procedure for estimating vehicle speeds. From a theoretical standpoint, it has several advantages over other planning methods now in use:

- It is based on predicting the effects of traffic over an entire day by taking each hour in sequence. Hourly volumes are developed using temporal distributions developed from a large (713) set of urban ATRs from around the country. The effects of peak spreading as congestion builds are explicitly accounted for in the distributions.

- Day-to-day variations in traffic are considered by the model. The ATR data were used to determine the variability in hourly volumes. This information was used to vary volumes

[1]For this research we used a queue spacing of 43 feet, comprised of an average vehicle length of 18 feet and a from bumper-to-rear-bumper gap of 25 feet.

stochastically within the QSIM model, resulting in a more reliable estimate of speeds than would be obtained if only averages were used. The reason for this is the nonlinear nature of the delay. Consider a volume very near to capacity; this is the average volume that might occur on the facility over the course of a year. Only a small increase in volume will kick the flow over into the unstable speed regime. This effect, which goes unnoticed if the average is used, is addressed by allowing volumes to vary stochastically.

- Uncongested speed functions based on applying the FRESIM and NETSIM microscopic simulation models were developed. The arterial speed function contains a term for signal density, a highly important determinant of arterial speeds. The positive effects of progression are also accounted for by the arterial equations.

- The effects of congestion are incorporated by combining queuing analysis with the hourly volume estimation discussed above. Queues are built and dispersed over time and their effects on speeds are computed. The model uses an assumed speed for queued vehicles on freeways based on extensive data from freeways in Orlando and Denver. Also, a freeway queue discharge rate lower than capacity is used to dissipate queues.

- Both tables and equations are developed that allow the user flexibility in how to apply the research. Equations are developed that predict speeds for both directions on a link for the peak hour (4-5 p.m. for AADT/C <= 10 and 5-6 p.m. for AADT/C > 10), the peak period (7-10 a.m. and 4-7 p.m.), and the entire day. If only one direction is required, the data tables in the Appendix should be used (Ref. 6). Separate equations were developed for weekdays, weekends/holidays, and all days combined, but most analyses will probably focus on the weekdays.

5. UPDATE OF EQUATIONS FOR *STEAM*

To develop speed equations for STEAM, the procedures described in Sections 1-3 of this paper were modified as follows:

- Curves were fitted to using the ratio of Average Weekday Traffic to Capacity (AWDT/C), rather than the ratio of Annual Average Daily Traffic to Capacity (AADT/C). STEAM is designed to operate with average weekday traffic, as developed from MPO travel forecasting models. The average speeds developed for STEAM do not include weekends and holidays.

- Most MPOs do not code signal spacings for signalized arterials as part of their network description files. Rather than requiring them to develop this information, a signal spacing of two signals per mile was assumed.

- The "uncongested speed function for freeways" (Equation 2 on page 9) was modified to include the effects of incidents. The methods used to derive the new speed function are discussed at length below.

Our analysis of incidents did not explicitly consider the interaction between incidents and recurring congestion (i.e., highway segments for which the demand volume is greater than capacity). The incident analysis procedure was limited to situations where the ratio of volume to capacity is less than or equal to 1.0. The relationship between incidents and recurring congestion is the subject of "Sketch Methods for Estimating Incident-Related Impacts", an on-going study being performed by Cambridge Systematics for FHWA.

The following steps were carried out to determine the effects of incidents on average speeds on uncongested freeways:

- Develop a model for estimating total vehicle hours of delay due to an incident as a function of the duration of the incident, volume, capacity before the incident, and the capacity during the incident.

- Apply the model and data on the magnitude, frequency, and duration of incidents to develop equations for estimating average incident delays as a function of volume-to-capacity ratio.

- Incorporate the equations for average incident delays into QSIM, in order to estimate peak, off-peak, and average weekday delays due to congestion for different AWDT/C ratios.

- Fit a curve to the results, in order to calculate congestion delay as a function of AWDT/C.

