SHRP 2 Capacity Project C16

The Effect of Smart Growth Policies on Travel Demand

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Accelerating solutions for highway safety, renewal, reliability, and capacity

TRANSPORTATION RESEARCH BOARD
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SHRP 2 C16 THE EFFECT OF SMART GROWTH POLICIES ON TRAVEL DEMAND

FINAL REPORT

Prepared for
The Strategic Highway Research Program 2
Transportation Research Board
of
The National Academies

Resource Systems Group
Fehr & Peers
Dr. Robert Cervero
Dr. Kara Kockelman
Renaissance Planning Group

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ABSTRACT

Smart growth policies are often considered by planning agencies as a strategy to reduce congestion, emissions and other impacts on travel demand, but most of the current planning application tools are not sufficiently sensitive to the aspects of smart growth policies needed to determine travel demand. This project reviewed available research to determine the underlying relationships between households, firms and travel demand and then turned these relationships into a regional scenario planning tool that can be used to evaluate the impacts of various smart growth policies. The Smart Growth Area Planning (SmartGAP) tool synthesizes households and firms in a region and determines the travel demand characteristics of these households and firms based on the characteristics of their built environment and transportation policies affecting their travel behavior. The software has been developed with a Graphical User Interface (GUI) to allow non-technical users to be able to use the tool for planning activities more easily. Three pilot tests were completed to demonstrate the usefulness and reasonableness of SmartGAP to evaluate how smart growth policies affect travel demand, environmental, financial and economic, location and community impacts.

EXECUTIVE SUMMARY

The Smart Growth Network, a partnership of the US EPA and other government and business and environmental organizations, defines Smart Growth in terms of ten basic principles:

- Mixed land uses
- Take advantage of compact building design
- Create a range of housing opportunities and choices
- Create walkable neighborhoods
- Foster distinctive, attractive communities with a strong sense of place
- Preserve open space, farmland, natural beauty, and critical environmental areas
- Strengthen and direct development towards existing communities
- Provide a variety of transportation choices
- Make development decisions predictable, fair, and cost effective
- Encourage community and stakeholder collaboration in development decisions

These characteristics of the urban form and built environment are generally associated with a variety of benefits to environmental protection, economic and social benefits, public health and quality of life. One of the better established benefits of Smart Growth is the reduction in unnecessary travel and resulting reductions in impacts on congestion and delay and their costs to business and households, and reduced infrastructure expansion, energy consumption, greenhouse gas and other emissions.

Comparisons of travel data among regions of different urban forms, among communities within those regions and development areas within those communities all demonstrate that smart growth development vehicle travel rates are lower than conventional suburban forms. They show that the extent of reduction is proportional to the degree to which the development is compact, diverse, location efficient, served with a variety of transportation choices, and endowed with a sense of place.

Overview of the Project

The second Strategic Highway Research Program (SHRP 2) was authorized by Congress to address some of the most pressing needs related to the nation's highway system. SHRP 2 addresses four strategic focus areas: the role of human behavior in highway safety (Safety); rapid highway renewal (Renewal); congestion reduction through improved travel time reliability (Reliability); and transportation planning that better integrates community, economic, and environmental considerations into new highway capacity (Capacity). SHRP 2 is administered by the Transportation Research Board of the National Academies under a Memorandum of Understanding with the Federal Highway Administration and the America Association of State

Highway and Transportation Officials. The goal of the SHRP 2 Capacity project (C16) was to understand and evaluate the effect of smart growth policies on travel demand.

While there is an abundance of literature on the transportation-land use connection and the impact of various smart growth strategies on travel demand, there a lack of practical guidance and tools for translating these insights at key decision points in planning and project development. The SHRP 2 project on Smart Growth (C16) will help practitioners to understand how smart growth impacts travel demand in two ways: first, through a synthesis of the research, and second, through a user-friendly software tool that can be used to evaluate the impact of smart growth policies on travel demand. The products of this research relied on existing information and resources. These products will be available through the Transportation for Communities – Advancing Projects through Partnerships (TCAPP) web site, which is the online delivery source for most Capacity research in SHRP 2. It provides a systematic approach for reaching collaborative decisions, and it identifies key decision points in transportation decision making.

Background Research

The background research sought to identify direct experience by practitioners and academics in the area of how smart growth policies affect travel demand. The work by practitioners was obtained through a series of interviews with directors, administrators, principal and senior transportation planners and engineers, and technical specialists and by reviewing published work by both practitioners and academics. The interviews provided a clear indication of information needs for metropolitan planning organizations and state departments of transportation agencies. Most agencies were interested in scenario planning as a strategy for evaluating smart growth, to allow for the testing of many higher-level scenarios across a broad range of issues with a quick turn-around. Many agencies also identified the need for coordination, cooperation and communication between regional and state transportation agencies and local land use agencies on land use policy, since land use regulations are controlled by local governments.

The synthesis of existing research covered five topics, as shown in Table ES-1. This research allowed for the summarization of the well-established relationships and the gaps in research. The well-established relationships are drawn primarily from studies where these impacts were observed and the gaps in the research are found in impacts that are reflected in other parts of the system (such as regional effects of congestion) or in other aspects of travel (such as peak demand or work trips) that are not directly observable.

Table ES-0-1 Summary of Background Research

Topic	Well-established Relationships	Gaps in Research
Built environment impact on peak auto demand	Impact on daily travel	Impact by time of day
Mobility by mode and purpose	Impact on daily travel	Impact by trip purpose
Induced traffic and induced growth	Capacity expansion on an expanded facility	Route shifts, time of day shifts, mode shifts, induced trips, new destinations, growth shifts on the network; effects of operational improvements, land use plans
Relationship between smart growth and congestion	Localized effects	Macro-level or regional effects
Smart growth and freight	Freight is necessary for population centers	Impacts of loading docks, truck routing, full-cost pricing, freight facilities and crossings, inter-firm cooperation, stakeholder communication

Background research also included a synthesis of performance metrics and analytical tools that are used to evaluate the impact of smart growth policies on travel demand. Performance metrics were summarized at three levels: transportation specific metrics, metrics that indicate the effectiveness of the regional and local integration of transportation and land use, and higher-level metrics that capture the effects of land use and transportation decisions on a "triple bottom line" of economic, environmental and societal impact. These metrics provided a starting point for the development of performance metrics to be included in this work. There were three types of analytical tools evaluated in this research phase:

- Simple spreadsheets to address a sub-set of planning factors and performance measures
- Sophisticated GIS tools that allow scenario planning at the land use parcel level and produce a large variety of performance indicators
- Travel demand and land use forecasting models developed by Metropolitan Planning Organizations (MPOs) that are sometimes supplemented with a visual interface "dashboard" for presenting smart growth results

These tools vary by the level of detail, level of sophistication, scale (micro/project level, meso/corridor level, and macro/regional) and performance metrics they can produce.

Smart Growth Area Planning (SmartGAP)

A Smart Growth Area Planning (SmartGAP) tool was developed for regional decision-makers of transportation and land use policies to conduct scenario planning of smart growth policies and determine their impact on travel demand. This tool was designed to address as many of the limitations identified in the research as possible and to provide a tool that filled a gap in the set of available tools. SmartGAP evaluates regional scenarios based on changes in the built environment, travel demand, transportation supply, and transportation policies being considered. SmartGAP is a robust statistical package which tracks the characteristics of individual households and firms in a region and determines the travel demand from these characteristics. The relationships in the SmartGAP tool were based upon the background research conducted for the project. The built environment is defined as a set of 13 place types, as shown in Figure ES-0-1.

	Area Type			
Development Type	Urban Core	Close in Community	Suburban	Rural
Residential	✓	✓	✓	
Employment	✓	✓	✓	
Mixed-Use	✓	✓	✓	
Transit Oriented Development	✓	✓	✓	
Rural/ Greenfield				✓

Figure ES-0-1 Place Types for Households and Firms in SmartGAP

SmartGAP evaluates a series of performance metrics resulting from smart growth scenarios: community impacts, travel impacts, environmental and energy impacts, financial and economic impacts, and location impacts. These provide a rich assessment of each scenario at a regional scale. SmartGAP is designed to operate at a regional scale and is flexible in how the place types are applied in each region. All of the input data can be developed from available data sources and these are provided with the application. If a regional agency has local data, these can be used in place of the available data in the system. The software was developed using R, an open source statistical package to allow for wide distribution. SmartGAP has a graphical user interface with a user-friendly set of menus and tabs as shown in Figure ES-0-2

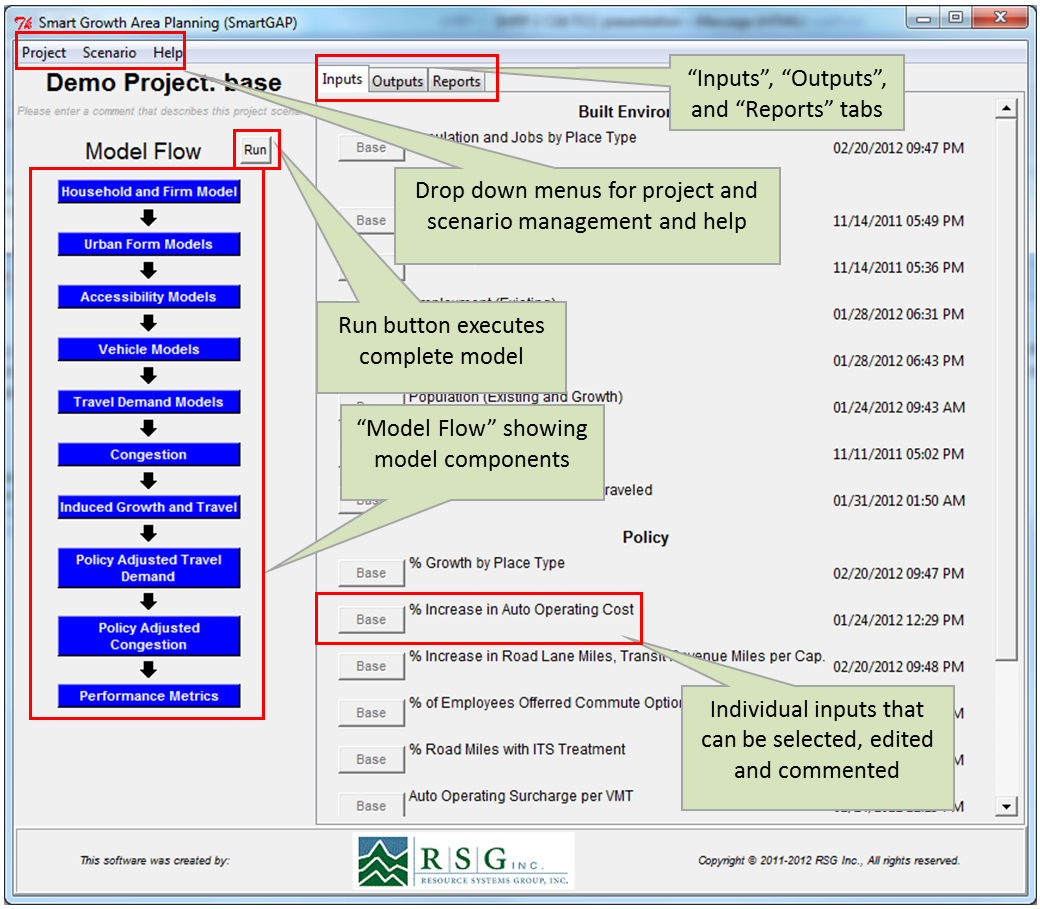


Figure ES-0-2 SmartGAP Graphical User Interface

Pilot Tests

In order to test the usefulness and reasonableness of the SmartGAP tool, three planning agencies conducted test implementations of the software and one additional in-house test was conducted:

- Atlanta Regional Commission (ARC) conducted a large MPO test
- Thurston Regional Planning Council (TRPC) conducted a small MPO test
- Maryland Department of Transportation (MDOT) conducted a larger urban/suburban county and a smaller rural county test
- RSG conducted a test in the Portland Metropolitan region

Each test consisted of 8 standard scenarios so that it was possible to compare cross regions and to understand the usability of the software, the complexity of developing input data, the usefulness of the performance metrics, and the reasonableness of the results. There are many other scenarios that can be tested, based on adjusting any of the data or policy inputs. The planning agencies provided valuable feedback to improve the software and user's guide:

- Performance metrics were consistent with expectations

- Installation and input file preparation were easy
- Regional policy scenario testing is useful for smaller MPOs without advanced travel demand models and for pre-screening policy scenarios in larger MPOs with advanced travel demand models
- Run times were reasonable

The research and software developed in this project offers a useful and effective means to better understand the impact of smart growth policies on travel demand. During the course of the project, there were some suggestions for longer term enhancements to SmartGAP that may be considered to provide additional capabilities and sensitivities but were not possible within the time and resources of the current work. These provide a road map for future versions of SmartGAP.

Products

In summary, the major results of the project offer two products to facilitate improved communication, interaction and partnerships between decision-makers and planners in both the transportation and land use arenas:

- A decision support software tool for regional and local planners to test smart growth scenarios and evaluate their impact on travel demand
- On-line resources to understand the dynamics and inter-relationships of smart growth strategies with the performance of a transportation investment as background and a supplement to the software tool

These resources can bridge the gap between regional planning visioning exercises and transportation plans in relation to the evaluation of smart growth strategies. This will allow state, regional and local agencies to engage in the evaluation of smart growth strategies quickly and easily so that promising smart growth strategies can be identified and pursued in the land use and transportation planning processes. This can also supplement more sophisticated modeling efforts, which can be used to evaluate specific smart growth projects. It is designed to be accessible to land use and transportation planners with no modeling experience.

CHAPTER 1. INTRODUCTION

Project Objectives

The overall goal of the SHRP 2 C16 project was to provide transportation planning agencies with improved tools and methods for more accurately and comprehensively integrating transportation investment decision-making with land development and growth management. To achieve this objective, there were several objectives:

- Understanding the critical decision points in the transportation planning process for highway capacity and assessing whether, how and to what extent smart growth approaches to land use policies and planning may affect demand for such capacity.
- Reporting on existing research to understand the dynamics and inter-relationships of smart growth strategies with the performance of a transportation investment.
- Building on existing applications to identify the range of features and capabilities these tools and methods need to represent, including the performance metrics needed to assess smart growth alternatives.
- Facilitating improved communication, interaction and partnerships between decision-makers and planners in both the transportation and land use arenas.

There were two primary products that were developed to meet these objectives. First, a synthesis of smart growth research and existing applications designed to evaluate smart growth policies was developed. Second, a software tool that filled the planning agency needs for evaluating smart growth scenarios and was easy to use was built, which allows decision-makers and planners in the transportation and land use fields to use the same package. In addition, the software was tested by three planning agencies in a series of pilot tests.

Research Approach

The SHRP 2 C16 project provided tools, methods, and resources for transportation planning agencies in the U.S. to evaluate the effects of smart growth policies on travel demand. The project built on existing work in this field, while recognizing that this is a relatively new arena of study in transportation planning. The development of tools and on-line resources relied on research, performance metrics and application tools already in use. All recommended tools and resources were reviewed by the Technical Expert Task Group (TETG) and by select Metropolitan Planning Organizations (MPOs) and state Departments of Transportation (DOTs) who engaged in the project's pilot studies. Figure 1-1 presents the overall approach to the project. The TETG is a peer review panel for this study that reviewed and guided the overall technical direction of the work. The approach involves collaboration with Framework for Collaborative Decision Making on Additions to Highway Capacity (SHRP 2 C01) and integrating SHRP 2 Products in the Collaborative Decision-making Process (SHRP 2 C07) teams at two points in the process, as shown in Figure 1-1. Presentations of deliverables were made to the TETG after the initial research was conducted, after the tools and on-line resources were developed, and after the final report was complete. Presentations were made to SHRP 2

Technical Coordinating Committee (TCC) for Capacity Research along with the C01 and C07 teams during Task 10 to present this solution for highway capacity research. In addition, the C01 team was consulted to put the SmartGAP products on the Transportation for Communities – Advancing Projects through Partnerships (TCAPP) web site.

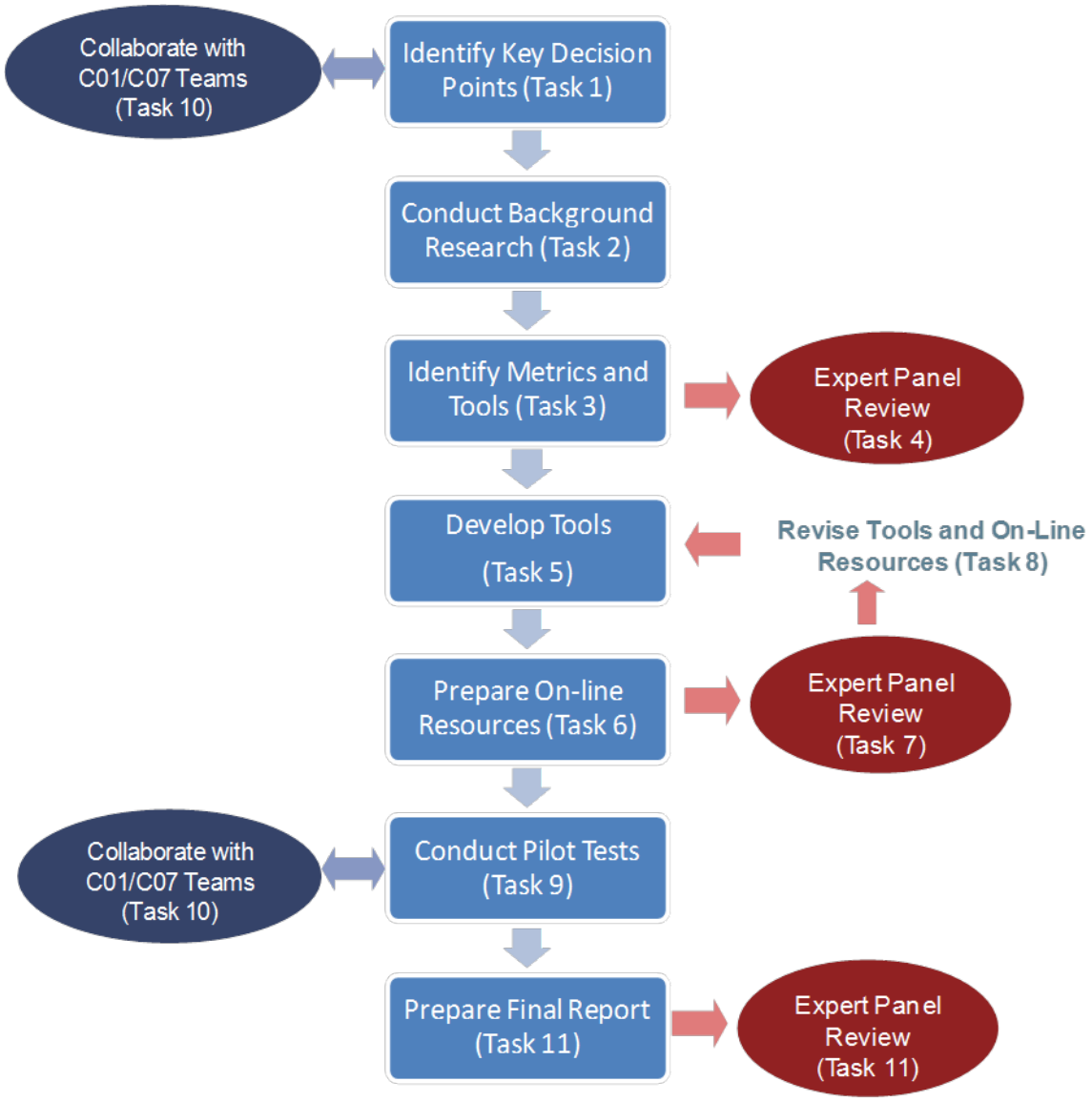


Figure 1-1: Overview of Approach

The research focused on a framework for how smart growth influences travel demand, as illustrated on Figure 1-2. This framework provides an understanding of these areas:

- The built environment's impacts on peak auto demand (focuses on how smart growth influences peak period demand (A ->C->D for variable-based analysis and B-> C-> D for case-based analysis as shown on Figure 1-2)
- Mobility by mode and purpose (addresses the built environment's impacts on peak auto demand for these market segments)
- Induced traffic and induced growth (can less traffic from smart growth be offset by the traffic inducing impact of better flowing traffic shown as E-> C and E-> B as shown on Figure 1-2?)
- Relationship between smart growth and congestion (denser development may cause spot congestion, even though trip generation rates and vehicle miles traveled (VMT) per person or per household may decrease shown as C-> D as shown on Figure 1-2)
- Smart growth and freight traffic (not shown explicitly in the framework)

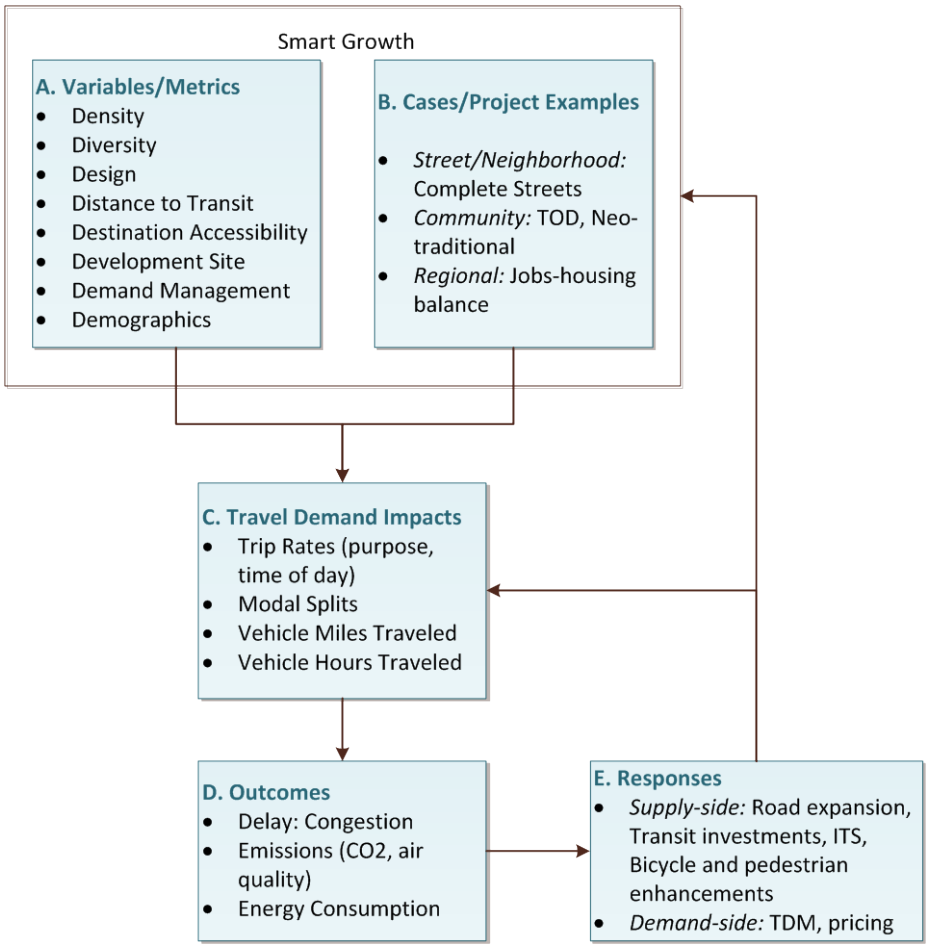


Figure 1-2: Smart Growth and Travel Demand Conceptual Framework

Organization of this Report

This is the draft final report for the project and covers the three primary products of this research:

- Background Research (Chapter 2) on key decision points for smart growth in the planning process, the built environment's impacts on peak auto demand, mobility by mode and purpose, induced traffic and induced growth, relationships between smart growth and congestion, and smart growth and freight traffic. This also includes a summary of the key findings from the research and the gaps in researchers' knowledge.
- Smart Growth Area Planning Tool (SmartGAP) (Chapter 3) including background and intended users, model structure, household and firm models, urban form models, vehicle models, accessibility, travel demand, congestion and induced demand, policies and performance metrics, additional resources and recommendations for enhancements.
- Pilot Tests (Chapter 4) including the Maryland Department of Transportation, Atlanta Regional Commission, Thurston County Regional Planning Council and lessons learned.
- Summary (Chapter 5) of the research findings, the use of the SmartGAP tool, and future enhancements for the software that have been identified during the process.

The report also includes an extensive list of references identified throughout the project and two technical appendices:

- Performance Metrics and Application Tools (Appendix A) providing more detail from the background research
- Smart Growth Area Planning Tool (SmartGAP) Documentation (Appendix B) providing more detail on the individual models in SmartGAP to support Chapter 3

In addition, a user's guide has been developed for SmartGAP as a separate document to provide users with information on installation and use of the software.

CHAPTER 2. BACKGROUND RESEARCH

Key Decision Points for Smart Growth in the Planning Process

The Highway Capacity Planning Process

State DOT highway capacity planning processes involve a series of decision points at which smart growth might be considered. Figure 2.1 and Figure 2.2 present these process maps for state DOTs and MPOs, respectively, and identifies the areas where smart growth levers are used. In some cases, there are only a few agencies using these levers, but in most cases, there are many agencies incorporating smart growth levers into their processes. This map also correlates the phases from the Transportation for Communities – Advancing Projects through Partnerships (TCAPP) on-line tool, where the smart growth products from this study will reside.

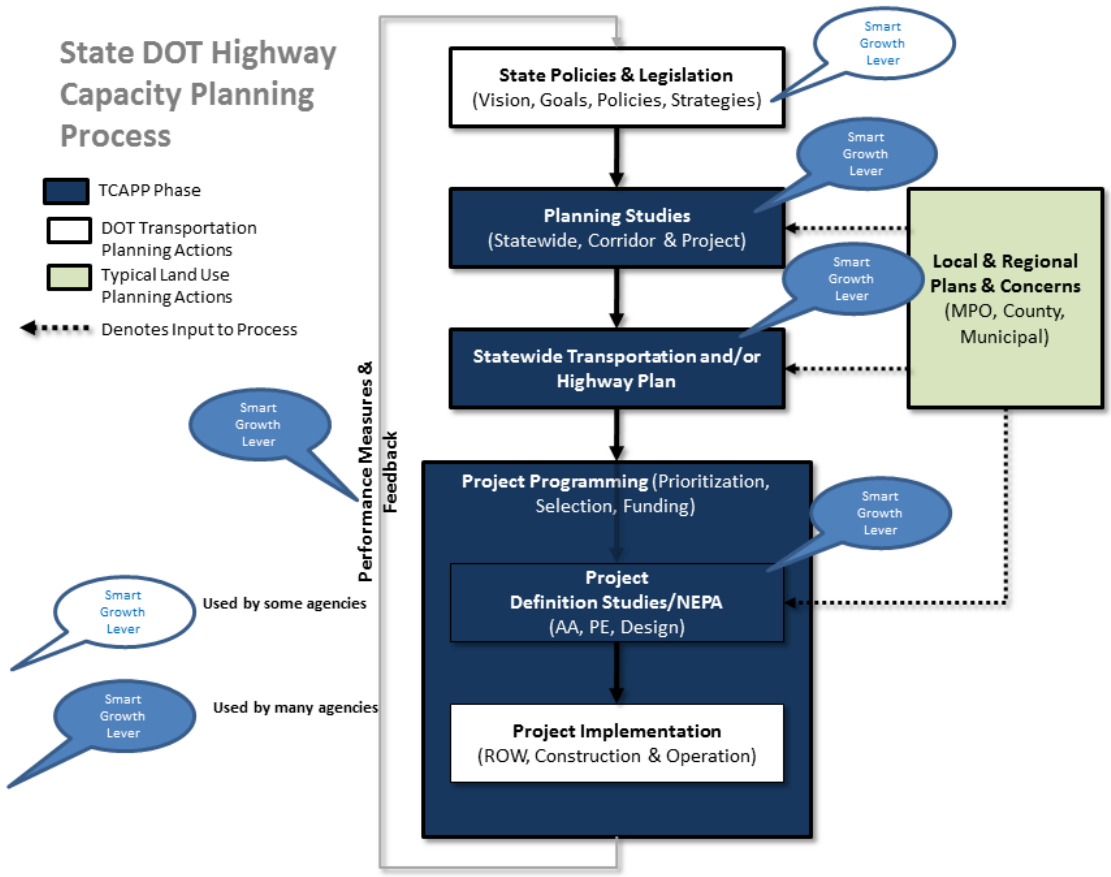


Figure 2-1: State DOT Highway Capacity Planning Process Map for Smart Growth Strategies

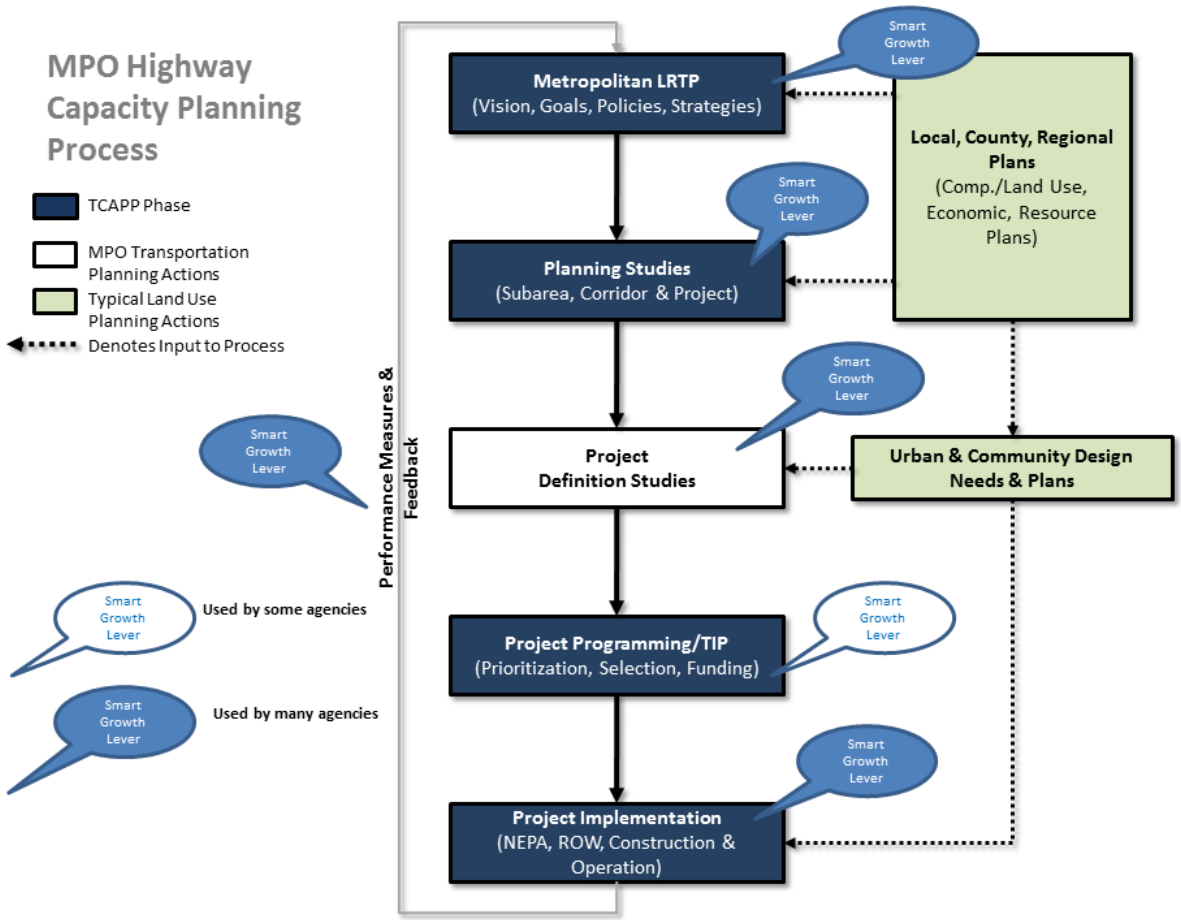


Figure 2-2: MPO Highway Capacity Planning Process Map for Smart Growth Strategies

In general, there are four dimensions of the capacity planning process in which smart growth considerations may be applied:

- Policy (Statewide Transportation Plan and Metropolitan Transportation Plan)
- Planning (Planning Studies)
- Programming (State TIP/Capital Program and MPO TIP)
- Implementation (including NEPA and Project Development)

Consideration of smart growth issues in the highway capacity planning process in each of these dimensions varies substantially across the country and is also changing rapidly, as more agencies find that consideration of smart growth strategies are useful and necessary to achieve reductions in congestion and emissions. And while there is significant research on the topic of evaluating smart growth strategies to evaluate transportation impacts, there are few applications

documented that clearly guide a planning agency in the process or consider the challenges in this type of analysis. The current state and MPO highway capacity planning process shows feedback from the project evaluation back to long range planning based on performance measures but does not reflect feedback from project evaluations to land use planning activities. When capacity thresholds are exceeded, the response could be to adjust transportation plans or land use plans, thus providing feedback to both aspects of long range planning. The feedback to the land use plans can identify areas suitable for new or expanded development.

TCAPP (http://www.transportationforcommunities.com/) is a decision- making framework software designed to encourage collaboration in the transportation planning process. The SHRP 2 program also has a related on-line resource called Transportation Visioning for Communities (http://shrp2visionguide.camsys.com/) or T-VIZ. The information available on this site is intended to assist transportation agency practitioners in assessing the possibilities of visioning, in identifying practical steps when engaging in visioning, and in establishing links between vision outcomes and transportation planning and project development processes."

Examples of smart growth considerations in different dimensions of the planning process are presented in Table 2.1. These examples are planning topics that state and regional planning agencies are engaged in to consider smart growth strategies in the planning process. While this list is not intended to be comprehensive, it does highlight the range of smart growth considerations that can be considered at different decision steps in the process.

Table 2-1: Examples of Smart Growth Considerations

Decision Step	Dimensions of Planning Process	Examples of Smart Growth Considerations
Definition of Corridor	Corridor Planning	▪ Recognition of impacts beyond the corridor
Problem Statement / Purpose and Need	Corridor Planning Permitting/NEPA	▪ Land-use patterns & growth forecast are critical ▪ Consistency with vision / community plans ▪ Accessibility, economic, congestion and mobility measures
Goals	Long Range Planning Corridor Planning	▪ Mobility ▪ Growth management ▪ Economic development ▪ Environmental ▪ Quality of life
Scope of Analysis & Review	Corridor Planning	▪ Induced development? Induced travel? ▪ Integrated corridor planning?
Evaluation Criteria & Performance Measures	**Long Range Planning**	▪ Built environment metrics ▪ Modal balance, accessibility & demand metrics ▪ Congestion and impact metrics ▪ System performance and safety ▪ Economic, social justice and equity ▪ Environmental sustainability
Identify Transportation Needs	Long Range Planning Programming Permitting/NEPA	▪ System performance and safety ▪ Modal balance ▪ Federal and State funding criteria, such as "livability", impact avoidance ▪ Social equity ▪ Effects of smart growth on travel demand, congestion, conformity ▪ Triple bottom line: economic, environmental, societal Return on Investment (ROI)
Financial Assumptions	Long Range Planning	▪ Federal and State funding criteria, such as "livability", impact avoidance
Identify Potential Strategies	Long Range Planning	▪ Land-use, transportation and policy considerations
Create Alternatives	Long Range Planning Corridor Planning Permitting/NEPA	▪ Integrated land use and transportation "blueprint" alternatives ▪ Trade-off and balance between transportation and land use criteria
Analyze Alternatives	Long Range Planning Corridor Planning Permitting/NEPA	▪ Integrated land use and transportation modeling ▪ Post-process travel model results to account for smart growth (sketch planning approach) ▪ Interactive, quick-response tools (for local factors, site specific evaluation) ▪ Validate/ adjust models as needed to account for smart growth and create consistency between local and regional analysis ▪ Consider induced demand
Select Preferred Alternative	Long Range Planning Corridor Planning Permitting/NEPA	▪ Triple Bottom Line: economic, environmental, societal Return on Investment (ROI)
Conformity Determination	Long Range Planning Permitting/NEPA	▪ Effects of smart growth on travel demand and congestion
Project Prioritization	Programming	▪ Does the project encourage smart growth patterns? ▪ Does the smart growth alternative reduce congestion? ▪ Does the smart growth alternative meet other criteria above?
Sequencing/Phasing Plan	Corridor Planning	▪ Consider growth inducement, primary /indirect impacts by phase.

One important fact is that most land use planning and regulatory authority remains in local government hands. As a result, most state and MPO efforts toward considering smart growth are geared toward enhancing communication, cooperation and collaboration. In order for smart growth strategies to be effective, goals among the land use planning and transportation

planning agencies could align or be complementary, and agencies could cooperate on the means to achieve these goals.

Most current smart growth strategies are developed for urban areas, and there is much less understanding of smart growth strategies in rural areas or small towns. There may often be different goals for rural areas, such as economic development, where urban areas would be more focused on mobility, the environment and growth management. State DOTs are challenged to evaluate smart growth strategies in rural areas.

Interviews with Planning Officials

- RSG conducted eight interviews on how smart growth is integrated and/or considered in the planning process with a small number of state DOTs, MPOs and federal agencies.Maryland Department of Transportation
- Oregon Department of TransportationCapital District Transportation Committee
- Metropolitan Washington Council of Governments
- Thurston County Regional Planning Commission
- Sacramento Area Council of Governments
- Federal Highway AdministrationEnvironmental Protection Agency

The candidates for the interviews were selected to reflect a wide variety of geographies, population sizes, and viewpoints. The list of questions varied for each type of agency, but was designed to understand the specifics of how smart growth strategies were included in the transportation planning process. The list of questions for each agency is provided in Table 2-2.

The interviews are summarized along several key dimensions to frame the discussions of smart growth:

- Legislative actions
- Goals and objectives
- Strategies
- Performance metrics and tools

Table 2-2: List of Questions for Smart Growth Planning Interviews

Questions for MPO Staff
1. Does your region or state have any laws mandating integration of land-use and transportation planning?
2. Has your agency formally adopted any objectives related to smart growth (e.g. jobs-housing balance, or land preservation), or goals which smart growth can significantly help achieve (e.g. carbon emissions targets)?
3. Does your agency have any specific strategies to encourage smart growth?
4. Does your agency do (integrated) scenario-based planning?
5. Does your agency consider smart growth with its technical methods?
a. Do you utilize visioning and scenario-comparison tools in your planning process (e.g. MetroQuest, INDEX, CommunityViz, Envision Tomorrow, iPLACES)?
b. Do you utilize specific smart-growth-related performance measures to help make transportation decisions?
• Balanced accessibility by variety of travel modes
• Benefits of location-efficient placement of transportation and land use to reduce travel demand
• Triple-bottom-line performance evaluation of the transportation system: economic, environmental and livability metrics
• Social impact and equity metrics such as health and safety
• System speed suitability to adjoining land use and activity
c. Are your models reliably sensitive to urban form variables (such as land use mix and walkability), and to TDM measures (both incentive-based and cost based)
d. Do you try to estimate induced travel? What about induced growth?
6. What strategies work best to accomplish the following goals: reduce congestion and reduce emissions?
Questions for DOT Staff
1. Does your region or state have any laws mandating integration of land-use and transportation planning?
2. Has your agency formally adopted any objectives related to smart growth (e.g. jobs-housing balance, or land preservation), or goals which smart growth can significantly help achieve (e.g. carbon emissions targets)?
3. Does your agency have any specific strategies to encourage smart growth?
4. Is your agency involved in funding any smart growth related research or studies?
5. Does your agency consider smart growth within corridor/environmental studies?
a. Do you utilize visioning and scenario-comparison tools in your planning process (e.g. MetroQuest, INDEX, CommunityViz, Envision Tomorrow, iPLACES)?
b. Do you utilize specific smart-growth-related performance measures to help make transportation decisions?
• Balanced accessibility by variety of travel modes
• Benefits of location-efficient placement of transportation and land use to reduce travel demand
• Triple-bottom-line performance evaluation of the transportation system: economic, environmental and livability metrics
• Social impact and equity metrics such as health and safety
• System speed suitability to adjoining land use and activity
c. Are your models reliably sensitive to urban form variables (such as land use mix and walkability), and to TDM measures (both incentive-based and cost based)
d. Do you try to estimate induced travel? What about induced growth?
Questions for National Agency Staff
1. How does your agency encourage consideration of smart growth in the transportation planning process? The project development (e.g. EIS) process?
2. Is your agency involved in funding any smart growth related research or studies?
3. What are some noteworthy examples of incorporating smart growth into transportation planning and project development efforts?

These interviews were designed to articulate the key information gaps and questions associated with them.

Legislative Actions. Several states identified laws mandating growth management (Maryland, Oregon, Washington) and one state (New York) has recently passed smart growth legislation that requires that state agencies evaluate public infrastructure projects they fund against smart growth criteria. The 10 smart growth criteria include topics such as:

- The use or improvement of existing infrastructure,
- Development in areas that are already developed or in areas that are designated for concentrated infill development in local land use plans,
- Mixed land uses and compact development,
- Preservation of open space,
- Improved public transport and reduced automobile dependency, and
- Collaboration among state agencies and localities to promote inter-municipal and regional planning.

In addition, several states have set greenhouse gas (GHG) reduction targets (Washington, Oregon, New York), which will lead to the integration of land use and transportation planning. California has also mandated incorporation of land use with transportation analysis and adoption of GHG reduction targets through SB 375 legislation, which encourages smart growth. The Sustainable Communities Strategy (SCS) provides land use and transportation connections to help meet these GHG reduction targets for MPOs in California. These sustainable community strategies must be included in the periodic update and revision of Regional Transportation Plans (RTPs). Also, there is an outlet that allows communities that are unable to meet GHG reduction targets through smart growth pursue TDM strategies, like parking restraints or road pricing – what is called alternative planning strategies (APS). There are, of course, likely synergies from pursuing SCS and APS in combination, however this is an area where empirical knowledge lags and for which forecasting and scenario-testing models probably fail to account for synergistic benefits.

Goals and Objectives. All of the interviewees cited goals and objectives that were formally adopted, although, to be fair, this short list of agencies was chosen because of their advances in this area. Goals were cited in statewide and regional transportation plans, climate action plans, and freight plans. Some goals were aimed at coordinating land use and transportation planning better; some goals were aimed at communicating and cooperating to achieve mutually beneficial land use and transportation objectives; and some goals were aimed at reducing transportation impacts through land use policy. The Albany MPO cited a Transportation Land Use Linkage Program as an important tool for achieving these goals. The Sacramento MPO adopted a “Blueprint” in 2004, which was a bold vision for growth that

promoted compact, mixed use development and more transit choices as an alternative to low density development.

The Olympia MPO (Thurston County) stated that congestion reduction is no longer a goal, since this improves the system for auto users and they are striving to improve the system for all users (not just auto users). Focusing on congestion reduction may be counter-productive, since smart growth includes compact development, which may result in more congestion for auto users, but more options or more mobility for non-auto users. This is an example where the goals and performance measures to achieve that goal need to be aligned with each other and with the overall purpose of any smart growth strategies.

Strategies. There were many land use and transportation policy strategies cited as examples in the interviews and many of these were cited by more than one agency. Some of the strategies were specifically aimed at coordination between land use and transportation. A selection of strategies cited in these interviews is provided in Table 2-3. These strategies have some common features around coordination (among policies, modes, centers, streets, etc.), growth management (urban growth boundaries, transit-oriented development [TOD], centers, etc.), and non-auto alternatives (transit, bike, and pedestrian modes). FHWA mentioned that they are providing scenario planning workshops to provide more focus on smart growth strategies, and scenario planning was also mentioned by several agencies as a potential strategy.

Table 2-3: Example Land Use, Transportation and Coordinated Strategies

Land Use Policy Strategies	Transportation Policy Strategies	Coordinated Strategies
Set urban growth boundaries	Establish connected streets policies (e.g. complete streets)	Coordinate policies between MPOs and cities and counties
Provide transit oriented development (TOD) and mixed land use	Provide transportation demand management (TDM) such as telework partnerships and guaranteed ride home programs	Provide funding for cities and towns to prepare community plans that coordinate land use and transportation
Support regional activity centers, urban re-investment, and concentrated development patterns	Establish arterial management program to promote properly located and spaced driveways and signalized intersections, use of raised medians	Conduct scenario planning
Set aside agricultural and natural resource lands	Set design details for sidewalks and bike lanes in street standards and provide impact fees to pay for these improvements	Public outreach/education
Break down barriers for better land use and mixed use by working with private sector through public private partnerships (PPP)	Coordinate signal priority for transit and other operational improvements for traffic and incident management	
Exempt urban development from concurrency regulations	Develop a partnership for safe walk routes to school and education on why you shouldn't drive your kids to school	
Down-zone rural areas	Provide alternatives to driving in the regional core and into regional activity centers	
	Build bicycle and pedestrian improvements	
	Price transportation corridors, areas, or facilities	

Performance Metrics and Tools. The interviews were designed to ask very specific questions about a series of tools and performance metrics:

- **Visioning and scenario planning tools –** The University of Maryland has a Scenarios Project being used by Maryland DOT. Oregon DOT has a scenario planning tool for greenhouse gas reduction called GreenSTEP, which is also being enhanced by FHWA for general use by other planning agencies; Thurston County will begin to use a scenario planning tool called CommunityViz as part of a regional sustainability grant. Some agencies did not use any such tools. EPA supports CommunityViz in various locations and the Utah Envision Tomorrow Plus effort. SACOG uses iPlace3s to evaluate urban and rural land use changes and has engaged in keypad polling to identify values and games to help develop inputs to iPlace3s.
- **Smart growth related performance measures –** Most agencies responded that they do include smart growth related performance measures in making transportation decisions. These include community quality of life, urban equity or environmental justice (EJ), economic, environmental, livability, safety, health, sustainability, and energy supply. EPA has been supporting the development of Smart growth related planning tools, such as Index and Smart Growth Index, and has funded the creation of a map of the 4 Ds at the census block group level. The concept of the 4 Ds is discussed in the next section on The Built Environment's Impacts on Peak Auto Demand.
- **Tools sensitive to urban form or TDM strategies –** The general consensus to this question was mostly "no" with some current work described that will provide some of these capabilities, such as expanding zones to represent mixed use centers better, modeling non-motorized modes directly, and modeling dynamic traffic to test the effects of staggered start times and improved parking access. One agency mentioned interest in a development tool to identify changes in trip making and VMT reduction in a planning area. SACOG was an exception here, since their travel demand model is an activity-based model with parcels and can address some of the urban form and travel demand management strategies.
- **Induced demand –** Most agencies said that they had discussed induced demand, but not formally estimated induced growth or traffic. The Albany MPO said they considered induced growth in the context of scenario planning rather than land use modeling. The Washington DC MPO considers induced growth using Delphi methods. SACOG considers induced growth using qualitative analysis because their current modeling tools are not able to estimate induced demand reliably. SACOG also has a policy not to fund capacity expansion at the urban fringes.

From these series of interviews, it was determined that there is room for improvement in the use of tools and performance measures to evaluate smart growth policies.

Key Practitioner Information Needs

The review of planning processes with a focus on smart growth and the interviews conducted with planning officials on this same topic revealed two primary areas that planning agencies are engaged in that are useful and supportive of engaging smart growth in planning processes. The first area is that most agencies are either engaged in or interested in scenario planning as a strategy for evaluating smart growth. Scenario planning offers many opportunities, but to date has not been developed into a tool for this purpose that could be shared or adapted for use by planning agencies. The second area is that many agencies reflected on the need for coordination, cooperation and communication with local governments on land use policy, since land use regulations are primarily governed by local governments. This interaction between land use and transportation planners has provided opportunities to engage in discussions about integration, interaction, and common goals.

The review also highlighted several topics where planning agencies feel additional guidance or tools would be worthwhile:

- Metrics and tools for induced demand, TDM, and urban form
- Understanding which strategies work best, i.e., what outcomes can be expected?
- Tools to evaluate impacts of smart growth on project selection
- Goals for congestion reduction may be counter-productive to smart growth

These topics were considered during the development of the software tools to ensure that the planning agencies needs were met, if possible.

The Built Environment's Impacts on Peak Auto Demand

Considerable Evidence on the Effects of Smart Growth on Daily VMT

Ewing and Cervero (Ewing and Cervero, 2010) conducted a meta-analysis that focused on aggregate vehicle trip and VMT results rather than specifically peak hour trips. Reviewing more than 200 built environment studies, it was found that VMT is most strongly correlated to measures of accessibility to destinations and secondarily to street network design variables.

The Ewing and Cervero meta-analysis provides elasticities tied to "D" built environment variables. These include:

- **Density** gauges how many people, workers, or built structures occupy specified land area, such as gross hectares or residentially zoned land. This is defined as the population and employment per square mile.
- **Diversity** reflect the mix of land uses and the degree to which they area spatially balanced (e.g., jobs-housing balance) as well as the variety of housing types and mobility options (e.g., bikeways and motorways). This is defined as the ratio of jobs to population.

- **Design** captures elements, like street network characteristics, that influence the likelihood of walking or biking – e.g., pedestrian- and bike-friendliness. Street networks vary from dense urban grids of highly interconnected, straight streets to sparse suburban networks of curving streets forming loops and lollipops.
- **Destination accessibility** measures ease of access to trip destinations, such as the number of jobs or other attractions reachable within 30 minutes travel time.
- **Distance to transit** measures the distance to the nearest transit stop.

The first four of these built environment variables are often referred to as the "4 D's" and when the fifth variable (distance to transit) was added, the term was adjusted to reflect "5 D's". These are not separate dimensions and indeed are often co-dependent. Having high rise housing and office towers will yield few mobility benefits if the two activities are far from each other. A diversity of uses and improved accessibility to destinations from home or work are needed if denser development is to translate into more pedestrian and transit trips. The densest part of most cities, downtowns, also tend to be the most land-use diverse and most walkable – e.g., small city blocks, complete sidewalk networks, and fine-grain grid street patterns. For each variable, weighted average elasticities of VMT are provided. The body of work reviewed in the study, as well as the resulting elasticities, focuses almost exclusively on VMT or vehicle hours traveled (VHT) per household rather than peak auto demand. The meta-analysis builds off of work previously conducted by Cervero and Kockelman (1997).

Studies Focusing on Peak Auto Demand

There are a few studies that have focused on connecting built environment characteristics specifically to peak auto demand. Generally, the built environment factors that have been highlighted to give some reduction to peak auto demand include the overall characteristics of a TOD, the mix of uses at the employment site, and the jobs-housing balance of an area. Historically, studies on peak auto demand have focused on commute trips. The National Household Travel Survey (NHTS) briefs show that non-work vehicle trips are an increasing percentage of peak period trips and thus highlight a need to study the built environment relationships to all type of vehicle trips.

While a considerable literature has evolved for measuring the impacts of smart growth on travel, broadly defined (e.g., average daily traffic (ADT), VMT, modal splits), work on peak-period impacts, and by implication the effects on road congestion, is far more limited. This could reflect the numerous objectives that propel smart-growth initiatives, which might include traffic congestion relief but more often than not stress other factors like reducing energy consumption and greenhouse gas emissions, expanding housing choices, encouraging increased physical activity, and reducing fiscal outlays for infrastructure and services relative to sprawl. For gauging energy consumption and tailpipe emissions, VMT might be a preferred performance metric. For the study of how mixed-use development and sidewalk investments might promote physical activity, the output metric of interest is apt to be modal splits – e.g., percent of trips by walking and cycling. Add to this the fact that little VMT data is broken down by the peak period and that the sample sizes of household travel surveys are sometimes too small to partition trips

by time-of-day for small geographic areas, a scarcity of data points has significantly constrained the ability to conduct research on how built environments influence peak auto travel.

One might be inclined to examine the effects of built environments on work trips under the premise that journeys-to-work are concentrated in the peak. In 2001, however, more than half of all trips during the 6:00 to 9:00 AM period were for non-work purposes and during the PM peak, the share exceeded 70 percent (FHWA, 2007c). On Fridays, four out of five vehicle trips during the afternoon peak were for purposes other than commuting. There are no easy alternatives to gauging the impacts of built environments on traffic congestion other than to study relationships during the peak period itself.

The NHTS briefs highlight that a significant number of non-work vehicle trips are being made during peak periods (FHWA, 2007a). On an average weekday, non-work travel constitutes 56 percent of trips during the AM peak and 69 percent of trips during the PM peak. The trends show that the amount of travel for non-work purposes is growing faster than work travel. Growth in these kinds of trips is expected to outpace growth in commuting in the coming decades. After trips to work, and giving someone a ride, the next largest single reason for travel during the peak period is to shop. Just since 1995, 25 percent more commuters stop for incidental trips during their commutes to or from work, and stopping along the way is especially prevalent among workers with the longest commutes. While e-commerce and internet shopping has reduced the need for some physical travel to retail outlets, some evidence suggests it can also have a stimulating effect by promoting consumerism and expanding knowledge networks, prompting some individuals to comparison-shop more often (Ferrell, 2005).

Two older Cervero studies (Cervero, 1988; Cervero, 1989b) provide some evidence on how to reduce peak auto demand specifically for suburban environments. The 1988 study looked at the effects of current land-use mixes on the commuting choices of suburban workers based on an empirical analysis of some of-the largest suburban employment centers in the United States. Overall, the findings show that single-use office settings seem to induce solo commuting, whereas work environments that are more varied generally encourage more ridesharing, walking, and cycling. While the synchronization of job and housing growth around suburban centers could be expected to encourage more foot and bicycle travel, at the same time, ridesharing and vehicle occupancy levels could be expected to fall off some. The 1989 study found similar results showing that single-occupant vehicle commuters decrease as a suburban employment center becomes denser and it features a wider variety of land uses. The availability of retail activities appears to induce a number of suburban workers to carpool and vanpool to work because in these settings they can get to banks, shops, restaurants, and the like without a motor vehicle.

This section divides the literature on the impacts of built environments on peak auto demand into two groups: (a) case-based analyses ("A." on Figure 1-2); and (b) variable-based analyses ("B." on Figure 1-2). This division partly reflects how the body of research appears in published literature. Some studies compare neighborhoods with versus without TOD or other smart-growth forms, ideally matching the cases on other factors that influence travel, like household income and levels of regional accessibility. Matched-pair analyses, sometimes also referred to as quasi-experimental studies, can provide real-world, grounded insights and contrasts

into the travel-impacts of land-use interventions. With the availability of rich GIS data, far more studies – particularly those over the last decade – have been based on statistical relationships between variables using various model structures, what is being called variable-based analyses. To the degree predictive models of, say, population density on VMT are well-specified, controlling for other explanatory variables, variable-based models are generally preferred. This is partly because results can be expressed in metrics, like elasticities, that provide order-of-magnitude estimates of impact and partly because they are considered more internally valid, reducing the chance of confounding influences or spurious results. That said, cases often resonate with politicians and the general public. Politicians often rely on case examples to drive home points. They also may be more inclined to listen to cases, in part because their constituents do. A study of urban poverty in Boulder, Colorado showed that case-based analyses were more effective at influencing political outcomes than variable-based analyses derived from statistical techniques (Brunner et al., 1987). Together, case-based and variable-based findings provide a rich and often complementary perspective on the subject at hand – built environments and peak-period travel.

Case-Based Analyses

From a case-based perspective, research on built environments and travel occurs at multiple scales: (a) micro: project and neighborhood scales; (b) meso: community, corridor, and subregional scales; and (c) macro: regional scales. Examples of micro-scale smart-growth initiatives include Traditional Neighborhood Designs (TND), New Urbanism, and TOD. At the meso-scale, smart growth might take the form of a mixed-use suburban activity center (versus a single-use office park) or a transit-oriented corridor (TOC) (versus an auto-oriented corridor). Regional-scale initiatives might include jobs-housing balance and urban containment programs like urban growth boundaries (UGB). Table 2-4 provides a summary of geographic scales and the settings and place types typically associated with each. Throughout this report, these scales will be mentioned, particularly with regard to tool applicability and geographic extent of case-based analysis.

It was hoped that empirical evidence on smart growth's influences on peak auto travel would be available at multiple scales. Upon an extensive canvassing of the literature, using various bibliographic search platforms like TRIS Online, Google Schoar, TRANweb, Melvyl, and ISI Web of Knowledge databases, case materials on smart growth and peak travel fell into a more limited grouping, notably two scale and two forms: micro – TOD; and macro – jobs-housing balance.

Table 2-4: Smart Growth Typologies

Geographic Scales	Settings/Place Types			
	Urban Centers	Close-in Compact Communities	Suburban	Rural/Exurban
Macro/ Regional	▪ Adaptive Reuse/Infill/ Redevelopment	▪ Mixed-Use Development/Activity Center ▪ Adaptive Reuse/Infill/Redevelopment Job-Housing Balance	▪ Mixed-Use Development/ Activity Center ▪ Adaptive Reuse/Infill/ Redevelopment Job-Housing Balance	▪ Telecommunities ▪ Mixed-Use Development/ Activity Center or ▪ Traditional rural township
Meso: subregional/ corridor	▪ Job-Housing Balance ▪ Transit Oriented Corridor	▪ Transit Oriented Corridor ▪ Job-Housing Balance	▪ Transit Oriented Corridor ▪ Job-Housing Balance ▪ Mixed-Use Development/ Activity Center	▪ Telecommunities ▪ Mixed-Use Development/ Activity Center or ▪ Traditional rural township
Micro: neighborhood/ community	▪ Transit Oriented Development	▪ Transit Oriented Development ▪ Traditional Neighborhood Design/New Urbanism (residential focus)	▪ Transit Oriented Development ▪ Traditional Neighborhood Design/New Urbanism (residential focus)	▪ Telecommunities

Transit-Oriented Development (TOD). The congestion-relieving potential of TOD has long been debated. Downs (2004b) argued that TOD will not reduce car traffic unless three conditions are met: (1) a critical mass of TODs in a region; (2) relatively high residential and/or employment densities within each TOD; and (3) a high percentage of employed-residents and workers of the TOD who transit commute. Both residences and destinations, like job sites and shopping venues, need to be concentrated around transit stations to assure both trip origins and destinations are linearly aligned along a rail or BRT served corridor (Cervero, 2007a). Even then, not everyone believes TODs will delivery mobility benefits in car-dependent societies like the United States. In an interview for Common Ground, a trade journal of the National Association of Realtors, Wendell Cox expresses this view: "TOD increases congestion. The overwhelming majority of travel to proposed transit-oriented developments will be by automobile. This will strain road space, slowing traffic and increasing pollution as a consequence" (Still, 2002). While concentrated development might lead to more spot congestion at intersections near rail stations, incidents of increased congestion needs to be weighed against research that shows smart growth in general and TOD specifically tend to be associated with fewer VMT per resident and per worker than conventional, more auto-oriented growth (Ewing and Cervero, 2001, 2010; Cervero, 2007b).

Several studies provide hints of how TOD might influence peak-period travel. The first, by Zhang (2010), simulated the peak-hour benefits of TOD at a regional scale while the second, by Arrington and Cervero (2008), empirically compared peak-period trip generation rates of TOD versus conventional rates for non-TODs for specific projects.

Zhang Macro Scale Study. Zhang (2010) applied conventional four-step travel-demand models to simulate traffic outcomes across three scenarios with varying levels of TOD for Austin, Texas: do-nothing; a rail-based TOD scenario with a limited number of TODs; and an aggressive express-bus TOD scenario with numerous TODs spread across the region. It should be noted that such an analysis is fairly coarse and may exaggerate or dampen relatively small changes in effects. As a result, results should be interpreted with caution. Densities for the rail-based TOD scenario ranged from 20 to 75 dwelling units per acre. For an express bus scenario, densities were assumed to be 1.5 higher than 2030 density levels under the do-nothing alternative. In the four-step modeling process, modal split estimates were adjusted to account for the ridership premium of TOD.

In addition to TOD scenarios reducing estimates of VMT and personal miles traveled (PMT), 2030 projections showed TOD could also significantly reduce peak-period congestion. Under the base case 2030 scenario, 3,729 lane miles (20.3 percent) of roadways in the study area are predicted to be congested in the morning peak. The rail-based TOD plan was projected to reduce congested roadways by 433 lane miles versus the base case, representing 18 percent of the region's lane miles. The most aggressive (All-Systems-Go) TOD scenario was expected to reduce congestion an additional 341 lane miles or to 16.1 percent of the regional total.

According to Zhang's analysis, the mid-level rail-based TOD can be expected to reduce traffic congestion by 11.7 percent relative to the base case. The All-Systems-Go TOD option would likely reduce it an additional 9 percent, or a total of 20.7 percent, relative to the base case. A more aggressive post-processing of the model results, reflecting for example evidence on the influences of density on ridership from direct-ridership models (Cervero, 2006), might have yielded more sizable drops in peak-period congestion levels. Zhang concluded that most of TOD's role as a congestion relief strategy lies in concentrated development that shortens trip lengths and thus lowers VMT and PMT relative to low-density sprawl. Specifically, "as a land use strategy, TOD reduces congestion by bringing closer trip origins and destinations and hence reducing average trip length, although shifting travel from cars to transit is ultimately desirable" (p. 154).

Because TODs were estimated to reduce VMT and PMT relatively more than peak-period traffic congestion, Zhang's study found that most of the congestion-relieving benefits were *outside* TOD neighborhoods. Within the TOD itself, congestion could worsen due to the concentration of people and jobs. Promoting walking and biking to minimize local driving, he concluded, will be critical for TOD success in Austin.

Arrington and Cervero Micro Scale Study. The Arrington and Cervero (2008) study of TOD and peak-travel occurred at a much finer grain of analysis: individual projects. This TCRP-funded study surveyed travel at 17 multi-family housing units of varying sizes near rail

transit stations in four parts of the country: Philadelphia/northeast New Jersey; Portland, Oregon; metropolitan Washington, D.C.; and the East Bay of the San Francisco Bay Area. Pneumatic-tube recorders were placed on all curb cuts and driveways to the surveyed projects and recorded daily and peak-period trip generation rates were compared to those for the same residential land-use categories in the Institute of Transportation Engineers (ITE) *Trip Generation* manual.

Figure 2-3 shows results for the 17 surveyed TOD-housing projects. These averaged 44 percent fewer vehicle trips than that estimated by the ITE manual (3.754 versus 6.715). The weighted average trip rate differentials were even larger during peak periods – 49% and 48% for the AM peak and PM peak, respectively.

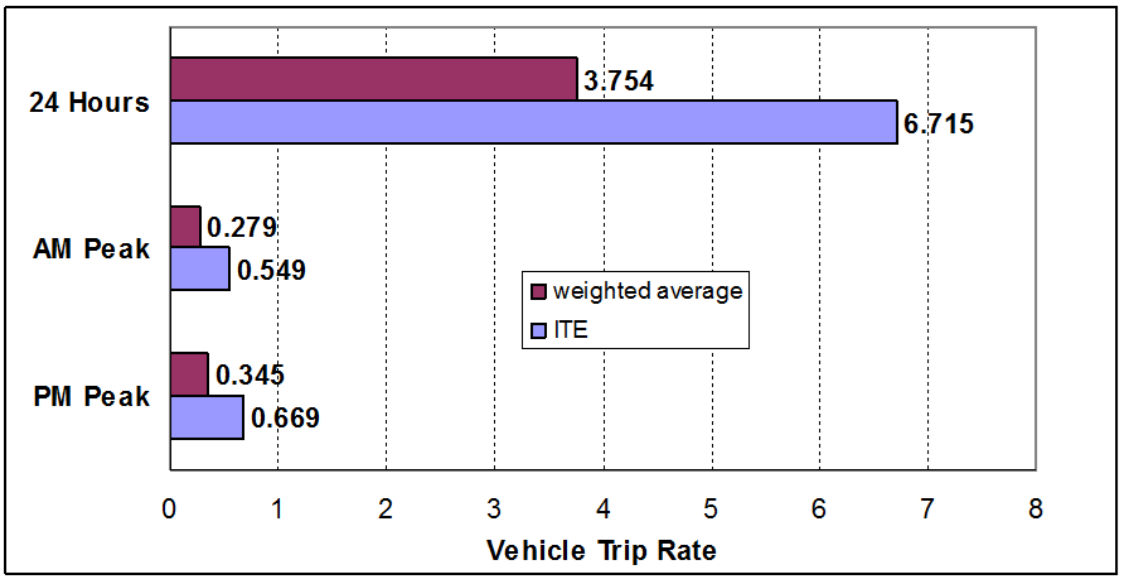


Figure 2-3: Comparison of Weighted Average Vehicle Trip Rates: TOD Housing and ITE Estimates.

Source: Cervero and Arrington (2008)

In general, denser, more urban TOD-housing had the greatest peak-hour trip rate differentials. For example, the PM trip rates for Portland's Collins Circle and Alexandria, Virginia's Meridian projects were 84.3 percent and 91.7 percent below ITE predictions, respectively. Statistically, a relationship was established that every 10 additional dwelling units per acre for a development located within ½ mile of a rail station was associated with a lowering of the PM peak trip generation rate of TOD projects relative to the ITE rate of 26 percent (Cervero and Arrington, 2008). The importance of density and proximity to the core in reducing PM peak-period trip generation rates is further revealed by Figure 2-4. Based on model results, the figure shows that a transit-oriented apartment 20 miles from the CBD in a neighborhood with 10 units per residential acre can be expected to have a PM trip rate that is 55 percent of (or 45 percent below) the ITE PM rate. If the same apartment in the same density setting were 5 miles from the CBD, the PM trip rate would be just 38 percent of the ITE rate.

A follow-up survey focused on parking demands at TODs, including some surveyed by Arrington and Cervero (2008), shed further light on TOD's transportation impacts (Cervero et al., 2010). In the case of Portland's transit-oriented housing projects, parking demand was 11 percent less than that estimated by the ITE *Parking Generation* manual, which is based on PM peak trip rates for peak parking periods (typically in the early morning). On average, the supply of parking exceeded peak demand by 30 percent at Portland's TOD projects.

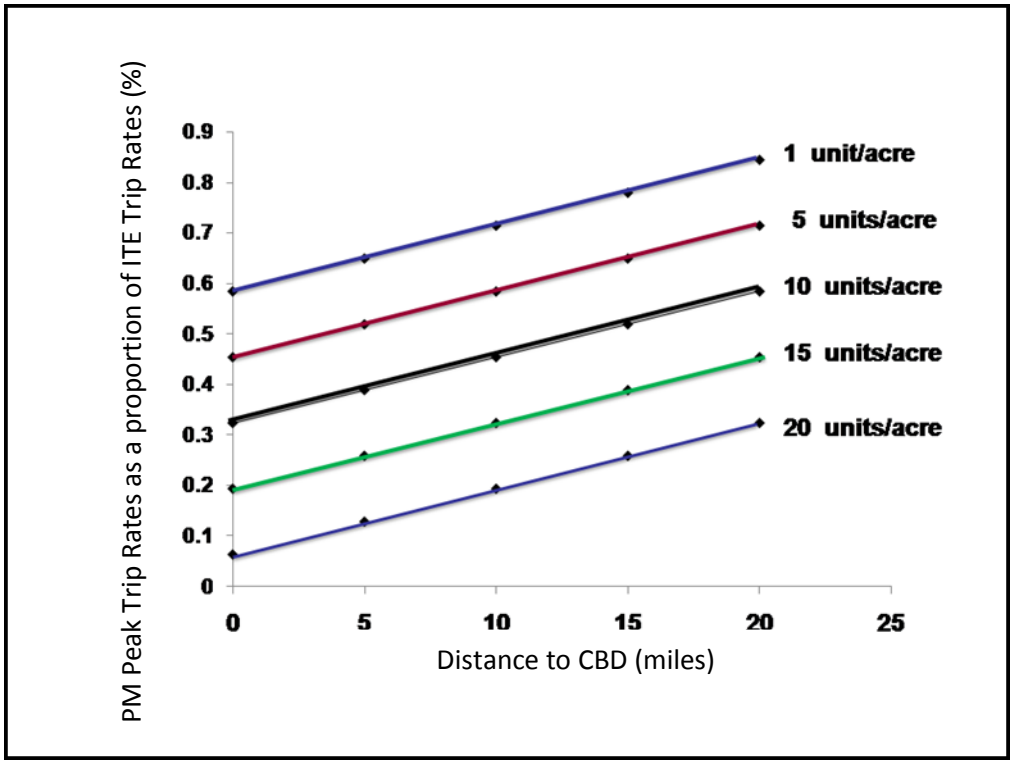


Figure 2-4: Influences of Residential Densities and Distance to CBD on Transit-Oriented Housing PM Trip Rates as a Proportion of ITE Rates.