Total Delay Due to an Incident

The following variables are used in the modeling of total delay due to an incident:

- V = average volume on the freeway (in vehicles per hour) upstream from the site of the incident. It is the rate at which vehicles arrive at the back of the queue after an incident occurs and a queue forms.
- C = the capacity (LOS E) of the freeway prior to the occurrence of the incident (in vehicles per hour).
- r = capacity reduction factor due to the incident. The quantity rC is the rate at which vehicles pass the incident before it is cleared. If $r = 0$, the freeway is completely blocked by the incident.
- g = average "getaway" volume from the queue after the incident is cleared, expressed as a factor of C.
- T_i = incident duration (in hours)
- T_g = duration of the getaway period during which the queue is dissipating (in hours)
- Q = maximum queue length (in vehicles)
- D_i = delay incurred during the incident (in vehicle hours)
- D_g = delay incurred during the getaway period (in vehicle hours)
- D = total delay incurred as a result of the incident (in vehicle hours)

The model calculates D as a function of V, C, r, g, and T_i. For simplicity, the model assumes that V is constant over the period during which the highway system is affected by queuing. If V is actually increasing over time, then the model will understate total delay; conversely, if V is decreasing then it will overstate total delay.

An incident will cause a queue if the freeway volume V is greater than the available freeway capacity during the incident (i.e., if $V > rC$). The queue will grow in length until the incident is cleared (T_i hours after the incident occurred). The queue growth rate during the incident (in vehicles per hour) is equal to the rate at which vehicles arrive at the end of the queue (V) minus the rate at which they get past the incident (rC). The maximum queue length, which occurs at that point in time when the queue is cleared, is calculated as follows:

$$Q = (V - rC)\, T_i$$

Because the queue grows from a length of zero (when the incident occurs) to a length of Q (when the incident is cleared), the average length of the queue during the incident is Q/2. Hence, the delay incurred by vehicles during the incident is calculated as follows:

$$D_i = (1/2)\, Q\, T_i = (1/2)(V - rC)\, T_i^2$$

After the incident is cleared, the queue will gradually dissipate, at a rate depending on the getaway capacity and the volume:

$$T_g = Q/(gC - V)$$

Hence, the delay incurred by vehicles while the queue is dissipating is calculated as follows:

$$D_g = (1/2)\, Q\, T_g = (1/2)\, Q^2 /(gC - V) = (1/2)\, (V - rC)^2\, T_i^2 /(gC - V)$$

Total delay due to the incident is then calculated (after much algebra) as follows:

$$D = D_i + D_g = (1/2)\, C\, T_i^2\, (V/C - r)\, (g - r) /(g - V/C)$$

Average Incident Delays as a Function of V/C

A spreadsheet was developed to apply the above equation to estimate average delays due to incidents as a function of volume-to-capacity ratio. In the spreadsheet, incidents were classified by type (abandoned vehicle, accident, debris, mechanical/electrical, stalled vehicle, flat tire, and other) and severity (shoulder; one, two, three, or four lanes blocked). For each class of incident, data from Sullivan et. al.1 were used to estimate the following quantities:

- Frequency (number of incidents per million vehicle miles)
- The capacity reduction factor (r in the above equation)
- Mean and variance of incident duration. To estimate the expected value of T_i^2 in the above equation, we use the fact that the expected value of the square of any random variable is equal to the sum of its variance and the square of its mean.

Getaway volumes (gC) were estimated based on outputs from FHWA's traffic micro-simulation program, FRESIM. Simulations of incidents on freeways using FRESIM indicate that incident getaway volumes are slightly higher than Level of Service E capacities, since vehicle spacings tend to be reduced as vehicles increase their speed together in departing from a standing queue. A value of 1.067 was used for g, based on the FRESIM results.

Estimates of average delays due to incidents were developed for volume-to-capacity ratios ranging from 0.05 to 1.0 for freeways with two, three, and four lanes in each direction. The following curves2 were then fit to the results:

---

1 Sullivan, Taff, and Daly *A Methodology for Measurement and Reporting of Incidents and Prediction of Incident Impacts on Freeways*; prepared for FHWA by Ball Systems Engineering Division; April 1995.

2 Equations are not applicable when V/C > 1.0; i.e., when demand volume exceeds capacity so that queuing occurs even if there are no incidents.