Source: Cervero and Arrington (2008)

Jobs-Housing Balance. Balancing the locations of jobs and housing confers mobility benefits by shortening trips, promoting alternatives to single-occupant car travel, and rationalizing commute sheds (e.g., less criss-cross, and lateral-moving traffic) (Cervero, 1989a, 1996; Ewing, 1996). To date, no research has been conducted specifically on the influences of jobs-housing balance on peak-period auto travel, however most studies have looked at influences on commute trips, many of which occur in peak periods. Evidence that balanced regional growth can reduce work-trip VMT has been unearthed in studies of the San Francisco Bay Area (Cervero, 1989a), Puget Sound (Frank and Pivo, 1994), and metropolitan Portland (Kasturi et al., 1998). Studies in Toronto (Miller and Ibrahim, 1998) and greater Los Angeles (Giuliano and Small, 1993), on the other hand, found little or no evidence that balanced growth can drive down commute VMT or durations.

Indirect evidence on the influences of balanced growth on travel performance, notably speeds, comes from empirical work by Cervero and Duncan (2006) of the San Francisco Bay Area. This study measured the number of jobs within four highway network miles that were in an employed-residents occupation, adding an important qualitative dimension to typical metrics of accessibility and jobs-housing balance. Occupational matching allowed the accessibility to jobs that individuals qualify for to be gauged. The research found that a doubling of occupationally matched jobs within 4 network miles of workers' residences was associated with a 32.9 percent reduction in commute VMT and a 33.8 percent reduction in commute VHT. The slightly larger elasticity of work-trip VHT as a function of job accessibility suggests that, on average, improved job access translates into slightly faster commute speeds. Cervero and Duncan (2006) conjectured this could be due to the rationalization of commute patterns, with sub-regional balances in jobs and housing marked by less cross-town, lateral, and zigzag patterns of commuting from one quadrant of a region to another. The research also showed that larger commute-trip VMT and VHT reductions occurred as a function of job accessibility than did shop-trip reductions as a function of retail access. While balancing where people live and shop matters in driving down VMT and VHT, balancing where they live and work matters even more.

Variable-Based Analysis

The Ewing/Cervero 2010 meta-analysis (Ewing and Cervero, 2010) computed elasticities for individual studies and pooled them to produce weighted averages. However, their work focused exclusively on daily auto demand –VHT and VMT.

The MXD tool (Ewing et al., 2011), based on 239 mixed-use sites from six U.S. regions, provides daily, AM, and PM peak hour external vehicle trips at both the meso and micro scale. Hierarchical linear models are utilized to calculate the probability that trip making will occur externally or internally from a mixed-use site, resulting in peak hour auto demand estimates.

Mobility by Mode and Purpose

Two meta-analyses along with other recent studies provide connections between mode choice, particularly transit usage and walking, to built environment factors. The VMT and VHT results from these same studies were described in the prior section. Mixed-use developments with good transit access tend to generate a significant share of walk and transit trips. Walking trips are most strongly correlated to jobs-housing balance, mix of uses, intersection density and proximity of destinations. Transit trips are correlated strongly with transit access of a development, transit supply, job accessibility via transit, intersection density, street connectivity, and population centrality.

Ewing and Cervero (2010) found that walking and transit trips have strong correlations to various characteristics of the built environment. The meta-analysis shows that mode share and likelihood of walk trips are most strongly associated with the design and diversity dimensions of built environments. Intersection density, jobs-housing balance, and distance to stores have the greatest elasticities. The mode share and likelihood of transit trips are strongly associated with transit access. Next in importance are road network variables, such as high intersection density

and street connectivity, and then, measures of land use mix. It did find that jobs-housing balance is a stronger predictor of walk mode choice than land use mix measures. Linking where people live and work allows more to commute by foot, and this appears to shape mode choice more than sprinkling multiple land uses around a neighborhood.

The 2009 TRB meta-analysis, *Driving and the Built Environment* (National Research Council, 2009), linked transit mode share to built environment characteristics. Population centrality and transit supply have a non-negligible effect on the share of commuting by rail, bus, and non-motorized modes (i.e., walking and bicycling). After controlling for self-selection, job accessibility via transit remains statistically significant. TOD studies conclude that the location of a TOD in a region—its accessibility to desired locations—and the quality of connecting transit service are more important in influencing travel patterns than are the characteristics of the TOD itself (e.g., mixed uses, walkability). For work trips, proximity to transit and employment densities at trip ends exert a stronger influence on transit use than land use mix, population density at trip origins, or quality of the walking environment.

Transit Modal Shares and TOD

A number of research studies have demonstrated that housing in close proximity to rail transit stations averages high transit modal splits for commute trips and that improved walking connections to rail stops increases this modal share even more (Cervero, 1994; JHK and Associates, 1987, 1989; Stringham, 1982). Similar relationships hold for employees who work near rail stops (JHK 1987; Cervero, 1994; Lund et al., 2004) and shoppers heading to retail outlets near rail (Bragado, 1999; Cervero, 1993; Lund et al., 2006). In the case of transit-oriented housing, some analysts (Cao et al., 2009; Chatman, 2009) show ridership premiums are partly due to self-selection (i.e., a lifestyle proposition to live in a neighborhood with good transit services), however even for pro-transit types, living in a well-designed TOD can induce even more transit travel (Cervero, 2007b).

Transit modal splits are also thought to increase when TODs take the form of a transit-oriented corridor, akin to a string-of-pearls. Perhaps the best U.S. example of this is the Rosslyn-Ballston corridor in Arlington, Virginia. Surveys show that 39 percent of residents living within a quarter mile of a rail stop along the corridor take Metrorail to work compared to just 17 percent of residents who reside farther away but also within Arlington County (Cervero et al., 2004; National Research Council, 2009).

Walk/Bike and Traditional Neighborhood Designs

Many early studies of built environments and travel focused on modal split impacts using cross-neighborhood comparisons. Typically, neighborhoods would be matched on the basis of household income and other sociodemographic controls, but would fundamentally differ in terms of built environments – e.g., auto- versus pedestrian- or transit-oriented (Ewing et al., 1994; Cervero and Gorham, 1995). While providing order-of-magnitude insights and receiving high marks for understandability, the fact that such cases generally rely on statistical means when representing travel characteristics raises suspicions about possible aggregation biases. This led

to the use of predictive models that included dummy and interactive variables to distinguish relationships between places with contrasting built forms (e.g., Cervero and Radisch, 1995; Holtzclaw, 2002; Lund et al., 2006).

Several case-based matched-pair studies that specified regression models to study relationships reveal that Traditional Neighborhood Designs (TNDs) significantly promote walking and cycling over automobile trips, particularly for retail shopping and neighborhood-scale activities. A comparison of two East Bay neighborhoods with similar household incomes, regional access, and transportation services showed that residents of the TND setting averaged 1.07 walk trips per day for non-work purposes compared to 0.33 daily walk trips for those living in a conventional auto-oriented suburb (Cervero and Radisch, 1996). For non-work trips less than a mile in distance, 28 percent of residents in the TND walked compared to just 6 percent in the conventional suburb. Matched-pair comparisons of TND versus conventional neighborhoods in Los Angeles County (Cervero and Gorham, 1995), the San Francisco Bay Area (Handy, 1992; Cervero and Gorham, 1995), Palm Beach County, Florida (Ewing et al., 1994), and Austin, Texas (Handy, 1996) reached similar conclusions: compact, mixed-use, traditionally designed neighborhoods encourage internal walking trips that substitute for out-of-neighborhood shop trips.

A six-regional analysis of mixed-use developments found that jobs-housing balance most strongly predicted whether trips made by residents to non-work destinations (i.e., home-based other trips) were internal to the project (Ewing et al., 2011). Balanced job and housing growth was also strongly associated with walking and shorter car trips for external trips made by residents. The research concluded that "for traffic impact, greenhouse gas, and energy analyses, the VMT generated by a mixed-use site depends…on the site's placement within the region, specifically, on the share of jobs located within a 20- or 30-minute drive of the site" (Ewing et al., 2011).

Activity and Health

In a comparison of New Urbanist and conventional suburban communities in central North Carolina with similar income and socio-demographic characteristics, Rodriquez et al. (2006) found little difference in the amount of leisure time involving physical activity among residents of both communities. Overall, however, new urbanist residents logged 40 to 55 minutes more walking and cycling each week than their counterparts in the conventional suburban neighborhoods. Utilitarian travel, such as to work or shopping, accounted for the difference. This finding concurs with that of Saelens et al. (2003) that neighborhood design is not related to leisure-time physical activity when one controls for individual- and household-level characteristics. Also, the North Carolina study found that increased numbers of walking trips came at the expense of automobile trips, consistent with prior evidence (Cervero and Radisch, 1995).

Emissions

A case-based study of office workers who relocated from rail-served downtown San Francisco to a low-density, single-use, campus-style office park in the East Bay served by freeway estimated that commute VMT increased by a factor of three following this relocation (Cervero and Landis, 1992). The largest contributor to the VMT gain was modal shifts from transit to solo-commuting. The study concluded that since tailpipe emissions are directly related to VMT, air quality impacts attributable to this workforce's commuting increased by a similar order of magnitude.

Greenhouse Gas Emissions

Most studies on built environments and GHG emissions focus on VMT per household as an intermediate explainer. For the cases of metropolitan Los Angeles, Chicago, and San Francisco, Holtzclaw et al. (2002) found that higher residential densities were significantly associated with fewer VMT per household in all three cities, with the relationship following an exponential decay function, implying the largest VMT reductions accrue when going from very low to moderate densities. Some observers claim that lifestyle preferences explain much of the lower levels of VMT in denser, more walking-friendly neighborhoods, and that failure to account for self-selection could bias results. In a study of neighborhoods in the Puget Sound area, Krizek (2003) removed possible self-selection biases by longitudinally examining changes in travel when households relocated. He found that moving to a neighborhood with denser, mixed-use, well connected street patterns was associated with lower VMT and PMT reductions (Figure 2-5).

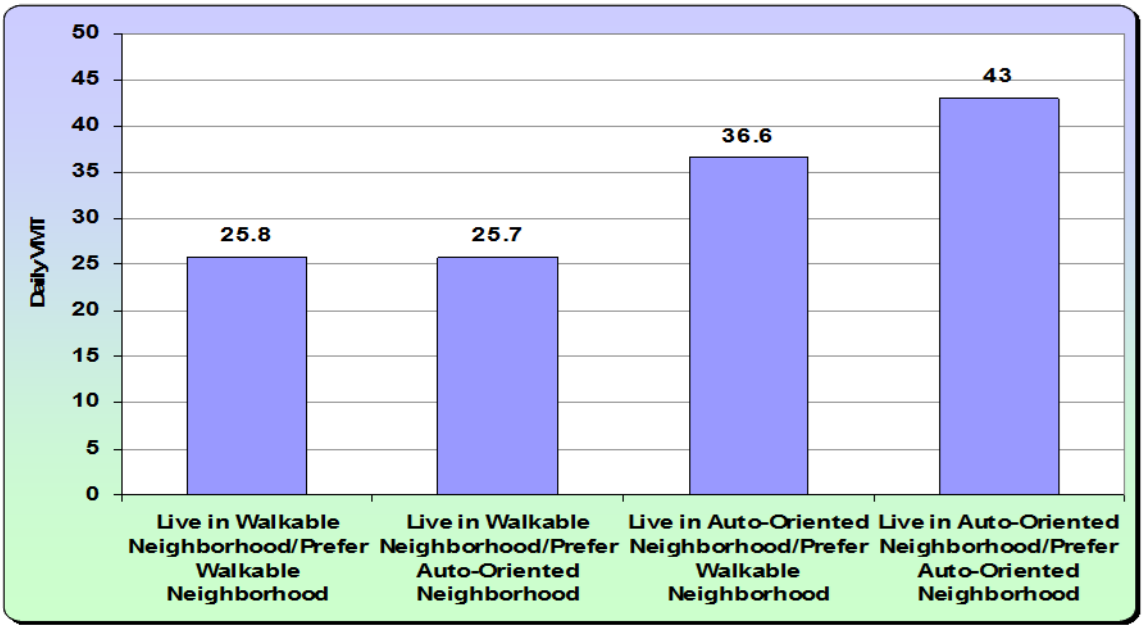


Figure 2-5: Daily VMT by Neighborhood Type and Preference

Source: Frank (2007)

Induced Traffic and Induced Growth

Few contemporary issues in the urban transportation field have provoked such strong reactions and polarized interest groups as claims of induced travel demand. Experience shows that supply-side solutions to traffic congestion provide mobility benefits that are mostly short-lived. Within a few years, newly expanded road capacity is sometimes fully absorbed, with traffic conditions largely the same as prior to the investment. The contention that "you can't build yourself out of traffic congestion" has become a rallying cry of many environmental advocacy groups aiming to halt new road construction altogether.

Figure 2-6 diagrams the flow of events attributed to the demand-inducing impacts of an expanded road. In the near term, increased capacity unleashes behavioral adjustments — e.g., trips previously suppressed are now made because of improved flows (i.e., latent demand); motorists switch routes, modes, or time-of-travel to take advantage of a new facility; motorists travel to destinations that are further away because of speedier flows (Downs, 1962, 1992, 2004a; Cervero 2002; Noland and Lem, 2002). New trips, longer trips, and modal shifts contribute to increased VMT, the strongest correlate to overall resource consumption and tailpipe emissions in the transport sector. Other adjustments, like route and temporal shifts, do not noticeably increase VMT and thus are largely redistributive in nature. Time-of-day shifts from the off-peak to the rush-hour underscore the limited congestion-relieving impacts of road expansion.

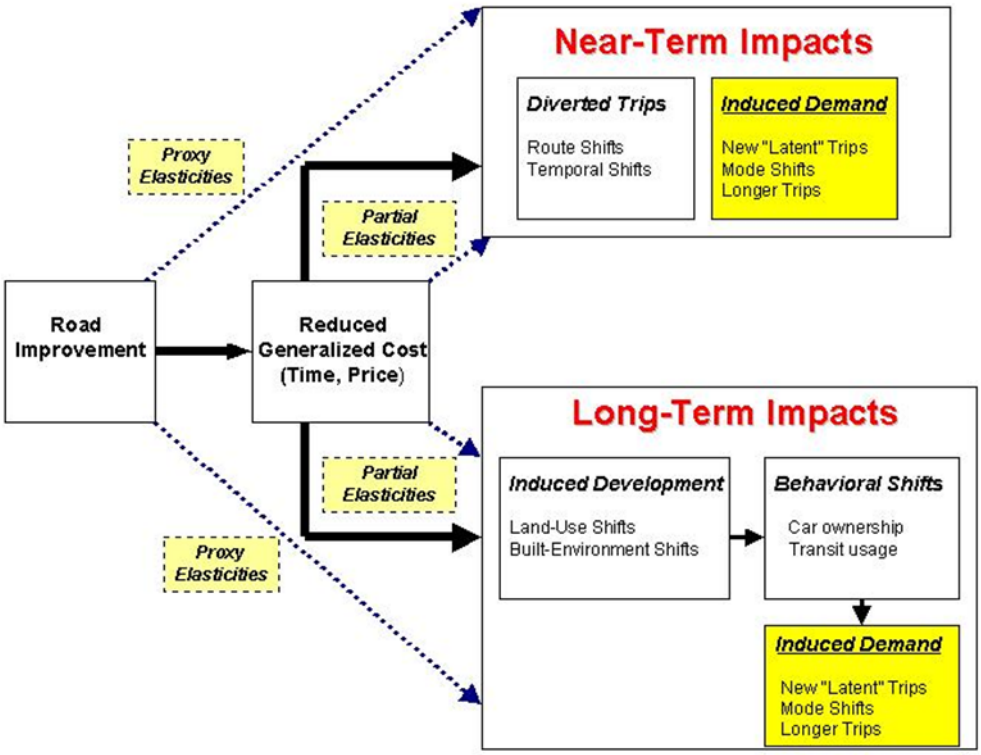


Figure 2-6: Tracking Induced Travel Demand

A meta-analysis found a mean short-term elasticity (between lane-km capacity and VKT) of several dozen roadway investments in the United States of 0.40 — i.e., all else equal, a doubling of road capacity was associated with a 40 percent increase in VKT within 1-3 years of the investment (Cervero, 2002). Over the long term, added road capacity led to more deeply rooted structural shifts, like increased car-ownership rates and more auto-oriented land-development patterns, what is sometimes referred to as *induced growth*. Adding structural impacts to accumulated short-term ones markedly increases long-term elasticities — on average, 0.73 in the U.S. (Cervero, 2002). Other studies have estimated even higher long-term elasticities (Heanue, 1997; Fulton et al., 2000; Metz, 2008). Overall, experiences reveal that travel adjusts to form a new supply-demand equilibrium of traffic congestion following road improvements. This traffic-inducing and thus benefit-offsetting impact is incompletely accounted for by most economic appraisals of transport-facility investments (Downs, 1992; Saloman and Mokhtarian, 1997; Pells, 1989; Cervero, 2002; Cervero and Hansen, 2002; Ory et al., 2004). The economic benefit for additional users is typically accounted for in these appraisals.

Figure 2-6 shows near-term (i.e., first-order) and longer-term (i.e., second-order) impacts of expanded capacity. Initially, a road investment increases travel speeds and reduces travel times (and sometimes yields other benefits like less stressful driving conditions, on-time arrival, etc.); increased utility, or a lowering of "generalized cost", in turn stimulates travel, made up of multiple components, including new motorized trips (e.g., latent demand, previously suppressed), redistributions (modal, route, and time-of-day shifts), and over the longer term, more deeply rooted structural shifts like land-use adjustments and increased vehicle ownership rates (that in turn increase trip lengths and VKT). Some of the added trips are new, or induced, and some are diverted. Relevant to discussions on the potential traffic impacts of smart growth is the flip side of the induced-demand choice – what is sometimes called *reduced demand* or *suppressed demand*.

Studies have gauged the effects of transportation programs that often accompany smart-growth initiatives, like the creation of pedestrian-only districts, rededication of traffic lanes to buses only, and other measures that reduce, instead of expand, road capacity. In a study of more than 100 cases of road-capacity reductions in Europe, North America, Japan, and Australia, Goodwin et al. (1998) found an average overall reduction of 25 percent, even after controlling for possible increased travel on parallel routes. This "evaporated" traffic was assumed to represent a combination of people forsaking low value-added (discretionary) trips and opting for alternative modes, including transit, walking and cycling.

In the U.S., perhaps the most dramatic example of promoting the objectives of smart growth and livability over automobility has been the tearing down of elevated freeways replaced by surface boulevards and transit improvements. The experiences with a freeway-to-boulevard conversion in San Francisco hints at the traffic inducement impacts of this early form of what might be called "complete streets" (Cervero et al., 2009). The closure of the middle section San Francisco's Central Freeway in 1996 prompted officials to predict a traffic nightmare, with "bumper-to-bumper traffic for 45 miles east across the Bay Bridge and south into the San Francisco peninsula (Cervero et al., 2009, p. 47). A survey mailed to 8,000 drivers whose license plates had been recorded on the freeway prior to the closure revealed that 66% had

shifted to another freeway, 11% used city streets for their entire trips, 2.2% switched to public transit, and 2.8% said they no longer made the trip previously made on the freeway (Figure 2-7) (Systan, 1997). The survey also found that 19.8% of survey respondents stated they made fewer trips since the freeway closure. Most were discretionary trips, such as for recreation.

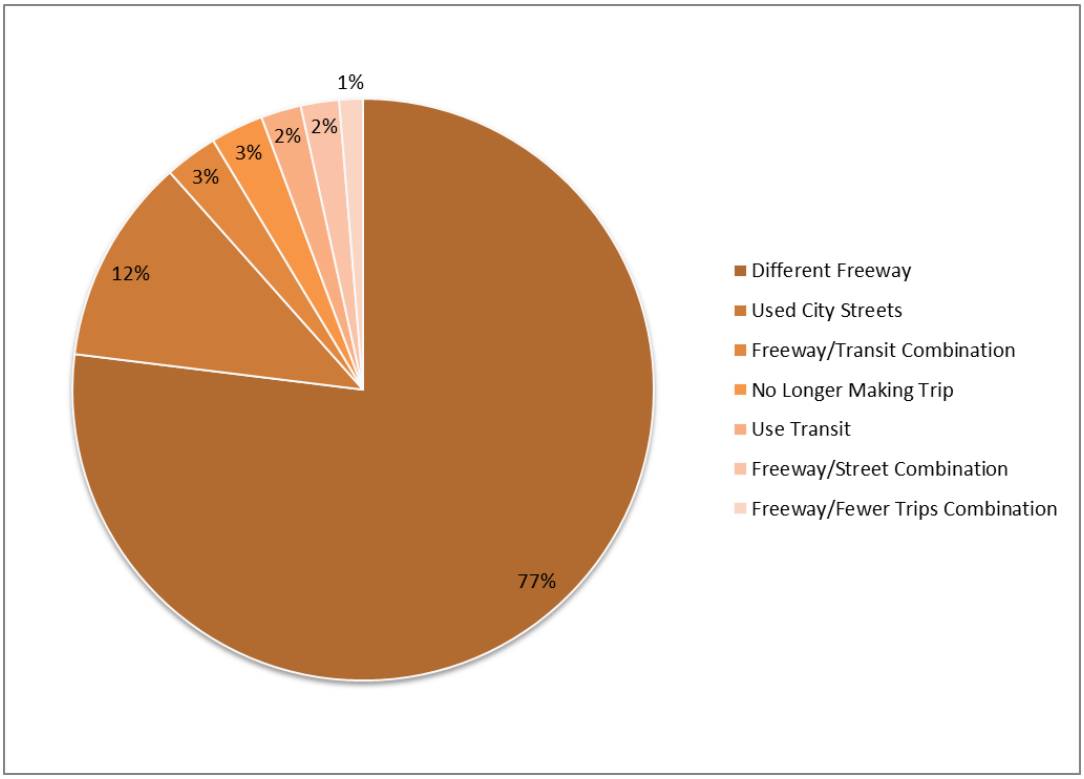


Figure 2-7: Source of Traffic Shifts Following Removal of San Francisco's Central Freeway

Source Systan (1997)

Some six months after the September 2005 opening of Octavia Boulevard, the former 93,100 vehicles recorded on the Central Freeway in 1995 had dropped by 52%, or to 44,900 vehicles. While this suggests substantial *reduced demand*, there likely was some rebound effect that eroded the traffic-reducing impacts over time, and certainly traffic conditions did not radically change along the corridor. Today, Octavia Boulevard and the network of streets that link to it operate at capacity during peak hours (Cervero et al., 2009). As a result, some motorists have opted to continue using street detours that were planned more than a decade ago for the first Central Freeway demolition (San Francisco Department of Park and Traffic, 2006). While VMT or traffic conditions might not have been altered over the long run, this does not mean the project did not deliver net social benefits: more walking and cycling trips are now being made along the corridor, which is a positive public-health outcome, and based on the higher land values and rents in the surrounding neighborhood, residents and merchants clearly have placed a higher premium on living near a well-landscaped boulevard than an elevated freeway (Cervero et al., 2009).

Little is known about the induced traffic and induced growth impacts of smart-growth initiatives themselves, as reflected by changes in attributes of the built environment, such as higher residential densities, increased mixed land uses, or improvements in the pedestrian environment. Based on a literature review, it does not appear that any empirical studies of this specific question have been conducted to date. Conceptually, however, the same dynamics should be unleashed by land-use initiatives like TOD or New Urbanism designs that reduce or suppress travel demand. The near-term impact of most smart-growth measures will be less car traffic matched by more transit usage, walking and cycling, perhaps over shorter distances. This normally translates into less VMT, both in peak periods and the off-peak. The question becomes, however, will the vacated slots on nearby roads and smoother flowing traffic induce intermediate and long-term responses? That is, will the short-term mobility benefits soon erode as people take advantage of better traffic conditions and react to the lowering of transportation costs? Over the long-term, might some of the attractive elements of smart growth that draw households and firms to locate in these communities diminish as traffic readjusts and perhaps congestion levels creep upwards? Similar questions could be posed about the intermediate to longer term impacts of Transportation Demand Management (TDM), strategies, such as improved parking management and dynamic ridesharing, as well.

Most attention about the possible induced demand, or rebound effects, of smart-growth have centered on one component: mixed land uses. In the case of neighborhoods with a mix of housing, retail shops, and other commercial outlets, home-based trips that would otherwise be made to destinations outside of a neighborhood by car might now be made within the neighborhood by walking or cycling – what transportation engineers refer to as "internal capture". However shorter trips and driving less reduces the cost of travel, which over the long term could prompt residents to make more trips. That is, the travel-reducing benefits of mixed-use development could erode over time and perhaps totally evaporate. Crane (1996) first raised the possibility that smart-growth strategies might have unintended consequences of inducing travel. Crane examined the potential impacts of three elements of neo-traditional neighborhoods (grid street networks, traffic calming, and mixed land uses) on three measures of travel demand (number of car trips, VMT, and modal splits). Only traffic calming was found to contribute to an overall reduction in automobile travel. The other elements, Crane conjectured, could actually increase motorized trips and VMT. Crane and Crepeau (1998) later empirically tested this idea of induced travel spawned by smart growth, finding that grid street networks in San Diego had no significant effect on the amount of automobile or pedestrian travel. The 1998 Crane study was based on a SANDAG data set from 1986, and was not entirely conclusive regarding the built environment/travel demand relationship.

Induced travel can also take the form of more non-auto travel, which does not necessarily increase VMT but nonetheless represents a second-order rebound effect. In a survey of residents in six neighborhoods of Austin Texas, Handy (1996) uncovered evidence of induced travel among residents making shopping trips. From a survey of residents who had walked to a local store, about one in eight stated they would have stayed home instead of drive if there was no nearby store within walking distance. This implied that the opportunity to walk to a store likely induced some extra pedestrian trips. Since these were not motorized trips, the presence of induced trip-making does likely mean no change in VMT or an erosion of the traffic-reducing

impacts of smart-growth strategies. If anything, such inducements are positive outcomes: more physical activity and perhaps social interaction.

A recent analysis of mixed-use development in Plano, Texas provides further insight into the possible induced travel impacts of smart-growth strategies over time (Sperry et al., 2010). Intercept surveys were used to ask those entering a destination of a mixed-use employment center on the edge of Plano: "Would you be making this trip if you had to travel outside of <*study site name*>?" A "no" answer implied the trip was induced because the marginal cost to travel off-site was perceived to be higher than the respondent valued the trip. Around one quarter of internal trips, the researchers estimated, were induced, meaning one out of four internal trips were additional trips and not replacements for trips that would have been off-site, on the external street system. Many of these internal trips were by foot however a number were also by private car. Among internal car trips, 17.2 percent were estimated to be induced. While these trips contributed to the mixed-use project's VMT, because they were internal to the site, they did not appear to contribute to increased traffic congestion on the external road network. The analysis concluded: "It is evident that some of the internal trips at mixed-use developments are not 'captured' from the external street network, but represent additional trips, induced by the characteristics of the mixed-use environment that reduces overall travel costs" (Sperry et al., 2010, p. 22).

Perhaps the element of induced travel with the strongest implications for peak travel and thus infrastructure capacity is time-of-day shifts. To the degree that congestion prompts some travelers to switch to the shoulders-of-the-peak, any measures – be they road expansions or smart-growth initiatives – that improves rush-hour conditions will have the opposite effects, encouraging some to switch from the off-peak to the peak. Pell's (1989) literature review of induced travel suggested most redistribution via time-of-day shifts. These shifts, however, can be considered discretionary reactions to lower travel impedance that produce greater mobility, accessibility, and possibly other social and economic benefits – without creating a need to expand roadway network capacity.

Recent research indicates that the nature of growth pattern changes is materially dependent on the context of the highway investment (Funderburg 2009). Funderburg's research in three diverse California counties pointed to strong linkages between growth patterns and the type of highway improvement (new extensions and expanded capacity, for example) and locational characteristics (rapidly growing urban area or a more rural context). A highway expansion may provide new benefits through enhanced access in one location, while a similar expansion could impose costs on a small town bypassed by new investment.

Travel inducement is not necessarily all bad. While the inducement of car trips can erode the benefits of both supply-side expansions and smart-growth initiatives, there are presumably benefits to travelers from the ability to make extra trips that were previously suppressed. Quite likely, however, these are low value-added trips (e.g., less essential, discretionary ones) since they were not worth making when the perceived marginal costs of making them were too high. Whether new roads or smart growth are on balance beneficial to society cannot be informed by

studies of induced demand; such important questions require a full accounting of social benefits and costs.

Relationship Between Smart Growth and Congestion

The United States' top 100 metro areas cover just 12 percent of the nation's land area, but hold 65 percent of its population and are responsible for 76 percent of its Gross Domestic Product (GDP) (Sarzynski et al. 2008). The success of urban regions is critical for the success of the nation, but the land use patterns and transportation system characteristics in most of these areas greatly impede their travel efficiency, economic productivity and quality of life. With much of the functional portion of these areas built after World War II, following the popular theme of outward expansion, lower densities and separation of land uses, travel in these areas substantially relies on highways and motor vehicles making trips over relatively long travel distances, equating to high rates of VMT per household and per individual traveler. Between 1976 and 2001 (dates of the FHWA's National Household Travel Survey), population grew at a rate of 0.45% per year, while the VMT generated by households grew at a rate of 2.02% per year -- a ratio of 4.5 to 1. It has been virtually impossible to match this disparity in growth of demand with new highway investment, resulting in ever-growing congestion and delay. These patterns have also greatly impacted rates of freight and commercial vehicle traffic, as addressed in the next chapter.

There is growing consensus that how community and activity centers are designed and built has considerable impact on how efficiently they can support both personal and economic travel needs. Transit obviously needs more compact development forms and higher densities in order to perform efficiently. Walking and bicycling become viable travel options when urban design co-mingles activities and brings them closer together. Transit is more likely to be used if it can be reached by walking (or bicycle) at both ends of the trip. The prior sections in this chapter provide but a small portion of the evidence from both empirical and statistical modeling research that areas with reasonable densities, a balanced mix of uses, effective design that ties the uses together in a way that allows them to be accessed by pedestrians, cyclists and transit users, and high regional accessibility via transit result in fewer vehicles owned by households, fewer trips made by private vehicle, overall shorter trip lengths, and rates of VMT production that are only one-half to one-third of those seen in conventional suburban/Euclidean-zoned settings.

Litman refers to a Surface Transportation Policy Project look at the Travel Time Index (McCann 2001) to explain how sprawling areas tend to have better levels of service on each mile of roadway or at various intersections, but higher per capita delays. He also cites 2002 Urban Mobility Report rankings for Portland, Oregon versus Atlanta, Georgia, in terms of Travel Time Index values and congestion delays (where Portland ranks high/poorly) versus overall hours of delay per capita (where Portland ranks much lower/better than Atlanta). Litman presents Cox's (2003a) simple (bivariate) plot of overall/regional densities versus commute times, which shows how job-access/work-travel times tend to rise in larger, denser regions (though other travel times may well fall, along with emissions and heart disease, for example). Cox (2003b) also estimates VMT per square mile versus population densities, showing an expected upward trend – but one

that is highly concave (once both axes are linearized), suggesting significant travel economies in the presence of added density.

Reduced VMT and greater shares of non-motorized travel are expected to reduce petroleum dependence and GHG emissions, but congestion can dramatically reduce vehicle fuel economies. Figure 2-8 shows that fuel economy of vehicles more recent than the 1997 models is typically maximized around steady state speeds of about 30 mph on local streets or highway speeds of 50 to 60 mph (Rakha and Ding 2003). Reduced fuel economy is associated with higher emissions of GHGs, NOx, VOC, PM, toxics, and other pollutants, as well as delays to personal travel and goods shipments. Lower speeds also reduce the attractiveness of vehicle travel, thus reducing emissions directly via forgone trips. A critical consideration in determining the effects of highway capacity expansion on congestion-related impacts is the degree by which reduced travel speed increases emissions and energy use relative to the degree to which it reduces travel volumes. Goodwin (1996) estimated an elasticity of travel demand with respect to travel time of -0.27 in the short run and -0.57 in the long run on urban facilities. If one considers slowing traffic from 60 to 30 mph, this will result in a doubling of travel time (adding 1 minute per mile traveled), and one can expect VMT to fall by 27 to 57%. If this slowed speed results in 3 fewer miles to the gallon, Figure 2-8 suggests roughly an 8% increase in fuel consumption and CO2 emissions, which would be more than fully offset by a 27% short run reduction in VMT. However, this would assume that the 30mph speed would be a relatively uniform, or steady-state, condition rather than stop-and-go travel, a scenario that might only be achieved through advanced in-vehicle and out-of-vehicle ITS technology. Another way to look at the trade-off would be to note that fuel economy would need to decline by about 27% (from 35 mpg at steady-state 65 mph to an average of 25 mpg at a slower more congested speed) to off-set the short-run VMT reduction that would result from travelers' avoidance of congestion. To off-set the long-run effects, fuel economy would need to decline by 57% (to 15 mpg). Thus slowing traffic down may reduce energy consumption and carbon emissions overall for personal travel.

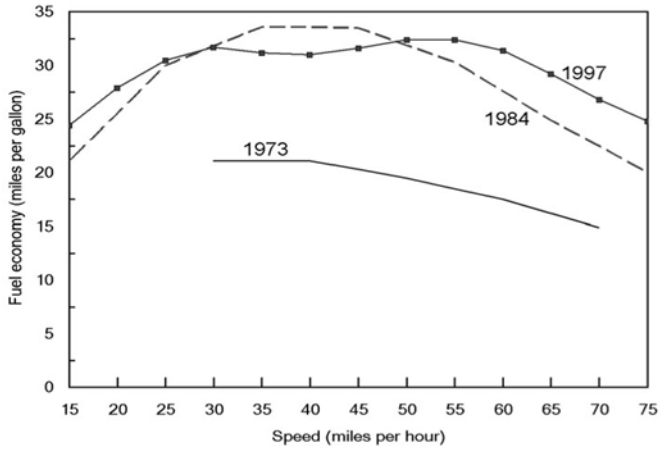


Figure 2-8: Fuel Economy-Constant Speed Relations

Source: Rakha and Ding(2003)

While a considerable body of research has successfully isolated and begun to qualify the effects of smart growth land use design on trip making, there has been a noted lack of research on the subsequent link betweensmart growth development and traffic congestion. The principal findings on the first-order effects strongly suggest that when communities incorporate higher levels of the "Ds" in their design, households that reside in those communities own fewer cars, make fewer trips by vehicle, and generate lower rates of VMT than household of comparable demographic composition living in more conventional single-use settings.

Similar results occur in employment and commercial activity centers. When these destination areas combine uses in more compact walkable settings, commuters, shoppers and visitors are found to be much more likely to travel to these locations by modes other than driving, and once there, to conduct a higher percentage of their work-related or non-home based trips locally by walking or by transit. Other than Cervero's early work on Suburban Activity Centers (1991), these relationships have not been nearly as well studied as the effects of built environment on the residential end of the trip – largely because that is where the travel behavior data (obtained from household travel surveys) is richest and most plentiful. Renaissance and Fehr & Peers are currently performing research under a Lincoln Land Institute grant that is examining these destination-end relationships in greater detail in the Los Angeles region.

Where the connection between the built environment and travel has been least studied, however, is in the link between travel behavior in response to these land use designs and the traffic that is actually occurring on the street and highway system. Skeptics of smart growth approaches suggest that, even if higher intensity land use designs reduce auto dependency for their residents, the fact that they still amount to putting more activity in a given land area space must imply that traffic levels will increase in these places or along the facilities that serve them.

The following section presents summary findings from two research studies performed by members of the study – from Phoenix (Arizona DOT) and suburban Washington, D.C. (Prince George's County) – that are relatively unique in addressing this link between smart growth land use and traffic congestion.

Arizona DOT Land Use and Congestion Study

In 2007, the Arizona Department of Transportation's (AZDOT) Transportation Research Center (ATRC) commissioned a study of the impact of higher density development on traffic congestion (Kuzmyak, et al., 2010). The study was in response to growing questions as to why the state was not more actively considering Smart growth land use practices to manage sprawl and to reduce congestion and demand for new highway capacity. The DOT sought to improve its understanding of how land use impacts travel behavior, but also in how it impacts traffic conditions on adjacent roads.

A two part approach was devised to address these issues, both focused on the Phoenix metropolitan area. The first part used travel survey data from the Maricopa Association of Government's (MAG) 2001 regional household travel survey combined with detailed GIS and transportation system data to create models of travel behavior in relation to land use. The second

part used case study analysis to examine the relationship between development patterns and on-road traffic conditions in four different locations where traffic congestion was perceived to be the result of local development patterns.

To address the question of whether Phoenix residents did in fact exhibit differences in travel in relation to development conditions, a set of regression models were estimated to explain household vehicle ownership, total daily household VMT, and daily household work and non-work VMT. The models accounted for household size, composition and income, regional transit accessibility to all jobs and retail jobs only, and local land use as measured through the variables of household density, land use mix (entropy) and walk opportunities. The models showed vehicle ownership to be negatively correlated with the 4Ds variables of household density, land use mix and walk opportunities (but not transit accessibility); total daily VMT negatively correlated with auto ownership, transit accessibility to both total and retail jobs, and land use mix; HBW VMT negatively correlated with vehicle ownership, transit accessibility for all jobs and land use mix; and non-work VMT negatively correlated with vehicle ownership, transit accessibility to retail jobs, and household density.

The region was then separated into 17 different areas (jurisdictions) of different character, and the comparison demonstrated some fairly substantial differences in the rates of vehicle ownership and VMT associated with differences in density, mix, design and transit accessibility. Older, more urban and walkable areas such as East and West Phoenix and South Scottsdale had rates of daily per capita VMT that were more than 30 percent less from newer but less compact communities like Mesa and Gilbert, and more than 70 percent less than the newest and most outlying places such as Glendale, Peoria and Chandler. The differences in VMT rates were comparable for both work and non-work travel, in contrast to similar studies in Baltimore that showed much bigger differentials among non-work VMT rates.

Again, this second part of the analysis assumed a case study format. Four areas were identified in the Phoenix region that featured different land use patterns, with each cited by local stakeholders as probably having traffic issues related to local development.

Three of the sites were located in the most densely developed portions of the region: Scottsdale Road near Old Town Scottsdale, North Central Avenue just north of the CBD, and the Mill Avenue/Apache Blvd. corridor through the most built-out portions of Tempe. A fourth corridor, West Bell Road, served as something of a control site, being located in a medium-density (but intensely developed) typical suburban setting on the region's northwest edge. Each site surrounded one or more major arterial highways and each was no closer than two miles from the nearest expressway.

A key finding was that despite the considerably higher densities in the three urban examples, measured traffic conditions on key roadways were found to be considerably better than those in the much lower density Bell Road corridor. Lacking information on intersection level of service (queuing and delay), the researchers focused on traffic level of service on key links in each study area, measuring volume-to-capacity (V/C) ratios in both the mid-day and PM peak time periods. These results, summarized in Table 2-5, revealed surprisingly reasonable

traffic flow on most of the critical links in the Scottsdale and Central Avenue corridors, with both mid-day and PM peak V/C's below 1.0. Tempe does not show as well, with measurably higher V/C readings, particularly on Mill Avenue which is the area's commercial strip. However, traffic conditions on Bell Road were easily the worst of the group, with V/C ratios in the 1.3 to 1.6 range, reflecting heavy traffic congestion.

Table 2-5: V/C Ratios on Selected Links (Adjusted to Counts)

Study Area	Location	Mid-Day		PM Peak	
		North/ East	South/ West	North/ East	South/ West
Scottsdale	Scottsdale Rd, N of Indian School	0.59	0.57	0.66	0.61
	Indian School, W of Scottsdale Rd.	1.05	0.85	1.11	0.99
	Goldwater Rd., N of Indian School	NA	NA	NA	NA
	Drinkwater Rd., N of Indian School	NA	NA	NA	NA
Bell Road	Bell Road, bet. El Mirage and 115th	1.88	1.63	1.68	1.91
Central Avenue	Central Ave, N of Osborne	0.41	0.64	0.59	0.49
	Thomas Rd., W of Central Ave	1.27	0.83	1.11	1.26
Tempe	Mill Av., North of University Dr.	1.38	1.25	1.33	1.70
	Rural Rd., North of University Dr.	0.60	0.46	0.71	0.38
	Apache Blvd, W of McClintock	0.56	0.58	0.99	0.56
	Broadway Blvd, W of McClintock	0. 71	0.7 4	0.96	0.87

Kuzmyak, et al., 2010

An important consideration in examining local traffic levels is accounting for the proportion of traffic that is simply passing through, having neither origin nor destination in the study area. This is always a key factor in evaluating the efficiency of a land use design, since travel which is totally unrelated to the development activity is part of the total volume contributing to demand on the facilities, and counting in any traffic test – in effect, being used as part of the test to determine the performance of "local" land use. The previous chapter dealt with the related issue of induced demand, whereby efficiency improvements attributable to good design (more trips made internally or by transit) free up capacity on adjacent roadways, which then attracts trips that previously wouldn't have been made or would have been made on other facilities.

Select link procedures were used to estimate the through traffic percentage on each of the sample roadway links in the Phoenix examples. Each of the areas' facilities were determined to be carrying appreciable levels of through traffic, with Scottsdale being least affected (23% to 28% range, peak and off peak), but with half or more of all peak period traffic in the other three areas being through traffic. What this showed was that while Bell Road could attribute half or its peak period traffic to through trips, both Central Avenue and Tempe were supporting similar ratios, but with much better net V/C measures. Indeed, if the through travel proportion on Bell Road were reduced to the 22-28% moderate ratio in Scottsdale, it would still have a V/C well over 1.0. The net take away from this exercise was to find that while the three urban higher density, mixed use sites had residential densities twice that of the suburban example, and employment densities greater by multipliers of 7 to 25, traffic conditions were in fact much better – and certainly not worse, as might have been predicted based on the differences in densities.

Several important differences helped account for this apparent paradox. The first is the presence of an articulated street grid in the three urban sites. While most of the region is served by a 1-mile super grid, Central Avenue and Scottsdale Road are embellished with a secondary street grid that features smaller capacity streets on quarter or eighth mile spacing. This not only makes walking and access to transit more convenient, but provides more effective capacity to handle traffic, plus the ability to specialize links, signals and turns to optimize flow for particular travel segments (e.g., local vs. through) or by time of day. Bell Road clearly does not possess such a network, and while there are many roads, few are designed to connect arterials, but mainly to serve internal circulation within subdivisions. Plus, the siting of commercial activity in strip centers and malls along the main arterials means that virtually all access to and between residential areas and these centers must be by driving.

The other difference has to do with how the smart growth design allows the three urban areas themselves to be more efficient in terms of travel demand. Resident households in the Scottsdale and Central Avenue corridors own fewer vehicles (1.4 – 1.47) than those in the Bell Road Corridor (1.7), while auto ownership levels in Tempe (which is generally less "urban" than Scottsdale and Central Avenue) being higher (1.63) and more like Bell Road. Daily household VMT rates are much lower in Scottsdale (19.5) and Central Avenue (17), and even appreciably lower in Tempe (24.2) than Bell Road (31.8). Reasons for this may be seen in higher rates of internal capture for work trips (18-21% vs. 13%); non-work trips have about the same high rate of capture (40-42%) in each corridor, but the Bell Road corridor likely earns this status because of its large size (17 square miles vs. 3 to 5 square miles for the urban sites). Average trip lengths are much longer for all trip purposes in the Bell Road corridor than at any of the three urban sites (about half as long for work trips, between 12 to 25% as long for non-work trips). The three urban sites also capture decent shares of trips either from or to the area by transit (3% to 10%), compared to less than 1 percent in the Bell Road corridor (where all transit is park and ride).

Prince George's County Smart Growth Development Study

The Prince George's County (MD) planning department commissioned a study in 2009 to investigate alternatives to traffic LOS-based adequate public facilities (APF) requirements for

evaluating the performance of compact mixed-use centers and corridors (Kittelson, et al. 2010). The County's adopted 2002 General Plan emphasized strategic development around its numerous Washington Metrorail and MARC commuter rail stations, as well as in other designated centers and corridors. Unfortunately, the County's planners found themselves stymied by local traffic violations of APF standards when attempting to move forward with these plans, causing them to seek alternative mechanisms to measure performance and adequacy for these activity areas.

Because the APF test is performed in proximity to a proposed development project, the use of standard trip generation and impact assessment methods place the burden of meeting local traffic standards on adjacent development, regardless of (1) whether the development is inherently efficient in its design, or (2) whether it is the primary source of traffic in the measured stream. The county planners were in search of an alternative way to determine both "adequacy" and "attribution," seeking a broader and more revealing set of tests and indicators that would be more appropriate and useful in encouraging the right types of development in the designated growth locations. Believing that research on the 4Ds provided strong support to the premise that "Smart Growth" (compact, mixed use, pedestrian friendly and transit-served) development reduces vehicle dependency and use, the goal was to establish protocols for defining the functional boundaries of these areas, the desired attributes of the development, and measures to more accurately represent the performance of the planned development.

A two-part methodology centered on case studies was developed for this assessment. The first part of the methodology was to measure and assess traffic conditions and the composition of traffic. The second part was to look at the characteristics and design of the given study area to ascertain whether it possessed good smart growth design properties, and the degree to which its design was beneficial to transportation objectives.

Six representative areas were selected as case studies, to allow for a thorough investigation of the relationships between land use patterns and traffic conditions. Each of these areas had been designated for intensified development under the 2002 General Plan, and they varied with respect to regional location, proximity to Metro and key highway facilities, density and mix of development, and overall scale. The areas ranged in size from 2.8 to 4.9 square miles, in household density from 0.3 to 3.8 households per acre, employment density from 631 to 6,660 employees per acre, jobs/housing ratios from 0.82 to 3.88, and retail jobs/housing ratio from 0.09 to 1.51. All areas were on or adjacent to one or more major state or US highways supporting inter-regional travel. Three of the areas had one or more Metro or MARC train stations.

Those principal road segments likely to be used in an adequacy determination were identified, and data on their utilization and performance was recorded. Traffic levels in the current (base) year were established by comparing model-generated link volume estimates with actual counts, and concluding that the estimating accuracy was acceptable. Conditions in 2030 were then forecast using the county's travel model, with planned development and transportation improvements in place throughout the region. (The county's model is based in TransCAD, includes the entire metropolitan Washington, D.C. region, and has a highly detailed road network

and assignment process.) These analyses showed that most of the identified facility segments in the case study areas would be carrying 2030 traffic volumes that would exceed established level of service thresholds. Hence, the development planned for these centers would probably not be permitted to go forward.

A first step in assessing these traffic conditions was to determine the proportion that was attributable to development in the subject study area vs. direct pass-through. This assessment was done using the "select link" procedure in the travel model, and showed that the major portion of traffic on the representative links was comprised of through traffic, with no less than 50% in any of the situations, and as much as 100% in the worst case (Brandywine). The clear implication was that the planned growth in almost of these areas was not the reason for a likely traffic LOS failure, but rather these areas are serving as conduits for through travel that substantially determines their performance.

The first part of the analysis thus demonstrated that a local traffic congestion test to determine the worth of a smart growth center plan would probably be inappropriate in several ways: first, by making the local area responsible for traffic volumes that were unrelated to local development activity; second, by reducing the development design and likely compromising the transportation efficiency potentials; and third, by focusing solutions on actions to increase road capacity instead of improving efficiency (such as through provision of a street grid).

The second part of the approach was to look in depth at the trip generation characteristics of the study areas themselves. If such smart growth designs were to be given special treatment for their presumed efficiency on travel, their characteristics should satisfy design standards and protocols that research has found to be associated with reduced vehicle dependency and VMT. The “Ds” provide such a checklist, offering guidelines on minimum densities, synergistic mixes of different uses, proper layout and design to support pedestrian, bicycle and transit use, and both good regional transit service and accessibility, as well as efficient access to transit within the study area.

Since the tested scenarios incorporated 2030 design assumptions and population/employment allocations – thereby implying that the county’s design plan for the area had been implemented -- it was possible to test each area's smart growth legitimacy using the following measures of performance:

- The number of trips generated by residents, by trip purpose: home-based work, home-based shop, home-based other and non-home based.
- The destinations to which these trips were made, allowing measurement of how effectively the y design retained trips internally.
- Average trip lengths.
- The modal split for trips made for each of the four purposes for trips made from, to and within the study area (and particularly the number made by transit or non-motorized modes).

- VMT generation rates for households residing in the study area vs. comparable households outside of such areas.

What this analysis showed was that the design of the designated growth areas fell far short of smart growth ideals: Overall densities were much lower than desired; the balance of residential, employment and retail was insufficient to retain a respectable portion of travel with the study area, and high rates of non-home based VMT were observed, suggesting auto-based trip chaining to accomplish basic travel needs. In terms of transit viability, aside from home-based work trips being made by Metrorail to well-served destinations in downtown Washington or Arlington, transit use for work trips by visitors to the study area or by residents to any other location were nominal, and negligible for non-work travel purposes. A contributing factor to the low transit use rates was the location of the actual transit station in a non-central location relative to the rest of the developed center, making access inconvenient.

This analysis was very revealing to the county's planners, making evident that what many people "thought" was smart growth was not reflected in the actual designs put forward. Thus, the dual message was taken that (1) smart growth projects can have a major impact on vehicle trip generation and congestion, reduced need for additional road capacity, and therefore deserve special performance criteria to measure their impact and worth, but (2) there are critical elements that define a legitimate smart growth design, that clearly were not evident in the designs that were reflected in the scenario. This implied that county also needed additional tools and protocols to support better design of its smart growth centers.

Smart Growth and Freight Traffic

Truck and rail modes each carried 40% of the nation's 3.34 trillion ton-miles of commodities-moved in 2007 (USDOT, 2010), with average distances of 206 and 728 miles, respectively. Intermodally, truck and rail carried 5.9 percent of ton-miles captured by the Commodity Flow Survey, with a (combined) average distance of 1,007 miles (USDOT, 2010). The FHWA (2007b) has forecasted a doubling in U.S. freight tonnage between 2002 and 2035, due to globalization and modern supply-chain management (including just-in-time manufacture and delivery of more higher-value goods). Congestion, crashes, pollution, noise and other issues are associated with moving goods in a world of rising population and incomes and population. Finding space for containers and vehicles, pickups and deliveries, within dynamic urban regions is a challenge.

While heavy-duty-trucks generally are responsible for less than 5 percent of most highways' VMT, urban truck VMT has outpaced overall freight-VMT increases (Bronzini 2008), and trucks are said to occupy 60 percent of road space on many "chronically congested roadways" in places like New York City (Move NY & NJ, 2007). Truck's share of U.S. ton-miles has increased over time (EPA, 2006), while mode energy efficiency has fallen (Davies et al., 2007). Kockelman et al. (2008) suggest this may be due to more trucks traveling empty (or "dead heading"), since HDT fuel economy has remained constant or increased over the same time period (FHWA, 2007b, Davies et al., 2006, Bertram et al., 2008). But growing roadway

congestion is another potential cause (with HDT fuel economy-speed relationships presumably similar to Figure 2-8 curves [though with maximum fuel economies around 6 mi/gal]).

Many argue for a shift of freight to rail transport (CEC 2011), where fuel use and emissions are arguably much lower (e.g., roughly 400 versus 100 ton-miles per gallon of diesel on rail versus truck), capacities are theoretically higher (e.g., roughly 200 versus 40 million ton-miles per track or lane per year, respectively), shipper costs are noticeably lower (e.g., 2.7 versus 5.0 cents per ton-mile by rail versus highway), and safety statistics are better (e.g., rail transport exhibits roughly one-third the number of injuries and fatalities per ton-mile shipped) – according to Move NY & NJ's McGregor (2006). Double-tracking of more rail corridors is hoped to dramatically improve rail's reliability and travel times, enhancing its modal competitiveness. Rising roadway congestion, the introduction of road tolls and higher gasoline taxes may incentivize shifts to rail and other freight modes.

Truck presence on highways varies significantly by location. In many U.S. corridors (e.g., major highways in the Chicago region, Atlanta's I-285, I-75 and I-20 – among others, and Southern California's I-710 [serving the Los Angeles-Long Beach port]), highways carry 30,000 or more heavy-duty trucks (HDTs) a day, with these HDTs contributing 10 percent or more of the facilities' VMT (Bronzini, 2008). U.S. Interstate highways typically carry less than 10,000 trucks per day, but their truck traffic often contributes 20 percent of more of their VMT (Bronzini, 2008, Wilbur Smith, 2003). Port areas are especially important for freight movement, with 2 billion tons of freight entering the nation at marine terminals each year. Associated population exposure to heavy vehicles, their emissions, and potentially devastating queuing are of key concern to planners, shippers, port operators, local residents, and business leaders; as Prasad (2011) recently put it: "Land-use decisions are critical" – to environmental justice, human health, the economy, and quality of life.

Land Development and Infrastructure

While mixed used and higher density land development patterns are expected to reduce goods-and-services-delivery-related VMT, coordination and cooperation may be key (e.g., to fill up delivery vehicles and meet customers' time windows). "Public logistics terminals" or multi-company distribution centers have been studied and, in some instances, adopted as a method for reducing delivery burdens via capacity consolidation by third-party operators (see, e.g., Hassall, 2005, and Taniguchi et al., 1999). Inland ports or "freight villages" exist in the U.S. (e.g., Alliance TX's multimodal hub and North Carolina's Global TransPark), as well as across Europe (Ballis 2006). These expertly designed trans-shipment points for warehousing by multiple operators facilitate intermodal transfers and goods storage while enabling consolidated operations (e.g., shared pickups and deliveries within the nearby cities), often relieving competition for scarce land (and road space) in densely developed regions (e.g., Athens and Paris) (Ballis, 2006). Though many firms are more accustomed to competing, rather than coordinating their movements, there are multiple benefits to consolidation of deliveries and pickups (including reduced fuel use and fewer employees needed on site to receive added deliveries). These freight villages can have growth inducing effects that counteract the positive reduction in truck VMT, when new exurban communities develop nearby and produce trips

among new residents and workers that result in higher auto VMT, given the low densities and remote locations. This phenomenon may be intuitive, but is not well understood; in a recent publication on freight and land use (FHWA, 2012) the positive benefits of freight villages are discussed but induced effects are not mentioned.

Klastorin et al. (1995) examined the decisions of six firms with distinctive logistics needs in the Seattle region over 15 years ago (including Safety, Avtech, and Boeing), and found that land rents drove location decisions more than transport access (though some level of highway access is presumably fundamental to site choice, but relatively well provided within and between most U.S. regions). Four of six firms preferred denser urban form for access to customers and clients, though the move toward larger/longer vehicles (to reduce shipping costs) makes many local street designs tougher to navigate. The conclusion that site access design (e.g., provision of curb loading zones, one-way alley protocols, and signage) "can have a big impact on urban goods movement" (Klastorin, 1995) was highlighted, and the use of smaller (24-foot) trucks by at least two of the six firms for intra-neighborhood operations was noted, with "satellite transfer facilities" for shifting goods to and from larger trucks.

The proximity of freight and non-freight activities often results in more trespassing issues and theft, more human exposure during hazardous materials incidents, and other unsafe conditions, along with complaints regarding emissions, noise and vibration issues, and light pollution at nighttime. (Straus-Weider, 2003) Relocation of freight activities requires a high-degree of communication and coordination among affected parties – public and private. Urban brownfield sites present an opportunity for such land uses at reasonable cost, with thoughtful location being key for carrier access, goods consolidation, and streamlining movements (ideally across carriers and shippers). Hush-kits on airport equipment, alternative fuels and electrified engines, reduced idling regulations, whistle-free (or modified-whistle) zones (for rail transport), grade separation, barrier construction alongside corridors and shipyards (Figure 2-9, corridor preservation (by purchasing underutilized industrial parcels and rights of way) and other strategies are also providing valuable in U.S. applications and abroad (Straus-Weider, 2003).

Figure 2-9: Barriers for Pedestrian Protection—Before & After

Source: Straus-Weider 2003, Figure 4

Designing street systems and associated infrastructure to accommodate large trucks and other forms of goods movement can be at odds with various smart-growth strategies. For example, wider lanes, longer loading areas, and longer turn radii mean more paved surfaces and greater exposure of pedestrians and cyclists. Longer, wider, heavier vehicles can mean more damage to special street surfaces (e.g., brick or textured surfaces), close-in curbs, medians, islands, street furniture and roadside vegetation. Smaller vehicles address such issues, but raise labor costs (and, presumably, fuel costs and emissions) per ton-mile transported. Limited rights of way and freight-loading zones mean more double-parking, backups into and across streets, and blocking of pedestrian and bike baths, thereby worsening congestion and traveler safety. Truck-only lanes (and access ramps), truck-restricted locations (enforced by size and weight, with permits for special shipments at less congested times of day), rail yard and corridor investments (including staging areas for deliveries and rest areas for truck drivers satisfying

work-time regulations), and congestion pricing or roadspace rationing (with travel credits for continued access and revenue-neutrality [see, e.g., Kockelman and Kalmanje [2005]) help avoid conflicts while incentivizing socially-preferred modes and routes.

Freight Delivery and Pickup

Pivo et al.'s (2002) more recent interviews of truck drivers (via Seattle-area focus groups) echo such findings, along with a strong impression that deliveries and pickups are now at all times of day (due to the changing nature of business) and loading zones are not often long enough (with 30 feet a desired length, per intended vehicle, ideally located at the ends of blocks [for added access]) or exclusive enough (with limos and sales reps with commercial license plates taking valuable space, or bus lanes precluding parking). Truck-driver complaints include the clutter and congestion of alleyways (e.g., dumpsters, misdirected trucks, mis-parked cars, and homeless persons), and the improper design of loading docks (e.g., at the bottom of steep descents with tight turn radii). Wider alleys, turn-tables for delivery trucks at space-constrained loading docks, standardization of good practices in dock designs, alcoves for dumpsters, higher emergency stairwell clearances, and shorter/single-unit trucks were all desired for urban stops. All-way pedestrian phases were also cited as desirable, to minimize pedestrian exposure and risk during truck turning movements. At shopping malls and large office buildings, centralized delivery locations, with intra-mall/intra-building delivery made onsite by specialized mall-managed vehicles or building-provided workers is also desired (to minimize parking times, freeing up limited parking space for others). Drivers reported a dislike of commercial strip development, since it is not so conducive to safe or efficient delivery practices. As congestion mounts, light-duty vehicles appear more likely to take chances around bigger trucks; business practices place more emphasis on time-sensitive pickups and deliveries while network unreliability increases, leading to a highly stressful situation for urban truck drivers.

More recently, Weisbrod and Fitzroy (2008) examined the economic consequences of urban congestion in terms of freight delivery and business operations. They cited literature describing the reduced customer, labor, delivery and input sheds (or catchment areas) that emerge from urban congestion, along with other potential agglomeration disbenefits, like higher input costs and shifted or narrowed delivery windows. They highlighted Vancouver, Chicago, and Portland (Oregon) examples, where business leaders were seeking to address concerns about sea, rail, truck, and airport activities being compromised by serious roadway congestion. Their interviews revealed that early-morning deliveries have been rising (to avoid congested times of day) and worsening PM peak traffic conditions have curtained certain backhaul opportunities, affecting carriers' bottom lines (and therefore shipper and customer costs). Just-in-time deliveries and increasingly complex supply chains are threatened by growing congestion. It was noted how air and maritime port schedules are relatively constrained (by time of day and frequency of departure to desired destinations, particularly for international shipments), putting more emphasis on truck travel, thanks to reduced uncertainties.

In terms of land use relationships, Weisbrod and Fitzroy (2008) noted that warehousing and distribution centers, traditionally drawn to the edges of urban regions, are finding the density of later infill development to limit their operations via congestion, vehicle-turn conflicts (on

space-constrained roadways), and higher land values for any desired expansions. While the costs of such congestion is difficult to estimate, reservation times at port facilities, congestion-based road and runway tolling, variable pricing of capacity-constrained rail corridors, and various impact fees for existing and new land uses may ensure reliability in movement of freight and passengers, raising some business costs while avoiding a host of others. The use of TREDIS software for multimodal modeling of the benefits and costs of network changes was suggested.

Quak and de Koster (2009) highlight the common response of municipalities to the issues of large-truck deliveries in the urban area: delivery time windows (usually to the early morning, to avoid conflicts with pedestrians and added street congestion and noise) and vehicle size limitations. Apparently, restrictions of delivery timing are very common in western Europe, particularly in the larger cities, where many of the most commercially developed locations date back over 100 years, well before the arrival of (and design for) large trucks. They model the cost and emissions impacts of different policies (by running optimal logistical patterns for various case-study retailers), emphasizing the following variables at play: number of distribution centers (which proxies for the inverse of average distance to the nearest distribution center), delivery frequency, vehicle capacity, unloading time (duration of stop), and available delivery windows. Delivery windows are most restrictive (and costly) for those businesses with smaller delivery sizes (since multiple drops per journey are preferred and feasible without the schedule restrictions in place). Similarly, vehicle-size restrictions are most problematic (and costly) for those with large drop sizes (that can fill more than one size-constrained vehicle). Reductions in delivery frequencies (by aggregating shipments and reducing the number of stops per journey) deliver significant cost savings for both types of businesses (but make the most sense for those with smaller drop sizes). Finally, size and timing restrictions were estimated to increase all emissions types studied (NOx, PM, and CO2), suggesting that there is an environmental tradeoff in the pursuit of such policies; reductions in delivery frequencies ameliorate this impact (as well as delivery cost implications).

Transportation Policies for Freight Mobility

Lemp and Kockelman (2009a) simulated a variety of scenarios for an Austin, Texas comparison of traditional/aggregate and disaggregate/activity-based demand model applications. Their "centralized employment" scenario moved half of the rural-zone jobs and 30 percent of the suburban-zone jobs into urban and CBD zones (in proportion to these latter zones' existing job counts). Interesting, predicted levels of region-wide VMT did not rise and, instead, fell slightly under both model specifications (0.46 and 1.47 percent, for the aggregate and disaggregate model specifications, respectively). The strongest overall reductions in VMT were forecast on lower-level roadways (2.14% and 4.57% reductions, respectively, on the collector/local class of coded links). Transit and walk/bike mode shares rose very slightly (10 percent or less of their already very low values), while average speeds during peak times of day fell negligibly. The researchers had expected significant speed reductions (via congestion) to arise from moving so many jobs downtown, with no network changes (to buttress the urban and CBD roadways, for example), and so were pleasantly surprised by the results. Zhou et al.'s (2009) simulations of Austin under an urban growth boundary (UGB), like those of Kakaraparthi and Kockelman (2010) and Tirumalachetty and Kockelman (2010), resulted in significant (roughly 15%) VMT

reductions, versus trend (similar to reductions stemming from stiff road tolls), and much higher long-term population and jobs densities (from application of land use models, in tandem with travel demand models). While Tirumalachetty and Kockelman (2010) modeled internal commercial trips directly, freight trips remain largely exogenous to modeling efforts (with external trip tables simply held constant or scaled up proportionally over time). And commercial trips remain difficult to characterize and forecast accurately (PSRC 2009).

Johnston (2007) reviewed 40+ simulation exercises across a variety of U.S. and EU regions and concluded that many transport pricing, land use policies, and investment strategies offer significant long-run reductions in VMT and emissions (relative to trend) without compromising highway levels of service or regional productivity. Increased pricing of road use, fuels and parking enhanced "the effectiveness of the land use and transit (provision) policies," while highway capacity expansion often resulted in predictions of worse congestion.

The CEC's (2011) Destination Sustainability report mentions the "need for more integrated land use-freight transport planning" several times, but without any details. The report offers more on the notions of enhancing freight- and truck-recognition and -inspection technologies, along with better supply-chain management practices to speed up cargo checks and moderate waste in the freight industry – particularly in the context of reducing border delays (which have significant local emissions impacts, and costly time expenditures for cargo, vehicle, drivers, and their customers). The CEC report also mentions the benefits of maritime and rail modes over truck transport – primarily in relation to energy consumption and CO2e emissions, but congestion also serves as a solid reason for such mode shifts in many locations. More full-cost pricing of mode choices, by all travelers, can reduce roadway delays by moderating the excessive use of modes and routes that carry greater social costs.

More thoughtful routing and delivery timing decisions can also reduce truck VMT, and associated emissions. Pitera et al. (2011) recently showed how application of an emissions minimization algorithm for University of Washington mail services could reduce GHG emissions by 6 percent and costs by 9 percent. If service frequency were reduced to once-a-day, emissions savings estimates rise to 35 percent. In associated work, Wygonik and Goodchild (2011a, 2001b) examined how added density of customers (and smaller vehicles) reduces the cost and GHG emissions of delivery. Like Quak and de Koster (2009), they find that less restrictive delivery windows and/or a higher density of stops/customers enables more efficient goods movement (in terms of GHG and cost savings per delivery, within a single carrier's routing plans). In all scenarios evaluated, cost savings far exceed the value of saved CO2 (since carbon markets value CO2e at less than $100 per ton, now and many years into the future). While smaller vehicles often prove more efficient for this type of multi-stop, less-than-truckload (LTL) delivery system, hybrid engines offered the lowest costs and emissions. Interestingly, it was noted how higher customer densities can offset tighter delivery windows, better meeting customer needs (or city ordinances).

Another policy for impacting freight movements is road pricing. Holguin-Veras et al.'s (2006) looked at carrier responses to the Port Authority of New York-New Jersey variable-pricing policy on 6 bridges and tunnels. Their survey results suggest that "productivity changes"

(e.g., load decisions and vehicle sizing choices) and transfer of increased costs (to receivers) were much more common than route changes/facility-use changes, in this particular instance. While much depends on the specific context of the pricing's implementation (e.g., price levels by time of day and availability of routing alternatives) – including the carrier-receiver relationship dynamics and market competition, they conclude that carrier responses may be much more "nuanced" than demand modelers expect, due in part to the many decision variables at play for carriers (as well as shippers). Over half the respondents (54.8%) indicated that customer schedule dictated travel schedules, with congestion avoidance posting second (with 23.1%). Only 3.1% indicated that lower tolls drove their scheduling decision (presumably because the toll differentials were rather small relative to overall vehicle, driver, and fuel costs, as well as customer needs and receiving costs). As expected, for-hire carriers exhibited much less trip-timing flexibility (and sensitivity to toll rates) than private carriers (who enjoy more accommodating [in-firm] receivers). Overall, these results suggest that road (and zone-based/cordon) pricing may not have much of an impact on freight-vehicle use of congested corridors and locations, unless there are clear alternatives.

Freight Trip-Making

Like commercial trips, many freight trips are LTL. Holguin-Veras et al.'s (2011) recent work explains how freight-trip generation is not proportional to firm size or zone employment in most cases and across most industry sectors, thanks to LTL shipping, shipment indivisibility, variable truck sizes, scheduling needs, and other logistical decisions. In general, there is an economy of size that comes with freight shipments for larger establishments (though their data also show some peaking of trip generation rates for certain types of mid-size-firms). Holguin-Veras et al. recommend that demand modelers turn to straightforward Economic Order Quantity equations to get a better sense of such economies in shipping decisions, along with finer-scale resolution of zones and firms, ideally to the parcel level, to better replicate and forecast freight movements. One land use implication of such findings is that a mix of business types (a typical smart growth objective) may require significant consolidation and coordination of shipments to avoid the more-than-proportional increase in local freight movements (and their associated congestion), relative to large-firm, separated-use styles of land development.

Allen and Browne (2010) point out the "deindustrialization" that has taken place in highly developed countries in recent decades (with production jobs shifting overseas), reducing the need for large industrial sites near urban areas, and their associated warehousing, while increasing the importance and activity of port locations. These trends have been accompanied by a "spatial centralization of stockholding", via large regional or national distribution centers outside urban areas. Such centers or transshipment points tend to be strategically located, often at the crossroads of accessible trade/travel corridors but away from congested urban sites, with their higher land values. They allow for storage and consolidation (and breakup) of shipments, preparation of items for final display and sale, and mode shifts – well away from the spatially intensive activities of the urban core.

Allen and Browne (2010) describe the nature of different freight trips, from single-stop to multi-stop/multi-leg deliveries and pickups, direct versus consolidated shipments. Such decisions

depend on the nature and size of shipment, including its time sensitivity, proximity of destinations, and travel costs. They state that land use plays *less* of a role in freight-related travel than in personal travel since fewer mode options exist for freight shipments (e.g., all trips must be motorized, except for final rounds of small-parcel delivery and pickup), price elasticities are presumably lower (though no citations are given for this), and most freight trip ends and route choices lie along arterial highways or urban commercial streets (rather than the more variable styles of residential and suburban development). While loading space is relevant to freight movements, parking provision (and cost) is not. Similarly, transit and sidewalk provision presumably have relatively little impact on freight movement. In looking at 2005-2007 UK commodity-flow data, Allen and Browne (2010) estimate that the share of intra-urban goods movement rises from about 20 to 40 percent (of tons and ton-km moved) as region size grows (e.g., from 464,000-population Edinburgh to 7.51 million persons across the Greater London region). The average (intra-urban) haul length appears to be 20 miles in the UK data, with the average carrying capacity of intra-urban vehicles being half that of vehicles carrying shipments to and from such regions (i.e., 10 tonnes vs. 20 tonnes). Lading factors (use of vehicle weight capacity) are also much lower for intra-urban movements (generally between 30 and 40 percent of vehicle weight capacity) than other movements (which range from 0.51 to 0.67 in the 16-region UK data set). Freight trips departing an urban region tend to run less full than those entering (due to partial pickups).