Freeways with Two Lanes in Each Direction

$$\mu = 0.0154\ (V/C)^{18.7} + 0.00446\ (V/C)^{3.93}$$

Freeways with Three Lanes in Each Direction

$$\mu = 0.0127\ (V/C)^{22.3} + 0.00474\ (V/C)^{5.01}$$

Freeways with Four or More Lanes in Each Direction

$$\mu = 0.00715\ (V/C)^{32.16} + 0.00653\ (V/C)^{7.05}$$

where

- μ is average delay due to incidents in hours per vehicle mile
- V is volume in vehicles per hour
- C is capacity in vehicles per hour

The above equations are based on field data regarding the magnitude, frequency, and duration of incidents. However, the equations themselves have not yet been subject to empirical testing. Obtaining a data set that can be used for testing these equations has proved to be extremely difficult. Serious incidents are rare events, so it's necessary to obtain a data set that covers an extended period of time to determine their (average) effects on delays. Also, most traffic monitoring data focuses on volumes, densities, and speeds at specific locations, not average speeds along an extended length of highway. Further, time periods during which speeds may be greatly affected by incidents are sometimes dropped from data sets as "bad" data.

The equations presented above reflect average delays due to incidents and do not explicitly include sensitivity to incident rates, type, severity, and duration. This is because STEAM is a system model, and planning agencies seldom have incident data to provide as input to STEAM. However, the spreadsheet developed for this study is sensitive to incident rates, type, severity, and duration, and could be used to analyze policies that affect these measures.

Revised Equation for Uncongested Delay

The equation for delay (in hours per mile) on highway sections not subject to recurring congestion was revised to incorporate the effects of incidents:

$$d_{vc}' = d_{vc} + \mu - Q_s\, \mu\, d_{vc}$$

where

- d_{vc} is travel time in hours per vehicle mile for highway segments not subject to recurring congestion or incidents.

- d_{vc}' is travel time in hours per vehicle mile for highway segments, revised to include the effects of incidents

- μ is the added delay in hours per vehicle mile due to incidents

- Q_s is average queue speed on freeways (15 miles per hour was assumed, as discussed in Section 1, page 11)

For d_{vc}, we calculated delays using the revised BPR curve developed by Skabardonis and Dowling:

$$d_{vc} = (1+0.2\ (V/C)^{10})/F$$

where F is free-flow speed in miles per hour on the freeway.

The third term in the above equation d_{vc}' is included to avoid double-counting incident and non-incident delay on highway sections that are covered by queueing as a result of an incident. The product $Q_s\ \mu$ is the fraction of highway sections covered by queuing as the result of an incident.

The new equation for uncongested delay was inserted into the QSIM program. QSIM estimates of total congestion delay were obtained for ratios of average weekday traffic to capacity ranging from 1 to 15. Smooth curves relating congestion delay and AWDT/C were then fit to the QSIM outputs (see Exhibit 1).

Exhibit 1
STEAM Speed Models

$$S = \frac{1}{\frac{1}{F} + D}$$

$$D = c_1 x^{c_2} e^{c_3 x} \qquad \text{for } x <= c_0$$

$$D = c_4\left(1 - c_5 x^{c_6} e^{c_7 x}\right) \qquad \text{for } x > c_0$$

where

- S is average speed in miles per hour
- F is free-flow speed[1] in miles per hour.
- D is congestion delay in hours per vehicle mile
- x is the ratio of average weekday traffic to hourly capacity for the section (AWDT/C)
- c_0 to c_7 are constants, given in the following table.

	Freeways				Signalized Arterials		
	Daily	Peak	Off-Peak		Daily	Peak	Off-Peak
C0	1.05E+01	1.21E+01	1.11E+01		9.74E+00	9.62E+00	1.26E+01
C1	2.39E-08	2.35E-07	1.13E-07		5.62E-04	8.44E-04	4.35E-04
C2	3.75E+00	3.29E+00	2.52E+00		8.62E-01	6.15E-01	9.37E-01
C3	2.87E-01	2.35E-01	2.59E-01		7.39E-02	1.24E-01	5.16E-02
C4	5.00E-02	5.00E-02	5.00E-02		1.66E-01	1.66E-01	1.66E-01
C5	1.494E-02	2.865E-04	1.058E-03		1.313E-01	8.591E-03	1.177E-02
C6	3.42E+00	7.00E+00	4.91E+00		1.61E+00	3.80E+00	2.91E+00
C7	-3.72E-01	-7.97E-01	-4.49E-01		-1.73E-01	-4.07E-01	-2.37E-01

1 Free-flow speed is that which occurs when traffic volumes are very low. On interrupted flow facilities, they include delays due to traffic control devices but exclude any congestion-related delays.

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