Allen and Browne's (2010) look at commercial-space data across 16 major UK regions suggest a limited rise in retail space (just 4 percent over the 1998-2008 20-year period, across England and Wales, and 5 percent in London), only moderate intra-urban gains in warehousing (e.g., just 5 percent in London), and sizable office space growth (within regions and across the island – averaging 24 percent), as the nation de-industrializes. While warehousing floor space across England and Wales rose 22 percent over the 20-year period, the *number* of warehouses grew just 3 percent. Finally, it was noted that office operations lend themselves to far less use of heavy-goods vehicles than warehouse, retail and industrial sites, per square meter of floor space. Lighter goods vehicles are also more common in urban freight movements (vs. inter-urban movements) across other land use types, for reasons of maneuverability and shipment size.

Truck Energy and Emissions

Bronzini's (2008) examination of Southworth et al.'s (2007) energy and truck VMT estimates across U.S. metro areas indicate how controlling for regional population alone can predict 75 percent of the variance in commercial truck VMT. Population is less of a predictor for such freight VMT because so much freight movement entails through traffic. Truck VMT and carbon emissions (per capita) were most correlated with job and population density measures ($\rho \approx -0.48$) – as compared to their correlations the shares of metro area jobs within 10 and 35 miles of the CBD, a couple coarse jobs-housing-balance measures, and the presence of rail transit (though all were significant) (Southworth et al. 2007). Obviously, metro structure is important for travel distances – with differences in origin and destination accessibility, roadway congestion, building sizes (per occupant) and design, parking costs, alternative mode availability, and variables like climate impacting travel decisions and energy use. Southworth et al.'s (2007) examination of U.S. data sets suggest more than two-to-one differences in VMT per capita when

comparing Top 100 U.S. metro areas like Bakersfield CA and New York NY, and potentially 4 to 1 ratios that emerge in simple per-capita GHG calculations across such region pairs. Sarzynski et al.'s (2008) follow-on calculations suggest that *freight-related* GHG variations (per capita) are even more pronounced between low- and high-density pairings: at ratios of 4 to 1 or more. Location is important, and HDT travel is a part of the equation. But little research exists to quantify the distinctions at relatively high levels of spatial resolution. To this end, Bronzini (2008) recommended simulation studies of various land use pattern scenarios versus truck travel patterns. Done well, such simulations can anticipate a variety of travel changes – alongside system benefits and costs.

Like Wygonik and Goodchild (2011a, 2011b) report, Allen and Brown (2010) remark on the travel and energy savings of higher density land use patterns for freight deliveries (and presumably pickups as well as shipper drop-offs). They note that land use mixing has this potential as well, but the relegation of distribution hubs to ex-urban sites may not support such supply-chain arrangements. Finally, they recognize some value of more connected networks (e.g., grid layouts versus cul-de-sacs) for efficient multi-stop routing strategies, and they acknowledge an almost exclusive reliance on the truck mode for intra-urban freight movements. Unfortunately, there is no data provided to quantify such expected relationships.

The trend toward electric and other clean-fuel trucks could allow freight delivery in off-peak and late-night periods since vehicles can operate quietly without disrupting the night-time tranquility of neighborhoods as much. Thus technology could enable a travel demand management response – off-peak delivery – which in turn could improve peak-period traffic conditions and reduce emissions from trucks. There has not been significant research on this topic to date.

Integrating Freight and Community Goals

The NCHRP 320 Synthesis (Strauss-Weider 2003), on the topic of Integrating Freight Facilities and Operations with Community Goals, highlights the conflicts of and opportunities for mixing major freight facilities with other land uses. Best practices for such co-location include replacing at-grade rail crossings with separated-grade facilities (to avoid traffic queue formation during train movements and stop periods) and incentivizing shippers and carriers to rely more on rail transport, to moderate highway congestion and safety concerns. Freight activity sties, like distribution centers, can make good sense for brownfield redevelopment projects in urban locations, along with buffer zones around freight-related uses (in order to transition into residential uses) and electrification of gantry cranes (or other, alternative fuels). Such modifications can improve safety and air quality (reducing particulate matter exposure from diesel engines).

Straus-Weider's review recognizes "the growing need to balance freight transportation and community goals" (2010, p. 4) to enable commerce without compromising basic health and quality-of-life objectives. Of course, co-location of consumers (and workers), producers and goods is fundamental to moderating travel costs while serving final and intermediate demands. She notes how the growth in population, intensification of land development near ports and trade

corridors, and shift to a largely service economy brings many conflicts to the fore amid a set of stakeholders that (mostly) do not have *direct* appreciation for (and understanding of) freight transport needs. Rising incomes and living standards reduce residents' tolerance of noise, delays, and pollution.

Summary and Recommendations

Strengths of Existing Work

A generous body of research has been completed – literally hundreds of studies – focusing on the relationship between the built environment and trip making, *on a daily basis*. This work has been documented in a number of meta-analyses, which have typically provided elasticities and other analytical methodologies. With these methodologies, users have developed defensible tools that allow "what-if" estimations of potential reductions in VMT and VHT related to alternative built environment scenarios. While most of this work focuses on the project scale, there are additional tools available for meso- and macro-scale analysis. Case studies have provided hints of how TOD might influence peak period travel. In addition, there is some research indicating that jobs/housing match improvements can reduce congestion. One study addressed the impact of higher density development on traffic congestion.

Two recent meta-analyses, along with other recent studies, provide connections between mode choice, particularly transit usage and walking, to built environment factors. Findings include strong correlations between walking and transit trips and various characteristics of the built environment.

Studies have established a link between increased road capacity and increased driving; these increases are reflected in both near-term and long-term impacts. Case studies indicate that the opposite also holds – reduction in roadway capacity can lead to mode shift and elimination of some trips.

Key Findings

Key Decision Points for Smart Growth in the Planning Process. The review of planning processes with a focus on smart growth and the interviews conducted with planning officials on this same topic revealed two primary areas that planning agencies are engaged in that are useful and supportive of engaging smart growth in planning processes. The first area is that most agencies are either engaged in or interested in scenario planning as a strategy for evaluating smart growth. Scenario planning offers many opportunities, but to date has not been developed into a tool for this purpose that could be shared or adapted for use by planning agencies. The second area is that many agencies reflected on the need for coordination, cooperation and communication with local governments on land use policy, since land use regulations are primarily governed by local governments. This interaction between land use and transportation planners has provided opportunities to engage in discussions about integration, interaction, and common goals.

The review also highlighted several topics where planning agencies feel additional guidance or tools would be worthwhile:

- Metrics and tools for induced demand, TDM, and urban form
- Understanding which strategies work best, i.e., what outcomes can be expected?
- Tools to evaluate impacts of smart growth on project selection
- Goals for congestion reduction may be counter-productive to smart growth

The Built Environment's Impacts on Peak Auto Demand. Peak period travel remains the primary focus of demand and supply analysis, yet time of day travel has become increasingly complex. The simple assumption that peak hour congestion is attributable to home-based work trips is clearly no longer valid. In 2001, for example, more than half of all trips during the 6:00 to 9:00 AM period were for non-work purposes and during the PM peak the share exceeded 70 percent (FHWA, 2007c).

Case-study analyses provide insights into smart growth and congestion relationships. Both residences and destinations, like job sites and shopping venues, need to be concentrated around transit stations to assure both trip origins and destinations are linearly aligned along a rail or BRT served corridor (Cervero, 2007a). Even then, not everyone believes TODs will deliver mobility benefits in car-dependent societies like the United States. According to one critical observer, TOD "increases congestion. The overwhelming majority of travel to proposed transit-oriented developments will be by automobile. This will strain road space, slowing traffic and increasing pollution as a consequence" (Still, 2002). TOD can become another major vehicular traffic magnet or major vehicular traffic generator without a *balance* of residential and non-residential uses.

A 2010 study of the Austin region found that TOD scenarios, in addition to reducing estimates of VMT (vehicle miles traveled), could also significantly reduce 2030 peak-period congestion. Under the base case 2030 scenario, 3,729 roadway lane miles (20.3 percent of the study area's coded-network total) were predicted to be congested in the morning peak. The rail-based TOD plan was projected to reduce congested roadways by 433 lane miles versus the base case, representing 18 percent of the region's lane miles. The most aggressive (All-Systems-Go) TOD scenario was expected to reduce congestion on an additional 341 lane miles or to 16.1 percent of the regional total.

According to the analysis, the mid-level rail-based TOD was forecast to reduce traffic congestion by 11.7 percent relative to the base case. The All-Systems-Go TOD option would likely reduce it an additional 9 percent, or a total of 20.7 percent, relative to the base case. There were 17 TOD-housing projects surveyed and these averaged 44 percent fewer vehicle trips than that estimated by the ITE manual. The weighted average differentials were even larger during peak periods: 49% lower rates during the AM peak and 48% lower rates during the PM peak. In general, denser, more urban TOD-housing had the greatest peak-hour trip rate differentials.

A survey focused on parking demands at TODs shed further light on TOD's transportation impacts (Cervero et al., 2010). In the case of Portland's transit-oriented housing projects, parking demand was 11 percent less than that estimated by the ITE *Parking Generation* manual, which is based on peak parking periods (typically in the early morning). On average, the supply of parking exceeded peak demand by 30 percent at Portland's TOD projects.

Other research focused on the commute trip found that a doubling of occupationally matched jobs within 4 network miles of workers' residences was associated with a 32.9 percent reduction in commute VMT and a 33.8 percent reduction in commute VHT. The slightly larger elasticity of work-trip VHT as a function of job accessibility suggests that, on average, improved job access translates into slightly faster commute speeds. Cervero and Duncan (2006) conjectured this could be due to the rationalization of commute patterns, with sub-regional balances in jobs and housing marked by less cross-town, lateral, and zigzag patterns of commuting from one quadrant of a region to another. The research also showed that larger commute-trip VMT and VHT reductions occurred as a function of job accessibility than did shop-trip reductions as a function of retail access. While balancing where people live and shop matters in driving down VMT and VHT, balancing where they live and work matters even more.

Focusing on the effects of smart growth at travel destinations, two studies found significant trip reduction resulting from development density, land use diversity, urban design at workplaces and other activity attractors. One study of all of Montgomery County, MD found that elasticities describing the selection of non-auto travel at were twice as high for the density and diversity at destinations throughout the county as they were for residential locations within the county. (Cervero 2002b). Another study in the Seattle region found significant influence of employment density on reducing single-occupant-vehicle use and increasing walk and transit for work trips (Frank and Pivo, 1994).

A national synthesis of over 200 research studies on the subject of travel and the built environment found consistent evidence of VMT reductions resulting from smart growth characteristics. Elasticities ranged from a 4% reduction in VMT per 100% increase in development density, to a 9% reduction for each 100% improvement in diversity, 12% per each 100% improvement in urban design, 22% for each doubling of destination accessibility, and 5% for improved transit accessibility (Ewing and Cervero, 2010).

Mobility by Mode and Purpose. A number of research studies have demonstrated that housing in close proximity to rail transit stations averages high transit modal splits for commute trips and that improved walking connections to rail stops increases this modal share even more (Lund et al., 2006; Chen, 2007, Cervero, 1994; JHK and Associates, 1987, 1989; Stringham, 1982). Others have reached similar conclusions: compact, mixed-use, traditionally designed neighborhoods encourage internal walking trips that substitute for out-of-neighborhood shop trips.

A six-region analysis of mixed-use development found that jobs-housing balance most strongly predicted the likelihood that trips made by residents to non-work destinations would be walking trips. Overall, however, new urbanist residents logged 40 to 55 minutes more walking

and cycling each week than their counterparts in the conventional suburban neighborhoods. Utilitarian travel, such as to work or shopping, accounted for the difference. This finding concurs with that of Saelens et al. (2003) which found that neighborhood design is not related to leisure-time physical activity when one controls for individual- and household-level characteristics. Also, the North Carolina study found that increased numbers of walking trips came at the expense of automobile trips, consistent with prior evidence (Cervero and Radisch, 1995).

The largest VMT reductions accrue when going from very low to moderate densities. Some observers claim that lifestyle preferences explain much of the lower levels of VMT in denser, more walking-friendly neighborhoods, and that failure to account for self-selection could bias results. In a study of neighborhoods in the Puget Sound area, Krizek (2003) removed possible self-selection biases by longitudinally examining changes in travel when households relocated. He found that moving to a neighborhood with denser, mixed-use, well connected street patterns was associated with VMT reductions.

The MXD tool, mentioned in the Chapter 2 (Table 2-4), uses hierarchical modeling to estimate walking and transit use (for external trips) from mixed-use development (Ewing 2011). The walking share of external trips is related to three types of D variables – diversity, destination accessibility, and demographics. The transit use share of external trips is related to measures of design, destination accessibility, distance to transit, and demographics.

A national study of 239 mixed-use and transit-oriented development sites in Boston, Atlanta, Houston, Seattle, Portland and Sacramento found that statistically verifiable evidence of travel reductions of between 20% and 45% by region resulting from trip internalization, and walking and transit use to off-site destinations. The study categorized the travel generation by trip purpose, allowing for the evaluation of trip reduction and trip length effects by time of day (Ewing, et.al. 2009).

Induced Traffic and Induced Growth. Research has concluded that over the long term, added road capacity led to more deeply rooted structural shifts, like increased car-ownership rates and more auto-oriented land-development patterns, what is sometimes referred to as *induced growth*. Adding structural impacts to accumulated short-term ones markedly increases long-term elasticities — on average, 0.73 in the U.S. (Cervero, 2002).

In a study of more than 100 cases of road-capacity reductions in Europe, North America, Japan, and Australia, Goodwin et al. (1998) found an average overall reduction of 25 percent, even after controlling for possible increased travel on parallel routes. This “evaporated” traffic was assumed to represent a combination of people forsaking low value-added (discretionary) trips and opting for alternative modes, including transit, walking and cycling.

A Texas study surveyed residents who had walked to a local store, and found that about one in eight stated they would have stayed home instead of drive if there was no nearby store within walking distance. This implied that the opportunity to walk to a store likely induced some extra pedestrian trips.

Relationship Between Smart Growth and Congestion. A number studies cited in previous sections address travel reduction effects of smart growth either by time of day or by trip purpose and destination, allowing the deduction of peak hour effects. These include studies performed at the macro scale (Zhang, 2010), and at the meso and micro scales (Ewing, et al, 2009), (Cervero 2002), (Cervero 2007), (Frank and Pivo, 1994).

While a considerable body of research has successfully isolated and begun to qualify the effects of smart growth land use design on trip making, there has been a lack of research on the subsequent link between smart growth development and traffic congestion. When communities incorporate higher levels of the "Ds" in their design, households that reside in those communities own fewer cars, make fewer trips by vehicle, and generate lower rates of VMT than household of comparable demographic composition living in more conventional single-use settings.

Similar results occur in employment and commercial activity centers. When these destination areas combine uses in a more compact, walkable setting, commuters, shoppers and visitors are found to be much more likely to travel to these locations by modes other than driving, and once there, to conduct a higher percentage of their work-related or non-home based trips locally by walking or by transit.

In one of the few known studies to address these issues head-on, the AZDOT commissioned a study of the impact of higher density development on traffic congestion (Kuzmyak, 2010). Using a case study approach comparing four sites in the Phoenix area – three very "urban" in density and character, and one more typically suburban – the key finding was that while the three urban sites had residential densities twice that of the suburban example, and employment densities greater by factors of 7 to 25, traffic conditions were actually much better in the higher-density, mixed-use urban examples. Further investigation showed that this result was attributable to higher rates of internal capture of residents' trips for all trip purposes, resulting in shorter trip lengths and lower VMT rates. The urban examples also had higher rates of transit use both by residents and visitors, and featured extensive street grids that both facilitate walking and allow for better management of vehicle traffic flow. All of the areas were impacted by high proportions of through traffic, though the urban examples – seemingly due to the street grid – appeared better able to absorb and dissipate the effects of this additional demand.

A second example, taken from Prince George's County, Maryland, examined the relationship between higher intensity development in designated centers and corridors and traffic impacts on local area LOS standards (Kittelson and Kuzmyak, 2010). Projected violation of traffic standards on measured facilities in the centers/corridors under 2030 build-out conditions imperiled adopted smart growth and TOD plans for these areas. In a detailed analysis of six centers, two key findings were made: (1) the majority of traffic in the areas of violation could be attributed to through travel, and not to the development activity of the development area itself; and (2) that the centers/corridors themselves could do a much better job in achieving desired travel efficiencies than their current designs enabled. Lacking tools or formal protocols for effective smart growth design, the centers were found to be deficient in terms of density, mix of uses, effective design (pedestrianization, connectivity, street grid), and taking best advantage of transit infrastructure. The methods developed and performance metrics used in this assessment

are perhaps its key contribution to the report, because they provide a mechanism for assessing this complex set of issues.

Smart Growth and Freight Traffic. Smart growth emphasizes accessibility, rather than mobility, though more efficient location choices and connected transport systems, for more "complete" neighborhoods. Like personal travel, goods movement is core to the health and wealth of all communities. However, freight offers fewer mode choices, along with many challenges. Truck and rail modes dominate goods movement, each shuttling over a trillion ton-miles of the United States' commodity movement annually (CFS 2007). While rail is a more efficient mode of freight travel in many ways, it cannot access most buildings or penetrate most neighborhoods, thus requiring integration with trucking systems for final delivery of many goods. Inland ports or freight villages, and public logistic terminals or multi-company distributions centers facilitate such intermodal operations along with cross-company consolidation for more efficient customer service in highly urbanized environments. Simulation studies, to examine the details of design and logistics choices, can be essential in the definition, siting and valuation of such programs and policies.

The research discovered the following factors linking freight traffic with land use patterns, and logistics management that might be addressed through smarter growth planning and regional and local logistics:

- In recent years freight energy efficiency has fallen, possibly due to more trucks traveling empty, or "dead heading"
- Double-tracking of more rail corridors could dramatically improve rail's reliability and travel times, enhancing its modal competitiveness. Rising roadway congestion, the introduction of road tolls and higher gasoline taxes may incentivize shifts to rail and other freight modes.
- Port operators, local residents, and business leaders are recognizing that land-use decisions are critical to environmental justice, human health, the economy, and quality of life.
- Trans-shipment points for warehousing by multiple operators facilitate intermodal transfers and goods storage while enabling consolidated operations, including shared pickups and deliveries within the nearby cities.
- In terms of smart growth solutions, studies demonstrate that micro, meso and macro-scale measures are needed to improve freight operations and rationalize land use and locational factors that influence them. Site access design, such as the provision of curb loading zones, one-way alley protocols, and signage can be beneficial as can use of smaller trucks for intra-neighborhood operations, with "satellite transfer facilities" for shifting goods to and from larger trucks.
- Freight operators cite the advantages of shorter/single-unit trucks for urban stops, all-way pedestrian phases to minimize pedestrian risk during truck turning movements. Centralized delivery locations, with intra-mall/intra-building delivery made onsite by specialized mall-managed vehicles at shopping malls and large office buildings

- Commercial strip development is undesirable, as it is not so conducive to safe or efficient delivery practices. Urban deliveries become much more difficult as congestion mounts and business practices place more emphasis on time-sensitive pickups and deliveries. Just-in-time deliveries and increasingly complex supply chains are threatened by growing congestion.
- Reservation times at port facilities, congestion-based road and runway tolling, variable pricing of capacity-constrained rail corridors, and various impact fees for existing and new land uses may ensure reliability in movement of freight
- Metro structure is important for travel distances – with differences in origin and destination accessibility, roadway congestion, building sizes (per occupant) and design, parking costs, alternative mode availability. Density of customers (and smaller vehicles) reduces the cost and emissions of deliveries.
- Simulation exercises across a variety of U.S. and EU regions and concluded that many transport pricing, land use policies, and investment strategies offer significant long-run reductions in VMT and emissions (relative to trend) without compromising highway levels of service or regional productivity.

Recommendations

Key Decision Points for Smart Growth in the Planning Process. Many planning agencies are evaluating smart growth policies and are looking for tools to understand the implications for induced demand, TDM, urban form, project selection, and congestion reduction as well as information on expected outcomes.

The Built Environment's Impacts on Peak Auto Demand. While there has been considerable study and syntheses leading to well-established relationships between smart growth and travel demand on a daily basis, the research on travel effects by trip purpose or by time of day is much more limited. This creates a challenge for the prospect of estimating the effects of smart growth development patterns and transportation management on peak period traffic conditions and congestion.

Mobility by Mode and Purpose. As is the case with evidence on smart growth effects on peak traffic, evidence on mode choice and mobility is much more limited under peak conditions than when expressed in term of full-day metrics.

Induced Traffic and Induced Growth. A moderate sampling of credible studies of induced travel and induced growth suggest that elasticities describing traffic demand growth tend to rest in the range of 0.3 to 0.4 in the short term and between 0.6 and 0.7 in the long term when expressed as functions of the amount of added traffic capacity. In other words, up to 70% of the added capacity would be used by induced travel. However, capacity expansion at a specific location is a very crude indicator of the effect of a traffic network improvement on travel decisions ranging from route shifting, to time-of-day shifting, to mode shifting, to trip generation and distribution and land investment and development. More empirical evidence is needed on the subject of induced travel measured as a function of travel-time benefits afforded by a

transportation improvement that captures the effects the facility's role in the network, the effects of non-capacity operational improvements, and the degree to which land use plans represent a priori conditions rather than effects of the added transportation access.

Relationship Between Smart Growth and Congestion. Research is quite limited on the subject of congestion effects of smart growth. There is some evidence that the combined effects of lower trip generation per unit of development, shorter trip distances and better interconnected circulation networks that characterize smart growth reduce overall regional congestion and, in several examples, reduce congestion at the local level even in spite of the increased land use intensity. The research sample is too small, however, to develop statistically strong relationships that might be transferrable to other regions and situations. There is a critical need for further data gathering at a macro level from sources such as TTI and at corridor and local levels from cities, counties, DOTs and GPS data vendors, and for statistical analysis to ascertain the transferable relationships between smart growth characteristics such as the Ds, including network density and connectivity, and levels of traffic volume and congestion on local streets, arterials and highway.

Smart Growth and Freight Traffic. Smart growth lends itself to relatively narrow street systems and higher shares of non-motorized modes (with their relatively vulnerable travelers), which poses issues for large-truck access and traveler safety. While density lends itself to more efficient routing of delivery vehicles, smaller businesses may generate more freight trips, per ton moved. And co-location of freight facilities and populated land uses poses safety, noise, pollution, theft, and other concerns. Ultimately, freight movement must occur to sustain the enterprise of human settlement. Better design of loading docks, better vehicle and routing choices, more full-cost pricing (of fuels, scarce road and parking spaces, and vehicles), separation of various freight facilities and crossings (to protect the public and avoid bottleneck queuing), and new systems to facilitate inter-firm cooperation and stakeholder communication all support reliable and safe goods movement within the smart growth context.

Information Gaps and Limitations of Current Practices

Relatively little information is available regarding the effect of smart growth on *trip purpose* and *peak hour congestion*. Where the connection between the built environment and travel has been least studied is the link between travel behavior in response to land use designs and the traffic that is actually occurring on the street and highway system.

In addition, while there is emerging information regarding the use of alternative modes attributable to smart growth, there are no calibrated and validated trip generation rates for bicycle, walking, and transit trips tied to the built environment. Little is known about the induced traffic and induced growth impacts of smart-growth initiatives themselves, as reflected by changes in attributes of the built environment, such as higher residential densities, increased mixed land uses, or improvements in the pedestrian environment. No standard, widely accepted kitbag of tools has emerged for estimating induced demand impacts of highway or transit improvements, much less of gauging the second-order, rebound impacts of smart-growth strategies.

An assessment of the strengths and limitations in the current practices of assessing the effects of smart growth on transportation capacity identified the following limitations:

- Most State and regional transportation agencies are either engaged in or interested in scenario planning as a strategy for evaluating smart growth but find that they lack suitable tools for this purpose.
- Many agencies feel the need for coordination, cooperation and communication with local governments on land use policy, since land use regulations are primarily governed by local governments, suggesting that tools need allow the planning process to operate at multiple scales, including regional (macro), corridor and community (meso) and development project such as specific plan or TOD (micro).
- The underlying relationships that define the effects of smart growth on peak travel and transportation capacity needs are not well understood. While there has been considerable research and well established relationships between smart growth and daily travel demand, research on travel effects by trip purpose or by time of day is much more limited. This creates a challenge for the prospect of estimating the effects of smart growth development patterns and transportation management on peak period traffic conditions and congestion.

As is the case with evidence on smart growth effects on peak traffic, evidence on mode choice and mobility is much more limited under peak conditions than when expressed in term of full-day metrics.

Reliable means of efficiently predicting the effects of induced growth and travel are also lacking. Some studies suggest that short-run traffic growth consumes 30% to 40% of added highway capacity and that long term traffic growth fills 60% to 70%. However, capacity expansion at a specific location is a very crude indicator of the effect of a traffic network improvement, as the travel responses are complex and nuanced. They include route shifting, time-of-day shifting, mode shifting, trip generation and distribution and land investment and development. There is a need for further study of induced travel when measured as a function of travel-time benefits afforded by a transportation expansion in a manner that captures the facility's role in the network, the effects of non-capacity operational improvements, and the degree to which land use plans represent a priori conditions rather than effects of the added transportation access.

Research is also quite limited on the subject of congestion effects of smart growth. There is some evidence that the combined effects of lower trip generation per unit of development, shorter trip distances and better interconnected circulation networks that characterize smart growth reduce overall regional congestion and, in several examples, reduce congestion at the local level in spite of the increased land use intensity. However, the research sample is too small to develop statistical relationships that might be transferrable among regions and situations. There is a critical need for data and statistical analysis to ascertain the transferable relationships between smart growth characteristics such as the development density and diversity and transportation network connectivity, and the resulting traffic congestion on local streets, arterials and highways.

With regard to freight planning, there are a number of smart growth and logistical strategies that can reduce the exposure of goods movement to congestion and delay. These strategies are often interregional as well as local in scope and, as tactics, are transferrable among regions. Modeling tools or resource materials should attempt to address freight logistics in public scenario planning, possibly through case studies and best practices for addressing freight issues and to test the effects of alternative regional growth patterns and transportation network investments on goods movement.

CHAPTER 3. SMART GROWTH AREA PLANNING TOOL (SMARTGAP)

Background and Use

The Smart Growth Area Planning (SmartGAP) tool was developed from the background research described in Chapter 2 to evaluate the impact of various smart growth policies. The tool is designed to be a high level evaluation at a regional scale that can bridge the distance between evaluating smart growth policies during a regional visioning process and evaluating smart growth policies at a project or alternative level in a regional transportation plan. The SmartGAP tool evaluates policy scenarios to identify the most promising policies that could be further tested using a more detailed project-level tool. Currently, SmartGAP can provide information on the following changes in the regional system:

- **Built Environment** – changes to the urban form (proportion of population and employment living in mixed use areas, transit oriented developments, or rural/greenfield areas)
- **Travel Demand -** changes in population demographics (age structure), changes in personal income, changes in firms by size or industry, relative amounts of development occurring in urban core, close in communities, suburban or rural areas, urban core, close in communities, suburban or rural area population and employment densities, auto and light truck proportions by year, induced demand – short term impacts
- **Transportation Supply -** amounts of regional transit service, amounts of freeway and arterial capacity
- **Policies -** pricing (vehicle miles traveled charges or parking pricing programs), ITS strategies for freeways and arterials, demand management (vanpool, telecommuting, ridesharing, and transit pass programs)

The software tool is designed to evaluate a region, which can be a multi-county metropolitan region. It distinguishes between population and employment living/working in the urban core, close in communities, suburban and rural/greenfield areas based on densities, diversity in land uses, street design or intersection densities, job accessibility by auto, distances to transit stops, and connectivity of the street system. The model can be developed using base data for these factors to identify the base and future demand (as well as the change) or simply providing changes in these factors to identify the change in travel demand.

The SmartGAP model was designed to address the limitations identified in the background research (Chapter 2). The design of the system as a regional strategic planning tool that is easy to use was specifically to address stated needs from the interviews conducted. The gaps identified in the background research were used to identify specific features of the model that were included (linkages between built environment and peak congestion, induced demand, alternative modes and freight). SmartGAP has a robust statistical foundation and can represent the dynamics of the interrelationships between the built environment and travel at a regional scale well, but also has opportunities for enhancements that were identified during the course of the project. These enhancements would add features and enhance capabilities to provide additional sensitivity in specific areas and are described in the summary (Chapter 5).

Model Structure

The Smart Growth Area Planning (SmartGAP) tool for smart growth is a disaggregate policy model that predicts travel demand impacts at an individual household level. Figure 3-1 presents the modeling system with inputs, model components, and feedback loops. Details on the modeling components, including equations used in each model, are provided in Appendix B. A higher-level description of the models and processes used to develop SmartGAP is contained in this chapter. A SmartGAP User's Guide is also provided as a companion document with instructions on installation and use of the software.

The tool does not provide specific spatial results beyond the built environment categories at the regional level, but does capture individual household and firm characteristics and the interactions between policies. The disaggregate nature of the model captures impacts that may be occurring for small portions of the population (say 0-vehicle households) where aggregate models have a more difficult time capturing these impacts. The model also has the capability to capture interactions between policies. For example, a policy that increases urban area density will decrease household vehicle miles traveled by increasing shorter trips and increasing non-auto travel. Higher densities also increase the market for car sharing. Increased car sharing in turn reduces household vehicle ownership, which also reduces household vehicle miles traveled.

The following is an explanation of major steps in the model execution in Figure 3-1. Each of these steps is described in more detail in subsequent sections of this chapter.

1. **Create Synthetic Households**- A set of households is created for each forecast year that represents the likely household composition for each county, given the county-level forecast of persons by age. Each household is described in terms of the number of persons in each of six age categories residing in the household. A total household income is assigned to each household, given the ages of persons in the household and the average per capita income of the region where the household resides.

2. **Create Synthetic Firms**- A set of firms is created for each forecast year that represents the likely firm composition for each county, given the County Business Pattern data of firms by size and industry. Each firm is described in terms of the number of employees in each of eight size categories.

3. **Calculate Place Types for Households and Firms** -Population and employment location characteristics are important variables in the vehicle ownership, travel demand, and accessibility models. There are 4 place types (urban core, close in community, suburban, and rural and 5 location categories (residential, commercial, mixed-use, transit oriented development, and Greenfield). Models for households were developed to estimate location characteristics from the National Household Travel Survey data. Firms are currently allocated randomly to fit the employment data since there are no national datasets from which to draw these relationships.

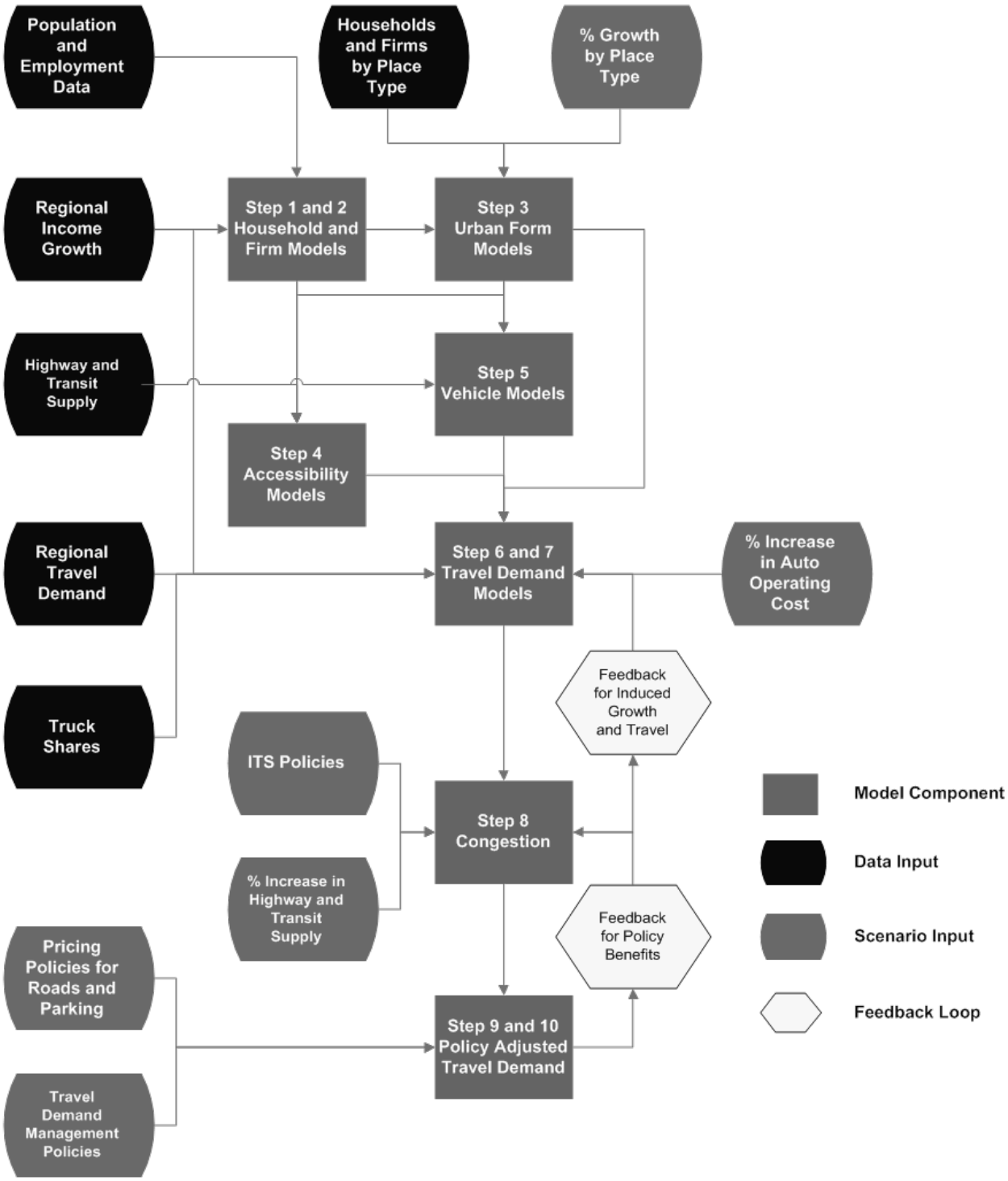


Figure 3-1: Overview of Modeling Process

4. **Calculate Accessibility**- The number of lane-miles of freeways and arterials is computed for each region based on the change in inventories for a particular scenario. For public transit, the inputs specify the change in transit revenue miles relative to the base. Inputs for each area also specify the revenue mile split between electrified rail and buses. These transportation supply inputs are then allocated to each household for input to the vehicle ownership and travel demand models.

5. **Calculate Vehicle Ownership -** Each household is assigned the number of vehicles it is likely to own based on the number of persons of driving age in the household, whether only elderly persons live in the household, the income of the household, the population density where the household lives, the freeway supply, the transit supply, and whether the household is located in an urban mixed-use area.

6. **Calculate Travel Demand -** The average daily vehicle miles traveled, auto and transit trips for each household is modeled based on household information determined in previous steps for the base and scenario conditions. The model is sensitive to household income, population density of the neighborhood where the household resides, number of household vehicles, whether the household owns no vehicles, the levels of public transportation and freeway supplies in the region, the driving age population in the household, the presence of persons over age 65, and whether the neighborhood is characterized by mixed-use development.

7. **Calculate Truck and Bus VMT -** Regional truck VMT is calculated based on changes in the regional household income. As a default, a one-to-one relationship between regional income growth and truck VMT growth is assumed. In other words, a doubling of total state income would result in a doubling of truck VMT. Bus VMT is calculated from bus revenue miles that are factored up to total vehicle miles to account for miles driven in non-revenue service.

8. **Calculate Scenario Travel Demand** – The average daily vehicle miles traveled for each household can be adjusted based on changes in growth patterns by place type, changes in auto operating cost, changes in road lane miles or transit revenue miles for any scenario. There are also a series of policy assumptions that can contribute to changes in vehicle miles traveled: pricing such as vehicle miles traveled charges or parking pricing, ITS strategies for freeways and arterials, and vanpool, telecommuting, ridesharing, and transit pass programs. All of these will contribute to shifts in travel demand for a given scenario.

9. **Calculate Induced Travel Demand** – Induced demand will be calculated for changes in roadway supply in the near term as a function of speed, based on potential mode and route shifts to produce changes in vehicle miles traveled. In the longer term, induced demand may also include structural shifts such as induced growth or changes in vehicle ownership, still as a function of speed. This does not include induced demand as a result of changes in growth that may occur as part of a smart growth scenario because the evidence is limited empirical evidence.

10. **Calculate Other Impacts** – The other impacts that will be produced for a given scenario include environment and energy impacts (GHG and criteria emissions and fuel consumption),

financial and economic impacts (highway and transit infrastructure costs, transit operating costs, and traveler costs), regional accessibility, and community impacts (livability and public health costs).

The model has 2 potential feedback loops, which allow for changes in travel demand and other impacts based on induced travel demand and for changes in policies for a given scenario.

Place Type Development Process

One emerging school of thought in land use planning is to consider land uses in terms of place types instead of simply residential or commercial or high density compared to low density. A place type refers to all of the characteristics of a developed area including the types of uses included, the mix of uses, the density and intensity of uses.

An initial typology or system to organize place types can be traced to the Smart Growth Transect (Thomas Comitta Associates, 2010), which contained six zones in its original configuration including:

- Rural Preserve
- Rural Reserve
- Edge
- General
- Center
- Core

This approach to classifying place types was further refined in the Caltrans Smart Mobility Handbook (2010) which defined the following seven place types including:

- Urban Centers
- Close-In Compact Communities
- Compact Communities
- Suburban Communities
- Rural and Agricultural Lands
- Protected Lands
- Special Use Areas

Several of these place type categories provided additional options such as the Close-In Compact Communities which had three sub-definitions including Close-In-Centers, Close-In Corridors, and Close-In Neighborhoods.

An alternative view of place types was provided by Reconnecting America (Center for Transit-Oriented Development, 2010), which developed a performance based place type approach for describing areas proximate to transit stations. Station areas would vary in terms of their relative focus between residential units, employees or a mix of the two, and are also characterized on their relative intensity as well as shown in Figure 3-2.

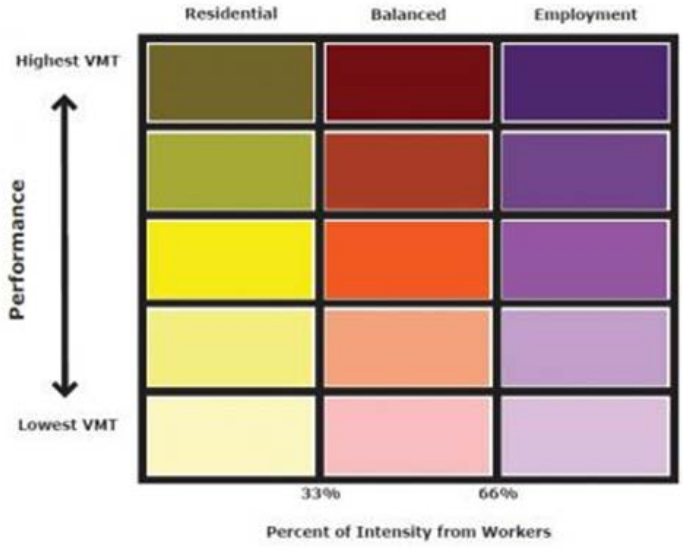


Figure 3-2: Performance-based Typology for Transit Station Areas

Source: Center for Transit-Oriented Development, 2010

The approach employed for the place types in this study is therefore an amalgam of all of these approaches, in that the terminology is borrowed from the Smart Growth Transect and Caltrans Smart Mobility Study, while the relative performance of each place type is taken from the Reconnecting America approach but applied to a region instead of transit station sites. Four general place types were then defined including:

- The **Urban Core** was determined to be high-density mixed use places with high jobs-housing ratios, well connected streets and high levels of pedestrian activities. It is anticipated that for many regions, the Urban Core will be the traditional downtown area of which they likely would be only one. One a Statewide level, the Urban Cores would be the downtown areas of the major cities, of which there would be a limited number.
- The **Close in Community** would be those areas located near to the Urban Cores and would consist primarily of housing with scattered mixed-use centers and arterial corridors. Housing would be varied in terms of density and type. Transit would be available with a primary focus on commute trips. These areas may be classified by their residents as suburban would

be considered to be Close In Communities given their adjacency to the Downtown and therefore the higher levels of regional accessibility.

- The **Suburban** place type is anticipated to represent the majority of development within regions. These communities are characterized by low level of integration of housing with jobs, retail, and services, poorly connected street networks, low levels of transit service, large amounts of surface parking, and limited walk ability.
- The **Rural** place type is defined as settlements of widely spaced towns separated by firms, vineyards, orchards, or grazing lands. These areas would be characterized by widely dispersed residential uses, little or no transit service, and very limited pedestrian facilities.

Further definition of the place types is allowed through the use of sub-categories within the Urban Core, Close in Community, and Suburban place types including:

- **Residential** includes all place types that are predominantly residential in character with limited employment and retail opportunities. Examples of this sub-category might include typical Suburban Residential or areas of the Downtown which are primarily residential as well. It is anticipated that this sub-category may be found in all of the place types except for rural.
- **Employment** includes those areas which are focused on employment with limited retail and residential. An example of this might include a Suburban Office Complex or a large cluster of office buildings within a Close In Community or Urban Core. As with the residential sub-category, it is anticipated that this type of use would be found in all place types except for rural.
- **Mixed-Use** are those areas within a region which have a mix of residential, employment, and retail uses. While this sub-category can be found in the Suburban place type, it is most commonly found in the Close in Community and Urban Core place type. Downtown areas that have retained their residential population to complement the employment are examples of this sub-category.
- **Transit Oriented Development (TOD)** which is similar to the other sub-categories, but applied to all place types except for Rural areas since it is thought to be highly unlikely that a rural TOD would be developed. The TOD sub-category is characterized by greater access to transit in all place types. Examples of this sub-category might include a Suburban TOD focused on a commuter rail station.

Input Data

Input data files are built primarily from national sources and can be modified based on regional data sources. Policy inputs are provided by the user for a particular scenario. All input data sources are assumed to be for a particular year of interest i.e. either a base year or a forecast year. The input data are tabular text files with a comma separated value (CSV) format. The CSV files include a header record on the first line, describing the variables in the files.

Built Environment. The built environment is described by 13 place types as shown in Table 3-1. These place types describe the part of the region where population or employment may reside in four categories (urban core, close in community, suburban, and rural) and the type of development at the specific location (residential, commercial, mixed-use, transit oriented development, or greenfields). The categorization of population and employment by place type is required only for the % growth in any scenario that is being tested. If these data are available for a base year or future year for the region, they can also be provided. If the baseline regional data are provided, these will be reported for comparison to the scenario results; if these baseline regional data are not provided, then only the scenario results are reported.

Table 3-1: Place Types

	Urban Core	Close in Community	Suburban	Rural
Residential	✓	✓	✓	
Commercial	✓	✓	✓	
Mixed-Use	✓	✓	✓	
Transit Oriented Development	✓	✓	✓	
Rural/Greenfield				✓

Travel Demand. Travel demand data includes demographic data, trips by mode and vehicle miles traveled:

1. **Population Data**— Population by age derived from Census data (Public Use Microdata Sample – PUMS) by county. Age categories are:
    - 0-14 years old
    - 15-19 years old
    - 20-29 years old
    - 30-54 years old
    - 55-64 years old
    - 65+ years old
2. **Employment Data—**Employment by firm size and industry derived from County Business Pattern data by county. Industries are categorized by the North American Industrial Classification System (NAICS) 6 digit codes. Firm size categories are:

- 1-19 employees
- 20-99 employees
- 100-249 employees
- 250-499 employees
- 500-999 employees
- 1,000-2,499 employees
- 2,500-4,999 employees
- Over 5,000 employees

3. **Regional Income**—average per capita income in year 2000 dollars. The data can be obtained from the U.S. Department of Commerce Bureau of Economic Analysis (http://www.bea.gov/regional/index.htm) for the current year or from regional or state sources for forecast years.

4. **Truck and Bus Vehicle Miles Traveled**—is a table of proportions of truck and bus daily VMT by functional class (freeway, arterial, other). These data can be derived from the Federal Highway Cost Allocation Study and data from transit operators. The Federal Highway Cost Allocation Study (Table II-6, 1997 Federal Highway Cost Allocation Study Final Report, Chapter II, http://www.fhwa.dot.gov/policy/hcas/final/two.htm) is used to calculate the average proportion of truck VMT by functional class. Data from transit authorities are used to calculate the proportions of bus VMT by urban area functional class.

5. **Base Daily Vehicle Miles Traveled**—is a table of thousands of miles of light vehicle daily VMT and proportions of daily VMT on freeways and arterials. These data can be derived from a combination of Highway Performance Monitoring System (http://www.fhwa.dot.gov/policyinformation/hpms.cfm) data, Federal Highway Cost Allocation Study data, and regional data. Light vehicle daily VMT can be estimated by subtracting truck and bus VMT from total VMT provided in the HPMS. The proportions of daily VMT on freeways and arterials can be derived from the HPMS data.

6. **Auto Trips per Capita**—is the regional average of auto trips per capita, including drive alone and shared ride travel. This data can be derived from the National Household Travel Survey (http://nhts.ornl.gov/index.shtml) by region or from a local household travel survey or regional travel demand forecasting model.

7. **Transit Trips per Capita**—is the regional average of transit trips per capita, including walk and drive access to transit. This data can be derived from the National Transit Database. http://www.ntdprogram.gov/ntdprogram/data.htm) by region or from a local household travel survey or regional travel demand forecasting model.

8. **Transport Supply.** Transport supply includes freeway and transit supply data.

9. **Freeway Lane Miles**—is a table of freeway lane miles. These data can be derived FHWA's Highway Statistics data. (http://www.fhwa.dot.gov/policy/ohim/hs05/roadway_extent.htm)

10. **Transit Revenue Miles—**is a table of annual bus and rail revenue miles per capita. These data can be derived from the National Transit Database. http://www.ntdprogram.gov/ntdprogram/data.htm)

Policy. Policy data includes land use, pricing, capacity, demand management, and operational scenarios.

1. **Percent Growth by Place Type**—is table of the percent growth for each of the 13 place types. Growth by place type can also be input as an allocation of growth in the base scenario if comparisons to the base are desired.

2. **Percent Increase in Auto Operating Cost** —is a single value of the percent increase in auto operating cost in cents per mile. This can be used to test different assumptions for future gas prices or the effects of increased gas taxes.

3. **Percent Increase in Road Lane Miles**—is the percent increase in road lane miles including freeways, arterials and other facilities.

4. **Percent Increase in Transit Revenue Miles**—is the percent increase in transit revenue miles for bus and rail modes.

5. **Auto Operating Surcharge per VMT**—is a cost in cents per mile that would be levied on auto users through the form of a VMT charge.

6. **Increase in Parking Cost and Supply**—is an increase in parking cost in dollars per hour or in supply in spaces.

7. **Percent Road Miles with ITS Treatment**—is an estimate of road miles that have improvements which reduce incidents through ITS treatments.

8. **Percent Employees with TDM Programs**—is an estimate of the employees that participate in travel demand management programs.

Output Data

Output data files are designed to address a variety of impacts that are helpful for decision-making. A longer list of potential output data were developed but only those with credible methods to produce, given the level of detail in the software tool were included. The remaining performance measures are described in additional resources (Chapter 13). All output data sources are assumed to be for the same year of interest that the input data represent i.e. either a base year or a forecast year. The output data are tabular text files with a comma separated value (CSV) format. The CSV files include a header record on the first line, describing the variables in the files.

Direct Travel Impacts.

- Daily Vehicle Trips
- Daily Transit Trips
- Daily Vehicle Miles Traveled
- Peak Travel Speeds by Facility Class
- Vehicle Hours of Travel, Delay

Environment and Energy Impacts.

- Greenhouse Gas and Criteria Emissions
- Fuel Consumption

Financial and Economic Impacts.

- Regional Infrastructure Costs for Highway
- Regional Infrastructure Costs for Transit
- Annual Transit Operating Cost
- Annual Traveler Cost (fuel and travel time)

Location Impacts.

- Regional Accessibility

Community Impacts.

- Livability (FTA Criteria)
- Public Health Impacts and Costs

Model Implementation

The software tool is implemented in R, which is a freely available language for statistical computing and graphics which provides a wide variety of functions. R was selected because it is open source and freely available to all users and because it provides the statistical computing and graphics needed to implement SmartGAP easily. In addition, R offers users to capability to or change the system over time. R is available from the Comprehensive R Archive Network (CRAN) (http://cran.r-project.org/), a network of ftp and web servers around the world that store identical up-to-date versions of code and documentation for R. R is an open source version of the S language developed at Bell Laboratories by Chambers et al. R can be used for routine data manipulation and analysis, and the analysis and visualization of model results. The software code has been developed with a Graphical User Interface (GUI) to allow for non-technical users to be able to use the tool for planning activities more easily.

Household and Firm Models

The purpose of the household and firm models is to synthesize households and firms for a region in a manner that is consistent with the regional distributions of households and firms for selected characteristics. For households, persons by age in a household and income are the defining characteristics. For firms, businesses by size and industry are the defining characteristics.

There are 3 models that are applied to synthesize households and firms across the age, income, size and industry dimensions (Figure 3-3):

- **Household Age Model** which identifies how many persons of which age category reside in each household.
- **Household Income Model** which identifies the mean household income for each household.
- **Firm Size Model** which identifies how many firms of a particular size category reside in each industry.

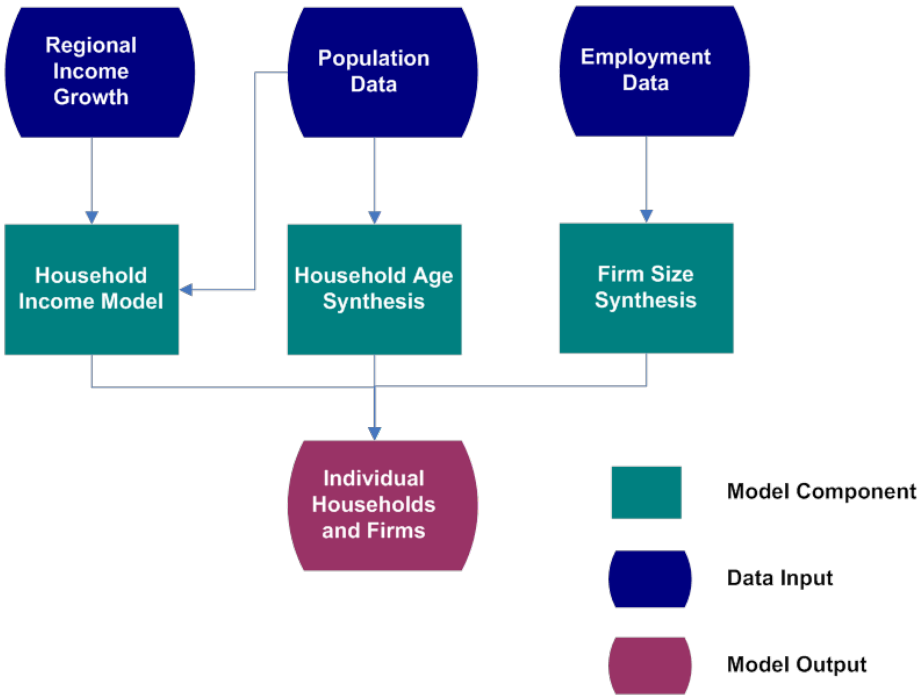


Figure 3-3: Household and Firm Modeling Process

The output of these 3 models is the individual households and firms in a region with age and income characteristics for households and size and industry characteristics for firms. The age categories for persons in households are:

- 0-14 years old

- 15-19 years old
- 20-29 years old
- 30-54 years old
- 55-64 years old
- 65+ years old

The size categories for firms are:

- 1-4 employees
- 5-9 employees
- 10-19 employees
- 20-49 employees
- 50-99 employees
- 100-249 employees
- 250-499 employees
- 500-999 employees
- 1,000-2,499 employees
- 2,500-4,999 employees
- Over 5,000 employees

Mean household income is provided in year 2000 dollars. Industry classifications are in the National American Industrial Classification system (NAICS) – 6 digit codes.

Urban Form Models

Urban form characteristics influence household vehicle travel in several ways. The purpose of these models is to allocate households and firms to different types of urban form. These include the type of area where the household or firm resides (urban core, close in community, suburban, and rural), the population and employment density (persons per square mile) of the Census tract where the household or firm resides, and the urban form characteristics of the Census tract where the household or firm resides (urban mixed-use vs. other).

The synthesized households and firms generated in the previous modeling step are not geographically located within the region in this modeling system. Instead, these households and firms are placed into 13 place types, defined in Chapter 2. The 13 place types are derived from three area types (urban core, close in community and suburban) and four development patterns (residential, commercial, mixed-use, and transit oriented development) plus the rural/greenfields place type.

The National Household Travel Survey (NHTS) provides a dataset which allows for the identification of relationships between demographic data and allocation of households to these area types. The model estimated using the NHTS dataset predict the probability that a household will reside in each of the area types based on their household income and a set of variables describing the household type:

- Households that are made up of one person of working age
- Households that made up of two people of working age
- Households that include children
- Households where all household members are 65 years old or older

The probability of a household residing in each of the area types is adjusted using a model calibration algorithm so that the overall allocation matches the growth by place type input for the scenario. A Monte Carlo simulation is used to allocate each household to a specific area type and then proportional allocation is used (based on the place type proportions) to allocate households to a development types within each area type.

There is no national data source that can define relationships between firms and area types and development patterns, although some regions have data that may be used to identify these relationships. The pilot studies may provide an opportunity to develop these relationships and provide guidance for future work. In the absence of these relationships, firms are allocated randomly to place types until the employment in an area is fulfilled.

Vehicle Models

The purpose of the vehicle models is to identify the vehicles and significant characteristics of these vehicles for each household in the synthesized population. The vehicles included in these models are passenger cars, light trucks, and bicycles (including electric bicycles). In addition to the number of vehicles for each household, fuel efficiency is assigned to each vehicle based on the age and type of the vehicles for estimation of fuel consumption.

There are seven sets of models in the vehicle modeling process and these are identified in Figure 3-4. The first five models are to identify the vehicles per household and rely on household income, characteristics of the population, urban form data and highway and transit supply data. The non-motorized vehicle model does not depend on highway and transit supply data. The other vehicle models estimate vehicles in relation to the number of driver age persons in a household. There are separate models for:

- Households with no vehicles;
- Households with more drivers than vehicles;
- Households with one driver for each vehicle; and
- Households with more vehicles than drivers.

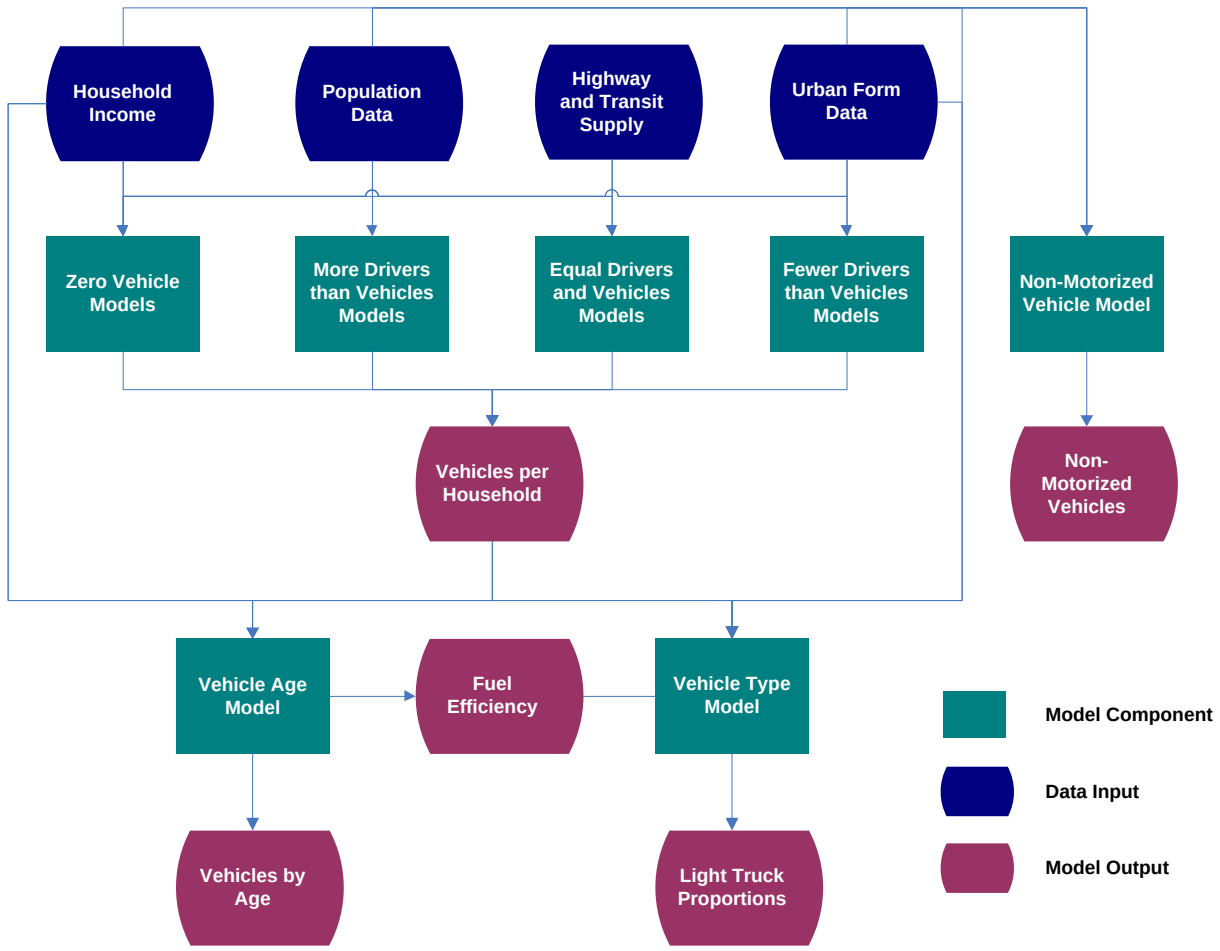


Figure 3-4: Vehicle Modeling Process

The last two models in this series predict the age of the vehicle using a Monte Carlo simulation to match an existing age distribution of vehicles and a proportion of the total vehicles that are light trucks, again to match an existing distribution. Once the age and type are determined, the model will assign a fuel efficiency rating for each vehicle.

Accessibility

The accessibility components of the model relate both transit and auto accessibility to travel behavior. Both transit and auto accessibility is referenced in terms of quantities of supply. In the case of the transit supply, the level of accessibility is dependent on the transit revenue miles operated in the region. For automotive or vehicular facilities, the level of accessibility is dependent on the level of freeway lane miles. Both variables are included in the vehicle ownership models and the travel demand models.

This component of the model processes all of the transportation supply inputs and allocates their values to each household for input into the vehicle ownership and travel demand models:

- Freeway Lane Miles
- Transit Revenue Miles (annual bus and rail revenue miles per capita)
- Percent Increase in Road Lane Miles
- Percent Increase in Transit Revenue Miles

The ownership and travel demand model both use per capita supply; therefore (even with no growth in supply) the values of the variables change when population changes. This component calculates several variations of the transportation supply variables: existing population/existing supply, population with growth/existing supply, and population with growth/increased (or decreased) supply. This allows the effects of growth to be separated from the effects of changes in transportation supply in subsequent steps in the model by recalculating vehicle ownership and travel demand with the different inputs and comparing results. The specific variables representing accessibility measures are:

- Freeway lane miles per 1000 persons
- Household income interacted with transit revenue miles
- Population density interacted with freeway lane miles
- Population density interacted with transit revenue miles
- Elderly populations interacted with freeway lane miles
- Elderly populations interacted with transit revenue miles
- Annual transit revenue miles per person
- Transit revenue miles interacted with freeway lane miles
- Transit revenue miles interacted with urban areas
- Transit revenue miles per capita interacting with households in an urban mixed-use area
- Urban mixed use areas interacted with freeway lane miles

Travel Demand

This component of the model calculates the average daily vehicle miles traveled (VMT). The regression model includes explanatory variables such as several describing the structure and demographics of the household, including the number of household member of driving age and household income,, the vehicle ownership of the household, and the characteristics of the transportation system in the region that the household resides (such as freeway lanes-miles). Following an initial VMT estimate that is not sensitive to travel costs, a household travel budget constraint is applied that allows pricing strategies to be tested in a disaggregate manner.

The household VMT models are focused on predicting VMT as a function of daily variation in VMT that occurs (Figure 3-5). The model first predicts the households who are not traveling and then predicts the daily VMT for all other households. This VMT estimate represents the VMT on a given day. Day to day variation in travel can affect these estimates significantly and so additional statistics on this variation were estimated to capture the full distribution of VMT per household.

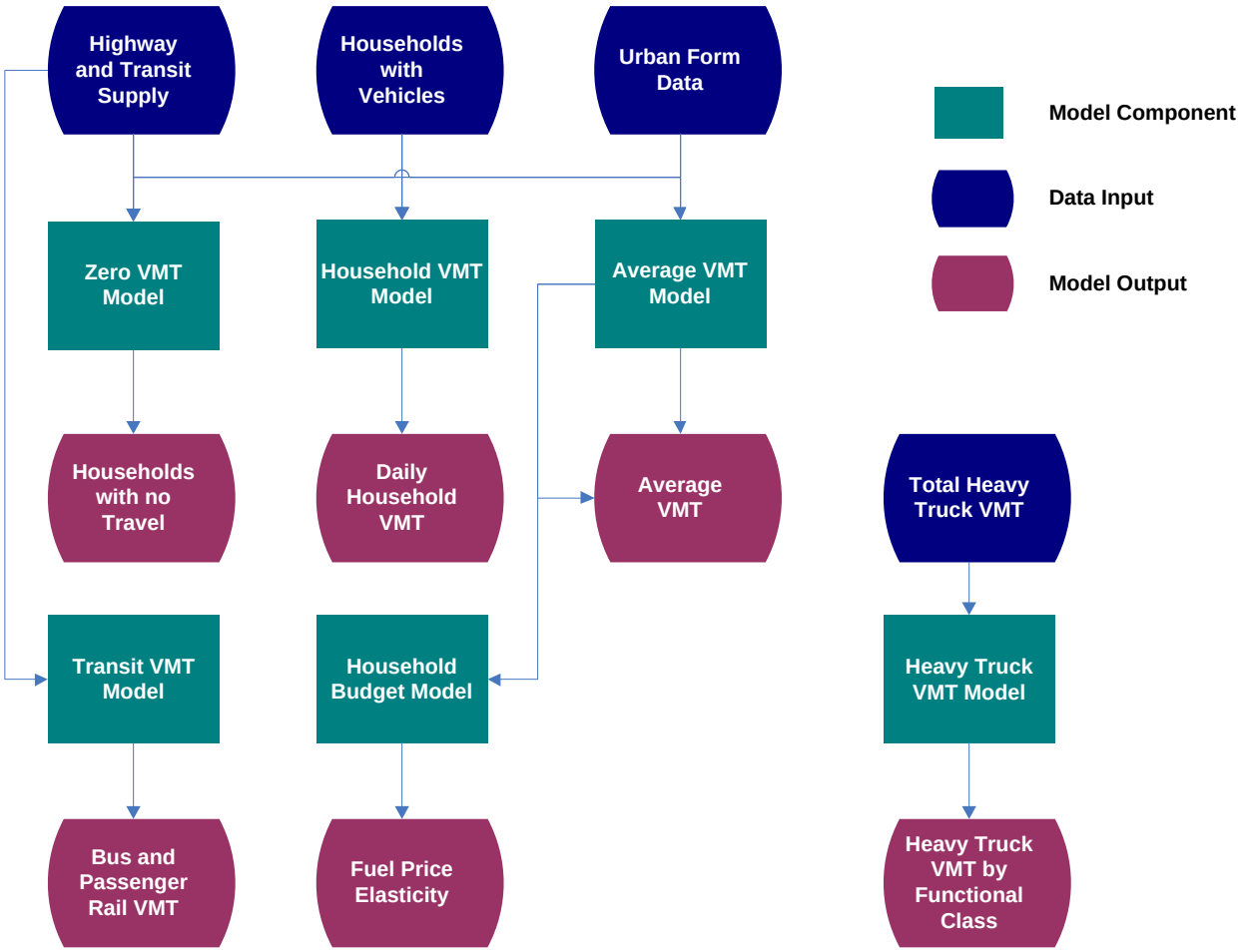


Figure 3-5: Vehicle Miles Traveled Modeling Process

The vehicle cost component is based on a household budget concept where households make their travel decisions within money and time budget constraints. Household spending on travel is done within the household transportation budget. Any additional travel that is made within this budget is relatively inelastic because households can shift expenses within this budget. Any travels that leads to this budget being exceeded will be more elastic and in response the household reduces their travel accordingly. Household budgets are necessarily a function of household income.

This model forecasts VMT for buses and passenger rail cars from the annual transit revenue miles and an assumption on the non-revenue service travel. Currently, this is assumed to be an average of 1.12 (12% increase of service miles to account for non-revenue service travel). VMT (and GHG emissions) is also calculated heavy trucks. Heavy truck VMT is calculated on a regional basis as a function of the base year estimate of heavy truck VMT and the growth in the total regional income. As a default, the model grows heavy truck VMT at the rate of total regional income, but the user can apply a factor to change the relative rate of heavy truck growth.

Congestion

There are three aspects of evaluating congestion in SmartGAP:

- VMT is separated into proportions for freeways and arterials and then allocated into various congestion levels based on an estimate of VMT per lane mile.
- Speeds are calculated for freeways and arterials based on congestion levels and then fuel economy for these speeds are calculated.
- Congestion in local areas due to increased activity is estimated separately to account for this impact on local area roads.

Congestion by Functional Class

The congestion model allocates the VMT predicted in the travel demand models to three functional class groupings – freeways, arterials, and other roadways – for household vehicles, trucks, and buses, so that estimates of vehicle speeds and hence fuel economy can be made.

For trucks and buses, VMT is allocated between the functional classes using fixed proportions. For household vehicles, the allocation is a two-step process. First, a fixed proportion is used to allocate some VMT to other roads. Then, the remainder is allocated to freeways and arterials using this regression model (Gregor, 2011), estimated using data from the 2009 TTI Urban Mobility Report (Shrank and Lomax, 2009):

*Freeway VMT Proportion=0.07686+2.59032*Freeway Lane Mile Ratio*

The freeway lane mile ratio is the share of lane miles in a region that are freeways. The output from this model, the quantity of VMT by functional class (for freeways and arterials) for household vehicles, heavy trucks, and buses, is divided by the lane miles for freeways and arterials to calculate a lane mile ratio in units of vehicle miles traveled per lane mile per day that is used in subsequent calculations in the model. The next step calculates the amount of VMT that experiences each of five congestion levels that are categorized in the TTI Urban Mobility Report (uncongested, moderately congested, heavily congested, severely congested, and extremely congested) by applying a set of regression equations that use the lane mile ratio to explain the proportion in each category.

Speeds by Congestion Levels

The five congestion levels from the Urban Mobility Report each have an average speeds. The speeds are used to estimate fuel economy based on a curve that relates speed and fuel economy. Fuel economy is lower at low speeds and also at high speeds.

Impacts of Connected Street Grid on Local Congestion

While smart growth development patterns are expected to reduce vehicle trip making overall, and VMT as a result of fewer and shorter trips, there is still the question about increases in local traffic congestion simply due to the concentration of activity. Research suggests, however, that compact mixed-use areas are better able to manage their traffic more effectively. An important reason for this is the existence of connected street grids in a balanced 5Ds land use design. Grids (generally) provide more regularity, which allows better signal coordination while also inducing more people to walk in highly connected areas (assuming it's a fine-grained, and not a superblock, grid).

In addition to providing more effective capacity, these grids lead to efficiency due to a greater number of feasible paths. An obstacle along one path need not lead to gridlock, but simply to the generation of a new system of paths to work around the obstacle. The grids also help to channelize traffic, such that different travelers with different headings and different travel styles can plot their own ideal course and free up space for others on the facilities they don't use. These patterns and outcomes can be seen empirically in places like Arlington, VA, and were also measured and documented in the Arizona DOT Land Use and Traffic Congestion Study reported earlier. (Kuzmyak, 2010)

Unfortunately, the cases above were too empirical to provide functional relationships between the composition of the grid, travel demand, and congestion impacts. To attempt to create such a relationship for the project's smart growth model, it was therefore necessary to go to earlier research from the 1990's that attempted to establish these relationships mathematically. Among the key studies found and reviewed were:

- Traditional Neighborhood Development: Will the Traffic Work (Kulash, W., et al., 1990)
- A Comparative Assessment of Travel Characteristics for Neotraditional Designs (McNally, et al., 1993).
- Linking Land Use with Household Vehicle Emissions in the Puget Sound Region (Frank, et al., 2000)

The 1990 study by Kulash, et al. used models to compare Traditional Neighborhood Development (TND) with Conventional Suburban Development (CSD) and concluded that TND networks produced 57% less internal trip VMT, 400% less volume on local streets, 15% less on collectors and 25% less on arterials. The Frank, et al. study was also interesting, but was much more qualitative in its finding that vehicle trip generation was correlated with land use mix and street network density, but with lower VMT due to shorter trip lengths more than counterbalancing the increased trip frequency.

The McNally & Ryan study (1993) was found to be most relevant to these objectives. They also used a model simulation approach, but with tighter control to better aid comparisons. They ran four-step model simulations on two areas which were identical in terms of activity levels and their location within and outside the modeled area. The only exception was the shape of the local road network. Both networks had exactly the same number of lane miles, and the same distribution of arterials, collectors and local streets, but as pictured in Figure 3-6, the TND network had much more connectivity. The TND network had 35 intersection "nodes" compared to only 26 for the CSD, and a much higher density of four-way vs. three-way intersections. Trips were generated, distributed and assigned to the networks. It is important to note that trip generation did not explicitly account for any benefits associated with the land use itself, i.e., no efficiencies attributable to the "Ds" were incorporated in the estimates.

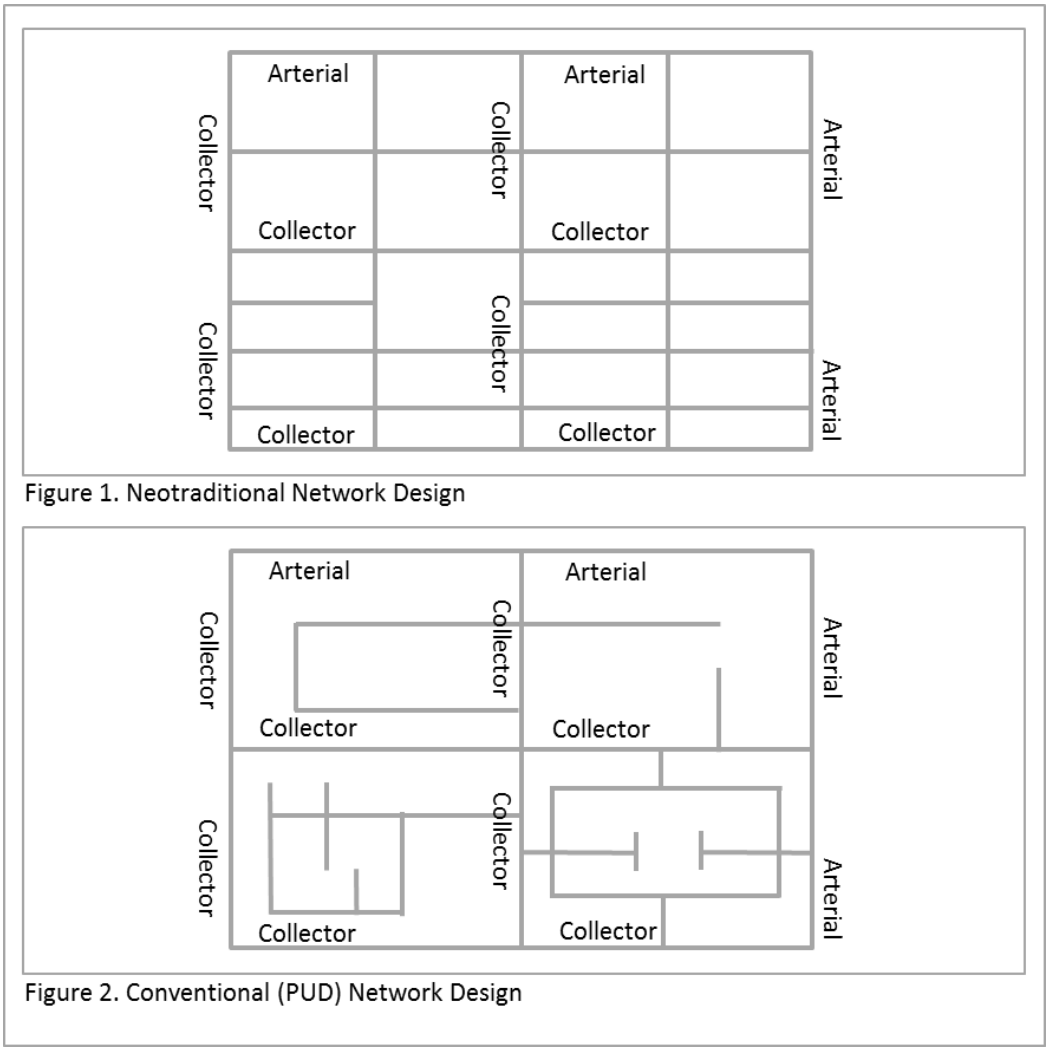


Figure 3-6: Local Road Networks for Traditional Neighborhood Development and Conventional Suburban Development

Source: McNally and Ryan (1993)

As a result of their simulations, McNally and Ryan found the following key travel impact differences between these two regimes:

- 10.5% less AM Peak VMT in the TND network
- 27% fewer hours of travel
- 15.5% shorter trip lengths
- 18% higher speeds (40.8 vs. 33.5 mph)
- A much lower proportion of VMT using collectors, 33% vs. 49%

It was possible to calculate elasticities quantifying the sensitivity of the relationship between network shape/connectivity and the corresponding VMT, VHT and percent of VMT on arterials. Both node density and weighted intersection density (4-way intersection get 1 point, 3-ways only ½ point) were used to represent the network connectivity. Elasticities were calculated using the arc elasticity format:

The *y* arc elasticity of *x* is defined as:

$$E_{x,y} = \frac{\%\text{ change in } x}{\%\text{ change in } y}$$

where the percentage change is calculated relative to the midpoint; and

$$\%\text{ change in } x = \frac{x_2 - x_1}{(x_2 + x_1)/2}$$

$$\%\text{ change in } y = \frac{y_2 - y_1}{(y_2 + y_1)/2}$$

x2 and y2 are the TND case while x1 and y1 are the CSD case.

The calculated elasticities are presented in Table 3-2. In attempting to accommodate this effect in the SHRP model structure, the desire was to link the calculation back to the land use module and the 13 land use types, but have the effect be separate from the VMT impacts already being calculated with respect to the 5Ds. In particular, there is already a D for design that accounts for intersection density effects on VMT, so it was not a goal to replicate that relationship.

Table 3-2: Elasticities for Local Congestion

Variable	Number of nodes	Weighted intersections
Vehicle Miles Traveled	-0.380	-0.211
Vehicle Hours Traveled	-1.05	-0.58
Percent of VMT on Arterials	-1.295	-0.718

Instead, the focus was only on the impact of the network on VMT distribution between arterials and non-arterials, since arterials are included as part of the regional highway system that is being used for congestion analysis. To implement this procedure, an additional line item was added to the earlier "place types" work sheet developed by Fehr & Peers that takes advantage of the same structure for defining and calculating the effects of place type 5Ds differences on VMT to calculate the effects of intersection density on the percent of VMT occurring on arterials.

Using the "base case = 1.0" index approach with the place types matrix, the following was assumed:

- Intersection density for the base TND case is 34.5, which will be associated with the CIC development types.
- McNally and Ryan's CSD example, which has 20 weighted intersections, was used to represent the conventional Rural and Suburban land use types, while in the Suburban Mixed Use and TOD cases, it was assumed that the road network would be more complete and thus fall mid-way between (roughly 27 intersections).
- In the Urban Core area, it is assumed that the network will be virtually complete, with local roads on roughly 1/8 mile spacing across the horizontal grid and ¼ mile across the vertical grid. This results in about 45 intersections.

Following through the template calculations as per the VMT example, it was possible to estimate changes in percentage of VMT on occurring on arterial roadways based on these assumed density/connectivity characteristics. Using the assumptions above, the value for grid connectivity is assumed to be 1.0 for all of the place types in the CIC group, 1.3 in the urban core areas, and 0.5 in the rural and suburban place types, except for suburban mixed-use and TOD, which were thought to have better infrastructure, so those areas were awarded a 0.75.

Applying the elasticity for weighted intersection density of -0.718, a 22 percent reduction was then calculated in the percentage of VMT occurring on arterials in the urban core areas, no difference in the CIC areas, a 36 percent increase in VMT on arterials in the rural and suburban areas, but only an 18 percent increase in the somewhat better designed suburban mixed-use and TOD areas, as shown in Table 3-3.

Table 3-3: Percent VMT Change from Local Congestion by Place Type

Diversity	Rural	Suburban	Close In Community	Urban Core
Mixed Use	Not Applicable	18% increase	No change	No change
Homogenous	36% increase	36% increase	No change	22% decrease

Induced Demand and Urban Form Effects on Travel Demand

After the estimate of congestion level in the base scenario, induced demand is determined as a function of future changes in the transportation system, and adjustments to the estimates of travel demand are made to reflect the effects of changes in the urban form of the region in the future. The sensitivity of the model to induced demand and urban form effects is based on work completed by Robert Cervero for the Path Model and documented in the Journal of American Planning Association (Cervero, 2003).

Induced Demand

Induced demand is estimated as a result of changes to the transportation system supply. These changes are introduced as changes in freeway lane miles or transit revenue miles. As freeway lane miles and transit revenue models are variables in both the vehicle ownership models and the travel demand models, these two components are both run again with the new transportation supply inputs to estimate the induced demand effect and to provide a revised to estimate of vehicle ownership and VMT.

These estimates of induced demand represent first order induced demand effects resulting directly from changes in the transportation supply, and do include long term effects such as changes in the vehicle fleet in response that occur over time in response to changes in transportation supply. Second order effects resulting from the rebound of demand following these initial induced demand effects are not estimated as these have not been defined in a manner that is quantifiably accurate enough to incorporate in a model.

Urban Form Effects on Travel Demand

Following the estimated of travel demand that incorporates induced demand, an adjustment is made to travel demand that account for changes in growth by the place types that are used in the model to describe urban form. These changes are interpreted as changes in design (intersection street density), accessibility (job accessibility by auto), distance to transit (nearest transit stop), density (population density) and diversity (land use mix). The effect on travel demand is determined as changes in VMT by these urban form categories, as shown in Table 3-4. The elasticities that are shown in the table are multiplied by the D values for each place type. The D values are proportion values for each place type that are relative to the regional average, which is set to 1.0. For example, household/population density is higher in the close in community place types than the regional average and so the D value for Density is more than 1.0. A complete set of D values for each place type is incorporated in SmartGAP.

Table 3-4: Changes in VMT by Urban Form Categories

Category	Urban Form Description	Elasticity for Change in VMT
Density	Household/Population Density	-0.04
Diversity	Land Use Mix (entropy)	-0.09
Design	Intersection/Street Density	-0.12
Destination Accessibility	Job Accessibility By Auto	-0.20
Distance to Transit	Distance to Nearest Transit Stop	-0.05

Source: Ewing and Cervero (2001, 2010)

Policies

There are three types of policies considered in the Smart Growth Area Planning (SmartGAP) tool for Smart Growth: pricing, travel demand management (TDM) and intelligent transportation system (ITS). In each case, there are specific types of policies that are modeled with the SmartGAP system.

The pricing policies considered are for vehicle use charges, such as VMT charges or gas taxes, and parking pricing. Vehicle use charges are considered as a factor of auto operating charges and parking pricing are considered as an additional cost at employment or other locations.

The travel demand component of SmartGAP evaluates the effectiveness of TDM strategies upon daily travel. There are four main components that implement TDM policies, including:

- Ridesharing Programs
- Transit Pass Programs
- Telecommuting or Alternative Work Schedule Programs
- Vanpool Programs

Each of these types of programs or strategies is commonly applied in various TDM programs throughout the United States. While these strategies do not represent all potential TDM options, they do include the ones most commonly applied.

The ITS policy represented in SmartGAP is to estimate speeds with and without incidents. This computes an overall average speed by road type and congestion level.

Vehicle Use Charge Policies

The effects of vehicle user charges, specifically VMT pricing, are modeled as an additional cost per vehicle mile traveled. The user input "Auto Operating Surcharge per VMT" in cents per miles is added to the other auto operating costs and the vehicle cost models described in above in the section on the Travel Demand model are reapplied to calculate reduced VMT due to increased travel costs. The resulting reductions in household VMT for charges ranging from 1 cent/mile to 10 cents/mile are shown in Table 3-5.

Table 3-5: VMT Reduction at a Range of VMT Charges

	VMT Charge (Cents per Mile									
	1	2	3	4	5	6	7	8	9	10
VMT Reduction	0.0%	0.2%	0.4%	0.6%	1.0%	1.3%	1.8%	2.3%	2.9%	3.6%

Source: Gregor, 2011

Parking Pricing Policies

Parking charges are either paid for each trip (most often at one end of the trip in the case of home-based travel) or sometimes on a long term basis. The parking price model adds parking costs into the calculation of other vehicle costs such as gas. The model represents both parking costs for employees who are charged to part at or near their place of work, and other parking costs. The model calculates daily parking cost for each household. The model has several variables that can be adjusted to represent different parking policies that might be enacted in a region:

- Workplace parking: percentage of employees that pay for parking, the amount of free parking close to employment sites, and the quantity of workplace parking that is changed from free to paid for under "cash-out buy-back" programs.
- Non-workplace parking: the percentage of non-workplace parking that is paid for, and the average daily parking rate.

Travel Demand Management Policies

The TDM model includes four separate sub-models addressing each of the four main types of programs identified above. Since each of these programs would operate in a somewhat different fashion, separate sub-models are required. There are two primary sources used to develop the TDM model. The overall structure and form of the model was derived from a Travel Demand Management Model developed for the Southern California Association of Governments (SCAG) by Rick Kuzmyak with support from Fehr & Peers. Key elements derived from this TDM Model include the various strategies evaluated in this model and the use of a participation

rate to modify the potential reduction in VMT since it is unlikely that these programs would be implemented uniformly throughout a region.

The VMT reduction percentages are extracted from the California Air Pollution Control Officers Association (CAPCOA) report on Quantifying Greenhouse Gas Mitigation Measures (August 2010). This document estimated VMT reduction based on several original sources include the Victoria Transportation Policy Institute (VTPI) and Travelers Response Handbook developed by the Transportation Cooperative Research Program (TCRP).

Ridesharing Programs. The ridesharing sub-model first evaluates the likely level of participation at the regional level. Since no region has 100% participation by households or businesses in ridesharing program, it is anticipated that the first input should be the level of participation. Monte Carlo processes are used to identify which households participate in ridesharing programs. The proportion of employees participating in this program is a policy input. This is converted into a proportion of working age persons using an assumed labor force participation rate (0.65) to sample working age persons in households.

The ridesharing sub-model then compares the anticipated level of VMT reduction resulting from the implementation of ride-sharing, based on the previously described Place Type typologies (Table 3-6). Previous studied have determined that the level of ridesharing participation will be less in the rural and suburban areas, as compared to the more urban areas. Typically, more people will carpool in the more urbanized areas due to the presence of parking charges, potential difficulties in finding parking, and other disincentives that are typically present in more urbanized areas.

Table 3-6: Effectiveness of Ridesharing Programs by Place Type

	Rural	Suburban	Close In Community	Urban Core
VMT Reduction	0%	5%	10%	15%

This VMT reduction is then applied to the increase in VMT identified for each Place Type, reduced to account for the level of participation defined initially in the sub-model. This VMT reduction is further reduced to account for the contribution of work trip VMT to overall VMT. This reduction in applied since a majority of overall daily VMT is generated by non-work travel. The reduction factor applied in this case is 25%, which reflects the overall percentage of daily travel which is work related.

Transit Pass Programs. The subsidized/discounted transit model similarly begins by evaluating the level of participation within the region. Monte Carlo processes are used to identify which households participate in transit pass programs. The proportion of employees participating in this program is a policy input. This is converted into a proportion of working age

persons using an assumed labor force participation rate (0.65) to sample working age persons in households.

The model then allows the selection of one of four potential subsidy levels, which influence the level of VMT reduction based the level of subsidy applied to the Place Type typology (Table 3-7). The anticipated level of VMT reduction is then further reduced by 25% to account for the contribution of work travel to overall daily travel.

Table 3-7: Effectiveness of Subsidized/Discounted Transit by Place Type on VMT Reduction

Transit Passes	Rural	Suburban	Close In Community	Urban Core
$ 0.75	0%	2.0%	3.4%	6.2%
$ 1.49	0%	3.3%	7.3%	12.9%
$ 2.98	0%	7.9%	16.4%	20.0%
$ 5.96	0%	20.0%	20.0%	20.0%
$ 0.75	0%	2.0%	3.4%	6.2%

Telecommuting Programs. The telecommuting or alternative work schedule model operates similarly to the other sub-models. The model first evaluates the likely level of participation throughout the region in terms of telecommuting or alternatively works schedules. Monte Carlo processes are used to identify which households participate in telecommuting programs. The proportion of employees participating in this program is a policy input. This is converted into a proportion of working age persons using an assumed labor force participation rate (0.65) to sample working age persons in households.

The model then determines that type of programs that might be implemented. Three potential alternatives are offered including:

- 4/40- 4 days per week with 40 hours per week.
- 9/80- working 4 days every other week with an average of 80 hours over 2 weeks
- Telecommuting- Workers may work 1-2 days a week remotely

Once the option has been identified and the level of participation, the estimated VMT is determined based on the parameters in Table 3-8.

Table 3-8: Percent VMT Reduction from Telecommuting Programs

Telecommuting	VMT Reduction based on Percent Employees Participating				
	1%	3%	5%	10%	25%
9/80 Schedule	0.07%	0.21%	0.35%	0.70%	1.75%
4/40 Schedule	0.15%	0.45%	0.70%	1.50%	3.75%
Telecommuting 1.5 days a week	0.22%	0.66%	1.10%	2.20%	5.50%

Vanpool Programs. The vanpool program sub-model operates similarly to the other three models by evaluating the likely level of participation. Monte Carlo processes are used to identify which households participate in vanpool programs. The proportion of employees participating in this program is a policy input. This is converted into a proportion of working age persons using an assumed labor force participation rate (0.65) to sample working age persons in households.

Those employers that would participate in the program are then categorized into three levels of involvement from low to medium to high. The level of involvement reflects the extent to which an employer would actively facilitate and promote vanpooling. For example, a low level of involvement might represent an employer who organizes only a minimal number of vanpools. The high level of involvement could represent an employer who has an extensive vanpooling program cover a large number of their employees. Based on the level of involvement, the reduction in VMT is estimated based on the values in Table 3-9.

Table 3-9: Effectiveness of Vanpooling

Vanpool Program	Percent VMT Reduction
Low Level of Participation	0.30%
Medium Level of Participation	6.85%
High Level of Participation	13.4%

Once the various sub-models have estimated VMT reduction for the various policy alternatives, the VMT reductions are summarized to reflect the cumulative effects of these programs.

ITS Policies

The process that the congestion model uses to estimate average speeds based on congestion category actually provides two speeds – a lower speed for roads without ITS and other technology and service to manage incidents that cause non-recurring congestion, and a higher speed for roads that do have such technology. The policy model interpolates between the two speeds based on the proportion of the highway network that is covered by the ITS and other incident management technologies and services to calculate an average speed for the region for each of the functional classes and vehicle types. This higher average speeds as the proportion of the highway system covered by ITS increases lead to reductions in vehicle hours and delay and also to improved fuel economy and reduced emissions.

Performance Metrics

Direct Travel Impacts

Daily Vehicle Miles Traveled. Daily vehicle miles traveled is calculated by the travel demand models, described in Chapter 7, with scenario changes that reflect the effects of changes in land use, transportation supply, and policies. The model produced estimates of light vehicle VMT for each household and regional VMT for heavy trucks and buses. The total light vehicle VMT is also summarized and reported for each place type.

Daily Vehicle Trips. The model's calculations generally work with VMT and not individual trips. The change in the number of vehicle trips is calculated using a set of factors from Index 5D Values (2001) shown in Table 3-10 that pivots from the current number of vehicle trips per capita based on the scenario's allocation of growth by place type. The elasticities that are shown in the table are multiplied by the D values for each place type. The D values are proportion values for each place type that are relative to the regional average, which is set to 1.0.

Table 3-10: Vehicle Trip Elasticities

Variable	Description	Vehicle Trip Decrease
Density	Household/Population Density	-0.043
Diversity	Land Use Mix (entropy)	-0.051
Design	Intersection/Street Density	-0.031
Destination Accessibility	Job Accessibility by Auto	-0.036
Distance to Transit	Distance to Nearest Transit Stop	0

Daily Transit Trips. The change in the number of transit trips is calculated using a set of factors from Index 5D Values (2001) shown in Table 3-11 that pivots from the current number of transit trips per capita based on the scenario's allocation of growth by place type. The elasticities that are shown in the table are multiplied by the D values for each place type. The D values are proportion values for each place type that are relative to the regional average, which is set to 1.0.

Table 3-11: Transit Trip Elasticities

Variable	Description	Transit Trip Decrease
Density	Household/Population Density	0.07
Diversity	Land Use Mix (entropy)	0.12
Design	Intersection/Street Density	0.23
Destination Accessibility	Job Accessibility by Auto	0
Distance to Transit	Distance to Nearest Transit Stop	0.29

Peak Travel Speeds by Facility Class. The congestion component of the model is used to produce both travel speeds by facility class and the vehicle hours of travel and delay. Chapter 7 discusses how VMT for each of light vehicles, heavy trucks, and buses, is assigned to speeds bins for the three facility types that the model considers – freeways, arterials and other roads. These speed distributions, in terms of the amount of VMT that occurs within each speed bin, along with average speeds, are reported by the model

Vehicle Hours of Travel, Delay. The congestion model calculates vehicles hours of travel using the VMT by speed distributions discussed above. The amount of delay is calculated by comparing the vehicle hours of travel with the amount of vehicle hours of travel that would have taken place if travel was at free flow speeds.

Environment and Energy Impacts

Fuel Consumption. Fuel consumption (in gasoline equivalent gallons) by vehicle type is calculated from the respective estimates of VMT and fuel economy. These estimates are then split into fuel types. The model addresses five fuel types: gasoline, ultra-low-sulfur diesel (ULSD), ethanol, biodiesel, and CNG. For each vehicle type, input data specify the fuel proportions by year. These data can be changed for future year scenarios to represent various fuels policies and assumptions.

For light vehicles (automobiles and light trucks), the first step is to allocate fuel consumed between gasoline, CNG, and diesel types. Past, present and future proportions are specified in a parameter file (see example in Table 3-12) that can be edited by the model user. Different proportions are provided for automobiles and light trucks. Fuel for gasoline engines is then split between gasoline, ethanol, and CNG based on input proportions. Similarly, diesel fuel use is split between ULSD and biodiesel. A similar process is used to split heavy truck and bus fuel consumption into fuel types.

Table 3-12: Example of Light Vehicle Fuel Parameters

Year	Auto Proportion Diesel	Auto Proportion CNG	Lt Truck Proportion Diesel	Lt Truck Proportion CNG	Gas Proportion Ethanol	Diesel Proportion Biodiesel
1990	0.007	0	0.04	0	0	0
1995	0.007	0	0.04	0	0	0
2000	0.007	0	0.04	0	0	0
2005	0.007	0	0.04	0	0.1	0.01
2010	0.007	0	0.04	0	0.1	0.05
2015	0.007	0	0.04	0	0.1	0.05
2020	0.007	0	0.04	0	0.1	0.05

Greenhouse Gas Emissions. Once fuel consumption is split into the five types (measured in gasoline equivalent gallons), CO2 equivalents of emissions can be calculated in a straightforward manner. The energy value of the fuel consumed by type is calculated by multiplying by the energy value of a gallon of gasoline. Then the CO2 equivalent (CO2e) emissions are calculated by applying the appropriate carbon intensities (grams CO2e per mega joule) of each fuel type. Values reflect "pump-to-wheels" emission rates, representing just the tailpipe emissions and do not include the "well-to-pump" emissions resulting from the production and transportation of fuels. Table 3-13 shows the values included as parameters in the model. The values are derived from the MOVES 2010a database (the fuel sub type table provides carbon contents and oxidation factors) and from Emission Facts: Greenhouse Gas Emissions from a Typical Passenger Vehicle (http://www.epa.gov/oms/climate/420f05004.htm#step4) to convert to CO2 equivalents (which includes the global warming potential of other gases emitted by vehicles such as CH4, N2O, and HFCs).

Table 3-13: Carbon Intensity by Fuel Type (Grams CO2e Per Mega Joule)

Fuel Type	Carbon Intensity (gm per mega joule)
Ultra-low sulfur diesel (USLD)	77.19
Biodiesel	76.81
Reformulated gasoline (RFG)	75.65
CARBOB (gasoline formulated to be blended with ethanol)	75.65
Ethanol	74.88
Compressed natural gas (CNG)	62.14

All of the light vehicle calculations of fuels and emissions are done at the disaggregate level of households. This allows emissions to be aggregated to place type and along other dimensions. Heavy truck and transit emissions are calculated at the regional level.

Criteria Emissions. Criteria emissions are calculated using emission rate inputs from the MOVES 2010a database, in combination with outputs from the model that describe VMT and speeds. The model calculates emissions of volatile organic compounds, carbon monoxide, oxides of nitrogen, sulfur dioxide, and particulate matter. Rates are based on MOVE 2010a default data but the model user has access to the rates through the parameters menu in the model and can replace the values with state or regional specific values from MOVES.

Financial and Economic Impacts

Regional Highway Infrastructure Costs. The source for highway infrastructure costs is FHWA's Highway Economic Requirements System model, or HERS. Information was obtained from Chapter 6 of the 2005 Technical Report for all US states. (FHWA, 2005) Table 8-1 in HERS provides unit costs (per lane mile) for both Rural and Urban highway systems, and distinguishes among three functional classes: interstates, freeways and expressways; other principal arterials; and minor arterials and collectors. Costs estimates are provided for the following improvements:

- Reconstruction and widening
- Reconstruct pavement
- Resurface and widen lanes
- Resurface pavement

- Improve shoulders

Additional choices are offered to distinguish between adding a lane at "normal" vs. "high cost," and also for pavement realignment, also under normal vs. high cost conditions.

For practical reasons, only "new construction" (which also includes adding lanes) costs were used as the basis for cost estimates; the categories of reconstruction, resurfacing, and realignment were ignored, although the normal vs. high estimates were used to provide a range for users. These construction costs include right of way, construction, and a "small" allowance for bridges and support facilities.

Only the "urban" system, not rural, were the focus, which also makes it possible to differentiate by three size classes: Small Urban, Small Urbanized, and Large Urbanized. The numbers in Table 3-14 are in 2002 dollars; FHWA advises escalation to current dollars using its National Highway Construction Cost Index (NHCCI) (http://www.fhwa.dot.gov/policyinformation/nhcci.cfm).

Table 3-14: Construction Cost per Lane Mile (2002 Dollars)

Functional Classification	Small Urban	Small Urbanized	Large Urbanized
Freeways	**$3.1 - $11.1**	**$3.4 - $12.1**	**$5.7 - $60.0**
Principal Arterial	**$2.6 - $9.4**	**$2.9 - $10.2**	**$4.2 -$15.0**
Minor Arterial/ Collector	**$2.0 - $7.0**	**$2.1 - $7.4**	**$2.9 - $10.2**

HERS includes a table of state cost indices if desired, although a spokesperson for HERS says that the general sentiment has been toward not using them for reliability reasons.

Regional Transit Infrastructure and Operating Costs. The source for transit capital and operating costs is the National Transit Database (NTD) (http://www.ntdprogram.gov/ntdprogram), and in particular the National Transit Profile which is available on the NTDB website. The most recent statistics published are for 2009, so CPI adjustments may be necessary if more current data are not available to the user at the time. Costs are available in a variety of index formats, e.g., cost per revenue mile or hour, though cost per passenger trip appears to be the most relevant association with estimation of future transit service needs. These costs are presented in Table 3-15.

Table 3-15: Net Cost to Supply an Unlinked Passenger Trip by Transit Mode (2009)

Mode	Capital Cost	Operating Cost	Total Cost	Fare Revenue	Net Cost
Bus	**$0.71**	**$3.40**	**$4.11**	**$0.91**	**$3.20**
Heavy Rail	**$1.78**	**$1.80**	**$3.58**	**$1.09**	**$2.49**
Commuter Rail	**$5.74**	**$9.80**	**$15.54**	**$4.69**	**$10.85**
Light Rail	**$7.82**	**$3.00**	**$10.82**	**$0.78**	**$10.04**

The modes are defined in the National Transit Database. Commuter Rail (CR) does not have a separate definition. Bus (MB) is a transit mode comprised of rubber-tired passenger vehicles operating on fixed routes and schedules over roadways. Vehicles are powered by:

- Diesel
- Gasoline
- Battery, or
- Alternative fuel engines contained within the vehicle.

Heavy Rail (HR) is a transit mode that is an electric railway with the capacity for a heavy volume of traffic. It is characterized by:

- High speed and rapid acceleration passenger rail cars operating singly or in multi-car trains on fixed rails
- Separate rights-of-way (ROW) from which all other vehicular and foot traffic are excluded
- Sophisticated signaling, and
- High platform loading.

Light Rail (LR) is a transit mode that typically is an electric railway with a light volume traffic capacity compared to heavy rail (HR). It is characterized by:

- Passenger rail cars operating singly (or in short, usually two car, trains) on fixed rails in shared or exclusive right-of-way (ROW)
- Low or high platform loading, and
- Vehicle power drawn from an overhead electric line via a trolley or a pantograph.

Costs are presented for each mode, since the capital, operating and revenue profiles are quite different for each. It is interesting to note that the comparative cost per trip of bus and heavy rail, while commuter rail and light rail are both considerably -- almost four times -- higher.

Annual Traveler Cost (fuel + travel time). The estimated travel cost for auto users is $0.585 per mile in 2010, obtained from US DOT's National Transportation Statistics website, Table 3-17. This cost includes both variable costs (gas, oil, maintenance and tires) and fixed costs (insurance, license, registration, taxes, depreciation, and finance charges). These estimates are updated annually.

Travel time costs are significantly affected by congestion delay, which of course varies by location. The best source for this information is the Texas Transportation Institute's annual Urban Mobility Report, which estimates average travel delay for individual metropolitan areas. An important question in completing this measure is in deciding how to account for travel time and congestion delay costs borne by transit users.

Land Market and Location Impacts

The performance measure for land market and location impacts is related to the regional accessibility calculations, embodied in the analysis of place types. The estimation of VMT by place types includes one variable related to regional accessibility which is jobs accessibility by auto. Job accessibility by auto would be highest in the urban core area and relatively lower in the other place types. The lowest job accessibility by auto would occur in the rural place types.

It is anticipated that the job accessibility by auto would vary based on the amount of new growth allocated to the various place types. If a majority of the new growth is allocated to the rural and suburban place types, it is anticipated that there would be limited growth in jobs accessibility by auto. Otherwise, if a majority of the new growth is allocated to the close in community and urban core place types, then there will be more growth in this measure.

SmartGAP reports the relative increase in jobs accessibility in auto compared to the base scenario. This relative increase is a function of the distribution of growth between the thirteen place types, weighted by the population and employment growth in each of the place types.

Community Impacts

Public Health Impacts and Costs. Three types of public health impacts are calculated by the model: road safety impacts, amount of walking as a proxy for physical fitness, and emissions of particulate matter, oxides of nitrogen and volatile organic compounds that can cause local health impacts.

Road safety impacts are calculated by factoring the amount of VMT. Daily VMT is converted to annual VMT using a factor of 347 (recommended factor by California Air Resources Board), and then to units of 100 million miles traveled. The following national average rates, from the Fatality Analysis Reporting System General Estimates System (2009) by

US Department of Transportation, are then applied to calculate the number of fatal and injury accidents and the value of property damage:

- Fatal: 1.14 per 100 Million Miles Traveled
- Injury: 51.35 per 100 Million Miles Traveled
- Property damage: 133.95 per 100 Million Miles Traveled

The percentage change in the amount of walking is calculated by applying a set of rates developed in their 5D Meta Analysis by Cervero and Ewing (Table 3-16). The elasticities that are shown in the table are multiplied by the D values for each place type. The D values are proportion values for each place type that are relative to the regional average, which is set to 1.0. The resulting products are applied to the place type growth quantities for the scenario.

The approach that the model uses to calculate criteria pollutant emissions is described above in the section on environmental performance measures. The emissions of particulate matter, oxides of nitrogen and volatile organic compounds that can cause local health impacts are reported alongside the other public health impacts.

Table 3-16: Walking Elasticities

Variable	Description	Walking Increase
Density	**Household/Population Density**	**0.07**
Diversity	**Land Use Mix (entropy)**	**0.15**
Design	**Intersection/Street Density**	**0.39**
Destination Accessibility	**Job Accessibility By Auto**	**0**
Distance to Transit	**Distance to Nearest Transit Stop**	**0.15**

Equity Impacts

This metric is a household income stratification of the regional accessibility measure. Income stratification is used to identify equity across income group and determine if regional accessibility is different for low and high income groups, thus confirming equitable investments across income groups or identifying disparities among different income groups. Often, transportation and land use policies are evaluated to determine if they are equitable for low income populations and this measure can support this evaluation.

Sources

The travel and environmental impacts are calculated from the models that were adapted from the Greenhouse Gas Statewide Transportation Emissions Planning (GreenSTEP) Model Documentation (November, 2010) prepared by Brian Gregor of the Oregon Department of Transportation, Transportation Planning Analysis Unit and the subsequent Energy and Emissions Reduction Policy Analysis Tool Model Documentation (draft August 2011) prepared by Resource Systems Group for the Federal Highway Administration.

The highway infrastructure costs are derived from the Highway Economic Requirements System (HERS) model developed for the FHWA in 2005. Regional transit costs were taken from the National Transit Profile in the National Transit Database. Fuel costs are from the US DOT's National Transportation Statistics and travel time costs are from the Texas Transportation Institute's annual Urban Mobility Report.

Additional Resources

There were three areas in the research to quantify the impacts of smart growth policies on travel demand where it was not possible to locate any existing research to develop algorithms for the software tool. These three areas (freight, second-order induced demand effects, and additional performance metrics) have additional resources identified that can be used to supplement the smart growth tool in qualitative ways.

Freight Impacts from Smart Growth

The software tool developed for this project contains VMT and GHG estimates for heavy trucks, based on the user providing inputs on truck demand. These are not sensitive to smart growth policies because current research on smart growth and goods movement is limited and does not provide quantitative assessment of the impacts that smart growth strategies might have on freight. The following discussion examines some new sources of information, as a way to think about what regions might best consider and do to pursue Smart Growth while enabling reasonable freight access to both shippers and receivers.

Smart Growth and Urban Goods Movement - NCFRP Research. As Goodwin and Bassock's (2011) recent NCRFP report has noted, examinations of freight movement for congested urban areas have considered more efficient delivery mechanisms for lower truck trip rates (e.g., Van Rooijen et al, 2008), methods for reducing environmental, time, and monetary costs of goods delivery (e.g., Quak and Koster, 2007 and 2009), delivery time scheduling decisions (Holguin-Veras et al., 2006), and vehicle-type choice, route planning, and other factors (e.g., Vluegel and Janic, 2004).

Some findings from five topic areas that relate smart growth and urban goods movement were:

- **Access, parking, & loading zones** – A demand for ample, adequate loading space exists and is a significant influence on driver satisfaction. The current research does not succeed in

identifying the appropriate balance between a need for adequate parking for goods movement and the other uses that road space can serve or the impact that different regulations on mobility may have on goods movement.

- **Road channelization, bicycle, & pedestrian facilities** – Little research has been done on how different types of street designs affect urban goods movement. While there is some research that shows narrower street designs can reduce accidents, there is no evidence that this extends to freight vehicles. Truckers are concerned with bicyclists, which they feel are erratic and not held to any operations standards, making them a liability for truck movements.
- **Land use mix** – There is little research on the impacts of truck travel in mixed use environments or dense urban areas, although mixed uses should allow shorter truck trips and lower the cost of urban logistics. The relative value of trip reduction from mixed use environments should be compared to the benefit of allowing off-hour service by trucks. Further study in the relationship between land use patterns and truck trip generation is also warranted.
- **Time and Size Restrictions and Vehicle Choice** – Societal desires to reduce emissions through different vehicles that set restrictions on private behavior, often result in higher emissions. Delivery providers choose their timing based on customer needs, so policy tools like congestion pricing have been ineffective in truck timing. Incentives that encourage receivers to accept deliveries during off-peak hours have shown to be more successful.
- **Warehouse Locations** – Warehouse locations can significantly affect distances traveled by trucks, but warehouse location is primarily determined by land cost, not transportation cost. Since land is often cheaper further aware from urban centers, warehouse locations often contribute to higher VMT and emissions as a result.
- **Network system management** – One of the main barriers identified by transportation managers to freight mobility is network congestion. Better traffic management or real-time information can provide modest reductions in VMT or CO2 emissions.

Enhancing Freight Delivery in Congested Downtowns: The Case of NYC. New York City is the nation's densest city, with an impressive mix of land uses in many neighborhoods, and tremendous economic activity – including unusually high freight movements. Parking is a perennial issue for truck use in congested downtowns, and Manhattan is the nation's busiest. According to Bomar et al. (2009a), NY City's Curbside Management Program has stepped up enforcement and management of loading and unloading zones in Midtown Manhattan, and has done away with individual-space cash meters and zero-fee loading zones, in order to enhance commercial vehicle parking by offering per-hour parking at escalating rates via ticket dispensers. The approach has clearly reduced parking durations (from 160 to 45 minutes) along with the incidence of double-parked vehicles (which averaged 140 percent occupancy previously), opening more lane space for the city's motorized travelers and more curbspace for truck operators. The operators rely regularly on pre-purchased parking tickets and/or NYC Parking Cards, thus facilitating legal deliveries and pickups. NY City's THRU Streets Program has designated many cross-town streets for more reliable, less congested, safer travel. Though measured flows rose 16 percent, speeds rose 38 percent and crashes fell 31 percent, with

noticeable pedestrian-safety improvements (Bomar et al. 2009a). Such benefits come from having truck operators, stopped and turning vehicles, and locally destined vehicles rely on other east-west streets. Loading zones were enhanced on these other streets.

New York also pursued a Truck Route Management and Community Impact Reduction Study in 2007, which modeled truck trip-making in a disaggregate fashion, flagged and then addressed high crash sites (via signal timing, signage, and geometric improvements), shifted key routes to reduce impacts on largely residential corridors, pursued a policy of enhanced designated-route signage for truck operators, and identified a clear need for substantive coordination among a variety of associated agencies (e.g., city and state DOTs, PANY/NJ, and NYMTC). Safety data, travel choice data, land use and networks data were key for this Study (Bomar et al., 2009a) and presumably should be central to Smart Growth implementations.

The Southern California Association of Governments (SCAG) has pursued similar investigations and policies, to improve traffic operations, in order to facilitate freight movements in the LA region. For example, the City of LA has turned to GIS and safety databases for its Goods Movement Improvement Plan (Bomar et al., 2009b), along with outreach to the trucking industry and other key stakeholders. Similar to Manhattan's improved enforcement of curbside parking laws, LA's Tiger Teams have sought to quickly catch abuse of limited parking space in key sections of the regions, and work with repeat violators and others to establish loading zones in key locations. (Bomar et al., 2009b)

Some Important Features of the Trucking Fleet: A Sacramento Study. In their urban-freight study for the Sacramento Area Council of Governments, the Tioga Group et al. (2006) noted that about two-thirds of California's heavy-duty trucks are in privately- (or government-) held fleets, with the remaining third for hire. Among the privately held fleets, over 80 percent of trips are under 50 miles in distance, and less-than-truckload (LTL) in size. In contrast, "(v)irtually all long-haul private fleet movements are truckloads" (Tioga Group et al., p. 7). They noted how Sacramento's trucking fleets "tend to cluster near heavy industrial areas, low rent commercial areas and freeways" (2006, p. 7), which makes good sense, since parked trucks do not care about their surroundings (though presence of crime may be a meaningful criterion for their placement) and easy access to shippers, receivers, and high-speed, high-design routes should be key. They also observed how Sacramento's trans-shipment terminals are largely for LTL operators, and located on the region's periphery, but centrally within market sheds.

While trucking tends to dominate freight mode alternatives in most U.S. shipments – and particularly those within urban areas, rail can and does play a meaningful role in many regions, like Sacramento, particularly for shipment of basic commodities (Tioga Group, 2006). Nevertheless, Sacramento's 1.4 million population was receiving an average of just 1.3 trains each day in 2003, and producing content for less than one train a day (268 a year in 2003, as estimated by the Tioga Group et al. [2006]). By 2020, forecasts are for 1.8 75-car inbound trains a day, on average (with each rail car representing 3 to 5 truckloads [70 to 125 tons of freight]) and 1 train outbound (with its 75 rail cars bound for a variety of destinations).

Such numbers appear inconsequential when compared to the thousands of trucks that enter, depart, and run through the region each day. It can be surprising how much reliance a majority of the nation places on truckers, who must share public roadways. In a Sacramento survey of freight-affected jurisdictions (Tioga Group, 2006), the biggest complaint was street deterioration from trucking (with an average ranking of 3.7, out of 5). Complaints regarding construction trucks (due to high growth in the region) and parking came next (with average ranks of 3.3). Noise, congestion and pollution associated with trucks had average ranks of 3.1, 3.0, and 2.9. Local delivery trucks, safety, nighttime operations, and hazardous materials transport came in the last four spots, with ranks of 2.6, 2.5, 2.3, and 2.2. (Tioga Group et al., 2006) The Sacramento study also noted the importance of adequate truck-route signage (and connectivity, where feasible), to avoid violations and associated problems (e.g., trucks entering residential areas without need). Separated grade crossings (for safety and to avoid noisy horn blows) were also mentioned. (Tioga Group et al. 2006) For cities with heavy passenger rail lines, some deliveries may be made off hours, as tested with San Francisco's BART system (Lu et al. 2007).

Some Land Use Implications of Freight Facilities. Fisher and Han's (2001) NCHRP project 298's synthesis report, titled "Truck Trip Generation Data", assessed the rather limited practice of estimating and reporting truck trip rates according to land use (and size of development). Challenges emerge from variations in units (e.g., tons and dollars, across a variety of commodity types) and type (and size) of vehicles used, along with the regular chaining of such trips, variable dwell times, and different business types and site-use details. Reasonable numbers of trip count studies appear mostly available for truck-intensive uses, like freight warehouses, distribution centers, and industrial parks. Far more data are needed, to allow cities to confidently design in the spirit of Smart (and sustainable) Growth, with balanced (and densely developed) land uses and non-motorized-travel-friendly "complete streets", while ensuring that the economy and viability of those land uses is not compromised by inadequate support of freight access.

Related to this notion of trip generation, trip distribution and travel distances are key. Allen and Brown (2010) have examined the reductions in average haul lengths and freight-related VMT in urban centers that come with locating distribution facilities closer to regional centers. And Andreoli et al. (2010) found that very large, multi-regional distribution centers increase travel distances. Goodwin and Bassock's (2011) review of the Smart Growth literature cites Klastorin et al. (1995) for noting that truck trip rates rise in urban areas, and cites Wygonik and Goodchild (2011) for some quantification of how each shipment's cost and environmental impacts tend to fall in denser areas.

Sacramento's many jurisdictions have adopted Smart Growth plans, including polices for more redevelopment and infill, jobs-housing balance, and greater housing choice. (Tioga Group, 2006) Infill and redevelopment tend to occur in older neighborhoods, where truck access and parking are more challenging. Taller buildings, with more occupants per acre of land, are still subject to the same roadspace constraints, resulting in a greater intensity of deliveries and pickups, of people and freight. In effect, functionality may be lost in the quest for sustainability and livability. Additionally, sales tax revenues of industrial land uses cannot generally compete with those from retail and other establishments (to offset California governments' regular budget

concerns). (Tioga Group, 2006) This is one reason that heavy industry may be departing, and the nature of trucking in these neighborhoods may change quite a bit (e.g., from multi-axle, tractor-trailer truckloads, to many more single-unit LTL carriers). Smaller vehicles will be helpful, but they cannot be guaranteed, and they still experience (and generate) many parking and congestion issues.

The Sacramento study (Tioga Group et al., 2006) examined the question of "coexistence of urban development and urban goods movement" (p. 24). They believe that use of truck-focused service hubs with ease of access to a line haul corridor may be challenging due to the incompatibility of land values, environmental issues, and public acceptability of such a land use so close to the urban center. Moreover, many truckers may not be interested, since so many belong to private fleets, with their own facilities. Strong policies would be needed to encourage (or force) operators to use such facilities. Florida has recently investigated methods for facilitating clustering of warehouse and distribution facilities in the form of "freight villages" (Bomar et al. 2009c), including a "warehousing and logistics" (WL) zoning designation, complete with design details for loading docks and appropriate timing of associated signals. Truck-trip generation or attraction also now receives a closer look in Florida than simply scaling up using passenger-car equivalencies (PCEs), for purposes of the Development Review Process: truck size and maneuverability and loading/unloading needs demand far more than simply added lane capacities that come with PCE-based reviews. (Bomar et al., 2009c)

Regional Simulations and Local Estimates of Congestion Effects. Ultimately, this SHRP research project is interested in the congestion effects of Smart Growth policies and land use patterns. Unfortunately, there is very little literature on this specific relationship. One piece of work that comes close is Lemp and Kockelman's (2009) "centralized employment" scenario for the Austin, Texas region, as compared to their status quo, capacity expansion and tolling scenarios. They used these scenarios to examine the distinct predictions of activity-based/tour-based and traditional methods of travel demand modeling. In the centralized-employment scenario, they removed half the basic, retail and service jobs found in the region's rural-designated traffic analysis zones and 30 percent of such jobs in the suburban-designated zones and placed these in the urban- and central-designated zones (in proportion to existing jobs counts for those zones).

Expecting system-level VMT and congestion to rise, and travel times to fall, the welfare changes for most travelers were estimated under the activity-based approach and "all" travelers (across zones, on average within each zone) to benefit from this shift in jobs. This scenario resulted in greater welfare benefits overall than the expanded-capacity scenario, which added 200 lane-miles on the region's most congested north-south freeways. (Of course, it also did "better" than the tolling scenario, where agency toll revenues were not counted against traveler expenditures on tolls.) Overall, the region's VMT predictions fell by about 1 percent (thanks in large part to a 1 to 2 percent drop on non-freeway arterials), as detailed in Lemp's (2007) longer thesis. The activity-based model predicted VHT to rise slightly (1.22 percent), while the traditional model predicted it to fall negligibly (-0.80 percent), with transit and bike/walk predicted shares rising in both instances (roughly 4 to 10 percent, depending on the model and the mode). Flow-weighted average speeds fell slightly in both cases (from -0.67 to -1.66

percent). Model freight trips and external movements, however, were not measured, so the 15 to 20 percent of the region's VMT were held constant (based on the Capital Area MPO's trip tables), and certainly should have adjusted with changes in jobs. Such neglect of freight movements is not uncommon, given the relative unavailability of commercial-trip survey data, with which to calibrate commodity movements in a reliable way.

Given the lack of existing studies on this important topic, a back-of-the-envelope calculation may be revealing when seeking a sense of the likely congestion impacts from adding development density in a region or neighborhood. Assume that one starts with a jobs + population density of 5 job-equivalents per acre, and assume this generates 5 vehicle-miles of traffic per hour per acre locally, with a volume-to-capacity equivalent of 0.5 (uncongested), and free-flow and actual access speeds of 25 and 24.53 mi/h (relying on a Bureau of Public Roads link-performance function with $\alpha = 0.86$ and $\beta = 5.5$ [consistent with NCHRP guidance for high-design roadways]). What if one increases the density of this location and its environs, without adding roadway capacity? Newman and Kenworthy's (1989, 1989) studies of world cities suggest that energy use and motorized travel miles per capita enjoy a -0.30 (approximate) elasticity with respect to (regional) population and jobs densities. Work by Holtzclaw et al. (2002), Cervero and Kockelman (1997), and others support this level of effect on VMT per capita versus density, especially when one quantifies the regional accessibility of locations (which is more informative than simple density measures). Thus, if the density doubles, to 10 job-equivalents per acre, distance per job may fall from 1 mile to 0.8123 miles (applying the -30% elasticity appropriately [via integration, rather than a discrete jump of 30 percent, to 0.70 miles]), but the doubled density results in a total local VMT of 8.123 miles now, rather than 5. The local v/c ratio rises to 0.812, and travel speeds fall about 25 percent (to 19.62 mi/h). Total system travel time on local roads has now more than doubled (from 12.23 minutes to 24.80 minutes), but travel time per job-equivalent remains roughly the same, at 2.4 minutes, thanks to shorter distances per job-equivalent.

If one takes this analogy a bit further, to a 20-job-equivalents-per-acre scenario, with VMT-per-job falling to 0.66 miles, v/c ratios jump to 1.32 and travel times are estimated to reach 11.9 minutes per mile (rather than 2.45 and 3.06 min/mi under the 5- and 10-jobs-per-acre density scenarios, respectively). Speeds fall to 5.05 mi/hr, and TSTT per job-equivalent is now more than 3 times what it was originally (7.84 minutes, rather than 2.45 and 2.48 under the other two scenarios). In other words, the congestion effects of adding site occupants without transportation system efficiencies and infrastructure could be crippling. One-way streets, major subway corridors, satellite parking, and other design features may be necessary, to avoid gridlock. While the above calculations are undoubtedly limited, they suggest that Smart Growth needs to be truly smart, to avoid such issues.

Second-Order Induced Demand Effects

The Smart Growth Area Planning (SmartGAP) tool includes a step that allows for possible adjustments to the VMT-reducing impacts of smart-growth scenarios to account for possible induced-demand effects. This reflects a second-order, rebound effect that could erode some of the VMT reduction benefits of smart-growth initiatives.

The idea of rebound effects as related to traffic and land-use initiatives are something that exist in theory however there is little, if any, empirical evidence to guide measurement. This is largely because the effects are, by definition, indirect and subtle, slowly unfolding over a number of years. To gauge impacts would require not only a rich time-series data base but also a well-specified model that contains all the explanatory variables that influence VMT and travel so as to remove possible confounding effects, thus allowing the long-term marginal influences of smart growth (e.g., the 5 "Ds") to be gauged.

One possible approach to adjusting for second-order induced demand effects is to borrow from prior studies. Most research to date has focused on induce-demand impacts of roadway expansions – i.e., a supply-side investment. Very little work has been done on the impacts of demand-side strategies, whether they be TDM (e.g., pricing, ITS) or land-use initiatives. One could argue that, in principle, it does not matter whether an intervention works on the supply or the demand side since it is the influence of the initiative on roadway performance (and more specifically travel speeds) that unleashes travel behavioral adjustments. However the relationship between road capacity expansion and travel versus initiatives like TOD and travel are no doubt quite different. While adding one or two lanes provides near-instantaneous traffic-flow benefits, smart-growth strategies change travel more slowly over time. Only when, say, high enough densities are accumulated might bus or rail services be improved enough to draw significant numbers of travelers out of their cars and into transit vehicles. Regardless, the impacts would be the same – removing trips previously made by car off nearby roads, thus increasing average speeds and performance.

The major study to date on induced travel demand is the meta-analysis by Cervero (2002), drawn from 28 studies from both the U.S. and abroad. This meta-analysis focused was on the induced-demand impacts of road expansion projects. The meta-analysis summarized past research, in the form of mean elasticity values, for facility-specific studies as well as area-wide studies. The advantage of area-wide studies is they allow the wider impacts of capacity expansion on entire networks (accounting for impacts on tributary roads as well as route shift impacts) to be gauged. Also, given the regional context of land-use scenario testing for the SHRP2 C16 project, findings from area-wide studies are most relevant. The mean short-term elasticity (of VMT as a function of lane-mile expansion) was found to be 0.4, reflecting impacts over a 1 to 3 year period. The mean long-term elasticity was higher, at 0.73, reflecting the cumulative impacts of not only behavioral (e.g., modal shifts and latent trips) adjustments but also structural ones like land-use and growth-inducing effects. The long-term elasticities apply to impacts over a 6 to 10year period, and possibly longer.

Several studies have relied on these meta-summarized elasticities, including the Growing Cooler report (Ewing et al., 2008). However these analyses focused on the limited benefits of roadway expansion in coping with traffic problems and did not apply elasticities from the 2002 meta-analysis to adjust for possible rebound effects of smart growth.

While the long-term area-wide elasticity of 0.73 might be viewed as most appropriate for accounting for rebound impacts, it is unlikely to pass the "reasonableness test". Applying this number would mean that the initial estimate on the traffic-reducing impacts of a TOD scenario

of, say, 100,000 vehicle-miles traveled versus a base-case scenario of 200,000 VMT would be whittled down to a 73,000 VMT reduction in the long term:

This would represent a substantial diminution of the traffic benefits of smart growth. It would be based on the questionable assumption that the induced-demand relationships are similar between supply-side and demand-side interventions. Given the lack of supportive evidence on this question, it has been decided not to incorporate the 2002 meta-analysis findings or any other empirical evidence on induced travel demand into the Smart Growth Area Planning (SmartGAP) tool, at least not for the initial rendition of the model.

The 2010 study by Sperry et al. (2010) provides perhaps more direct insights into how smart growth might produce a rebound "induced demand" effect. For a mixed-use suburban activity center in Plano, Texas, the researchers estimated from a travel survey that 17.2 percent of internal car trips were induced. However these induced trips did not load onto the regional network thus their impact on off-site traffic levels was likely imperceptible and their applicability to a regional scenario evaluation tool is questionable. Since internal trips within the activity center are quite short, moreover, the contributions of these induced trips to total VMT associated with the mixed-use center was likely far less than 17.2 percent. For these reasons, along with the fact that this evidence is drawn from a single case and thus may not be representative of other situations, it has further been decided not to incorporate these results be applied in the Regional Scenario Evaluation Tool either.

Because there is no reliable and defensible empirical evidence from which to base the calculations, it has been decided that no adjustments for induced demand impacts be used in the Smart Growth Area Planning (SmartGAP) tool at this time. To try to do so would pose the risk of introducing substantial errors into the analysis which could in turn propagate through remaining calculations in the model. It is unclear, moreover, whether future refinements of the model might be able to successfully incorporate induced-demand adjustment factors. Rather than trying to model this second-order impact, consideration should be given to funding future research that specifically focuses on measuring induced-growth impacts of smart-growth initiatives as well as other demand-side initiatives, such as TDM or ITS (intelligent transportation systems). Such an analysis would likely take a fair amount of time thus one should not expect that induced demand impacts could be incorporated into a Regional Scenario Evaluation Tool anytime soon. The only other plausible alternative for trying to incorporate second-order induced demand effects into the analysis would be to draw from the opinions of a group of experts who study relationships between land use and travel and perhaps who have observed changes in travel behavior over time of smart-growth projects. Regardless, a Delphi-like process of eliciting opinions about rebound effects would not be grounded in empiricism. Delphi techniques work best when there is some empirical evidence available to guide the views of experts. This is not the case, however, for the matter of induced demand impacts of smart growth.

Additional Performance Metrics

The initial research on performance metrics identified a long list of performance metrics that would be useful in evaluating smart growth policies, but the research for many of these was not able to support inclusion into SmartGAP, so these are included here with resources that can be used to provide understanding of the metric and details about quantifying these metrics from smart growth strategies.

Environment and Energy Impacts

- **Land Consumption -** The Cost of Sprawl, Revisited study (1998) identified one issue related to sprawl as being the preservation of land and natural habitat. Chapter 5 of this study provides a literature review regarding the impact of development on the land use and natural habitat. Chapter 11 of this study documents an annotated literature review in which commentary is provided on notable studies related to potential impacts of land development on the natural habitat.

  The Cost of Sprawl (2002) document evaluated the various impacts of sprawl development including land conversion, which was defined as the process by which land is converted from rural and agricultural uses to residential and commercial uses. Part II, Chapter VI discusses the issue of land conversion including estimates of land savings that would occur in various locations throughout the United States with the implementation of growth control measures.

Financial and Economic Impacts

- **Local Infrastructure Costs – Development** – The Cost of Sprawl (2002) document addresses several types of costs associated with sprawl including both local infrastructure costs and the cost of real estate development. The local infrastructure costs are provided in Chapter 8 for Roadway Infrastructure and Chapter 9 for the other infrastructure costs. The cost related to real estate development, primarily land costs are provided in Chapter 10.
- **Fiscal Impact** – The Growing Wealthier (2011) study presents economic benefits of several Smart Growth related strategies. The discussion of one strategy related to the direction of development to existing communities (Principle 9) addresses several potential fiscal savings related to more compact regional growth. These savings include not just infrastructure but also impacts associated with fire and police services.
- **Job Creation -** The Growing Wealthier (2011) study discusses potential job creation associated with various smart growth strategies. Specific strategies were then identified as having employment related benefits such as the creation of additional construction jobs, support for small businesses, and better access to jobs.

Location Impacts

- **Location Efficiency** – The Pennywise and Pound Fuelish (2010) study quantifies the relative benefits of more compact development by creating an index of housing and transportation index. Key findings of this study is that location efficient neighborhoods have lower

transportation costs, which when combined with housing costs, means that these locations are actually more affordable than more remote areas when both factors are taken into account. This document also provides additional information regarding the Center for Neighborhood Technology (CNT) online index of housing and transportation affordability which provides information for areas with over 80% of the US population.

- **Property Values** – The Walking the Walk- How Walkability Raises Home Values in US Cities (2009) study applies a statistical analysis to analyze the relationship between the pedestrian accessibility and walkability as it relates to housing values. The study concluded that property owners will pay a premium for locations and housing that are more walkable as compared to other locations.

  The Effects of Walkability on Property Values and Investment (2009) study related walkability to market value and return on investment at various types of properties throughout the United States include office, retail, apartment, and industrial uses. This analysis applied a statistical model which concluded that market value for all types of properties were higher for all types of properties when higher walkability was present.

Community Impacts

- **Building Energy Use and Cost/Household** – The Location Efficiency and Housing Types- Boiling it Down to BTU's (2011) study evaluated the potential energy benefits of conventional suburban development as compared to more compact and mixed-use communities. The analysis combined the energy associated with transportation and buildings to develop a composite measure of energy usage. The study concluded that compact communities will produce greater energy savings than traditional suburban development.
- **Building Water Use and Cost/Household** – The Smart Water- A Comparative Study of Urban Water Use Efficiency Across the Southwest (2003) study evaluates water usage across different development densities in Chapter 4 and concludes that compact development reduces water usage as compared to traditional development patterns. Most of this savings was determined to occur through a reduction in outside watering, which constitutes the majority of water usage for many single family homes.

Social and Equity Impacts

- **Social Return on Investment (ROI)** – The Cost of Sprawl (2002) study evaluated the quality of life impacts related to sprawl and alternative forms of development. A quality of life model was identified using variables related to urban form, socio-economic variables, crime, weather, and other factors. The analysis concluded that the addition of growth controls did not negatively impact quality of life results.

CHAPTER 4. PILOT TESTS

The SmartGAP software was shared with three agencies who were asked to test the software by implementing it in their regions, while a parallel implementation and further testing were performed. The findings of the pilot tests are summarized here and recommendations for further enhancements to SmartGAP based on those findings are also presented.

Pilot Test Objectives

The pilot tests were intended to produce implementations of the SmartGAP software in three varying agency settings in order to provide a range of feedback on the usability and usefulness of the software. The three agencies that agreed to participate in the pilot tests were:

- Thurston Regional Planning Council (TRPC)
- Atlanta Regional Commission (ARC)
- Maryland Department of Transportation (MDOT)

The agencies were selected to represent a small to medium sized MPO – TRPC falls into this category, a large MPO – ARC falls into this category, and a department of transportation – MDOT falls into this category. The three categories were designed to represent a range of institutional capability and planning needs that covers that of the target audience for SmartGAP.

The specific objective of the pilot tests that was communicated to the participating agencies was to apply the software so that the following could be better understood:

- The usability of the software
- The complexity of and any difficulties or problems with developing input data
- The usefulness and clarity of the output metrics produced by the software
- The reasonableness of the results

In addition, an objective of the pilot tests was to generate feedback from the software users that would inform the final updates to the software and the user's guide that took place as part of this project, and to identify suggestions for future updates and features that could be added to software after this project has been completed.

Pilot Test Process

The pilot tests took began with a webinar to introduce the three agencies to SmartGAP. The webinar described the objectives of the pilot tests, provided an overview of the SmartGAP model, discussed the development of the input data, and included a demonstration of how to use the software. Following the webinar, the agencies were provided with the software, a draft of the user's guide, and preprocessed Census population and County Business Patterns data that simplified the creation of some of the base year model inputs.

The agencies were asked to accomplish the following tasks and to provide feedback on their experience at each step:

- Install the software and successfully run the demonstration model included with the software
- Develop model inputs for their region
- Run eight standard scenarios and submit the results

The set of eight standard scenarios were devised so that each agency would evaluate a range of policies that tested how the model represented changes in transportation supply, changes in policy assumptions such as travel demand management policies, changes in land use allocation assumptions, and combinations of those three types of inputs. Asking each agency to test the same set of eight scenarios was intended to allow for comparisons of the results across the three agencies. The design of the eight scenarios is shown in Table 4-1.

Table 4-1. Scenarios for Pilot Testing

Scenario	Land Use	Transportation	Policy
#1. Baseline	Baseline	Baseline	Baseline
#2. Increase Transit Supply	Baseline	+ 20% in Transit Supply	Baseline
#3. Increase Roadway Supply	Baseline	+ 20% in Roadway Supply	Baseline
#4. Add ITS	Baseline	Baseline	+20% in Lane Miles with ITS
#5. Shift 10% Growth to More Dense Areas	Shift 10% Pop, Emp to Close in Community, 10% to Urban Core, from Suburban Area	Baseline	Baseline
#6. Shift 20% Growth to More Dense Areas	Shift 20% Pop, Emp to Close in Community, 20% to Urban Core, from Suburban Area	Baseline	Baseline
#7. Shift 30% Growth to More Dense Areas	Shift 30% Pop, Emp to Close in Community, 30% to Urban Core, from Suburban Area	Baseline	Baseline
#8. Shift 30% Growth to More Dense Areas and Add ITS and Transit Supply	Shift 30% Pop, Emp to Close in Community, 30% to Urban Core, from Suburban Area	+20% in Transit Supply	+20% in Lane Miles with ITS

- Scenario #1 is the baseline scenario, which was intended to be the agency's expected future for their region, assuming existing policies such as those embodied in their Long Range Plans. The remaining seven scenarios then introduce some change from that baseline.
- Scenario #2 and #3 evaluate the effects of changes in transportation supply – testing an increase in transit services and highway construction respectively.
- Scenario #4 tests the impact of a transportation system management policy, where additional ITS is added to the regions highway system to improve traffic flow by managing incidents and thereby reduce congestion.
- Scenario #5, #6, and #7 alter the allocation of future growth in housing and commercial development in the region, moving increasingly larger proportions of that growth from the suburban area type to the close in community and urban core area types to test the impacts of locating development is denser, more accessible locales.
- Scenario #8 was designed to evaluate how the model combines the effects of several changes, in this case a large shift in the land use allocation, a change in transportation supply and additional ITS provision.

Over the course of the pilot test period, the agencies were provided with varying degrees of assistance. This included telephone calls, email exchanges, reviews and corrections to input files, and review of outputs. At the end of the pilot tests, the agencies were asked to provide input and output files for the scenarios that they had run, and written feedback on their experiences.

A fourth implementation of SmartGAP was developed in parallel to the three agency implementations. This implementation, based on the Portland metropolitan region, was used for model testing and to provide a fourth set of results from the standard scenarios. The intensive testing that was carried out early in the pilot tests period resulted in the release of two new versions of SmartGAP to the three agencies. The agencies all used the third version of SmartGAP for the production of the final pilot test results presented in this section of the report.

Maryland Department of Transportation

Agency Introduction

MDOT is the statewide agency in Maryland responsible for planning, building, operating, and maintaining the state's transportation network. MDOT are responsible for the entire state of Maryland, which is comprised of 24 counties and a population of 5.8 million people. Rather than using SmartGAP to evaluate the entire state, MDOT elected to model two separate counties, Montgomery County and Cecil County.

Montgomery County is a populous county situated just north of Washington, D.C. In 2005 (the base year that MDOT used for modeling purposes) the population was 975,000, and the projected population in 2035 (the future year that MDOT used for modeling purposes) is 1,117,000. This represents a relatively slow rate of population growth of 20%. Cecil County is a more rural county in the northeast corner of Maryland. Its 2005 population was 100,000 and its

2035 projected population is 170,000, which represents growth of 70%, a much higher rate of population growth than Montgomery County. The relative locations of Montgomery and Cecil counties are shown in Figure 4-1.

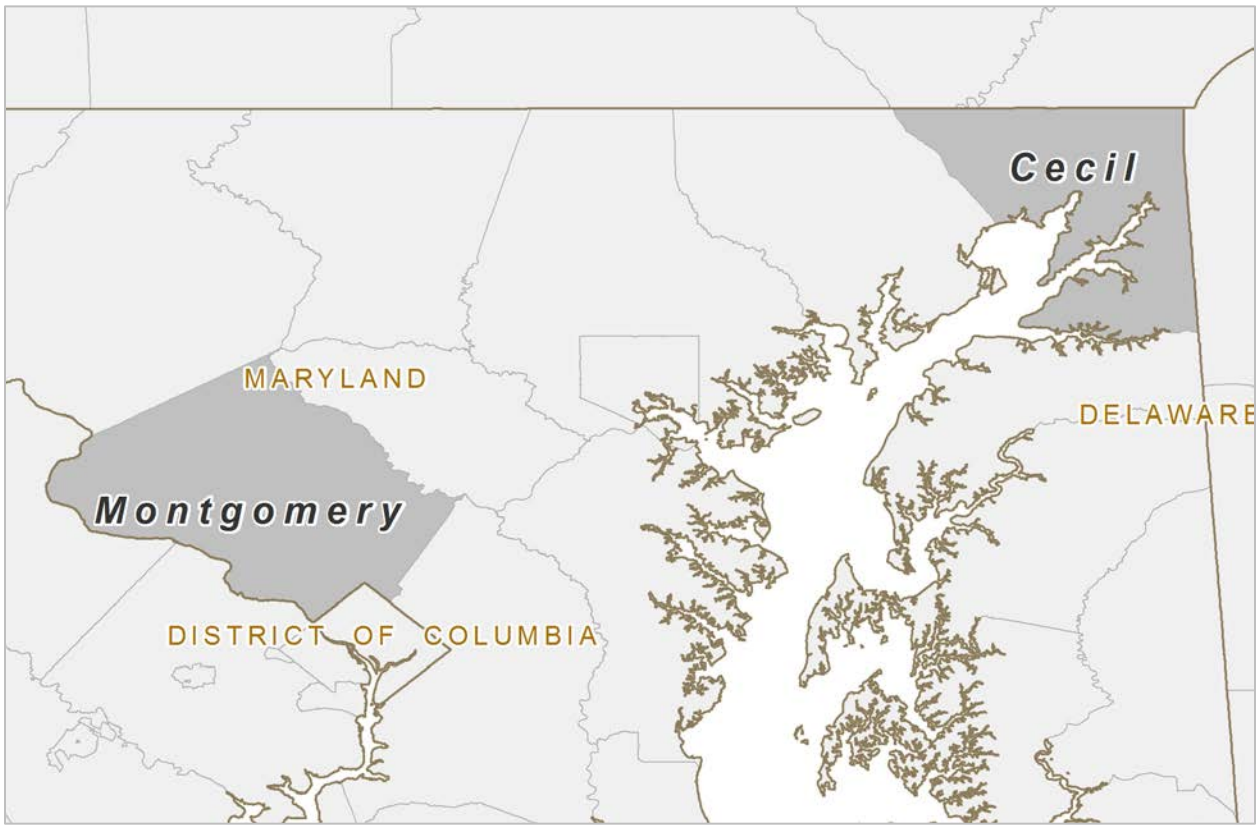


Figure 4-1: Map of Montgomery and Cecil Counties, Maryland

Development of Model Inputs

MDOT developed local inputs for two counties, Montgomery County and Cecil County. They did not employ a complex, GIS based, place type allocation process such as that described in the summary of the ARC pilot test. However, the general differences in existing and expected future land use patterns between the two counties were represented in their input files. Figure 4-2 compares (to the left) population by area type for Cecil County (the first series, in red) and Montgomery County (the second series, in blue). Montgomery County is more largely suburban with a significant proportion of people living in areas that MDOT identified as close in communities and urban cores, while Cecil County's population lives predominantly rural and suburban areas. The employment comparison between the two counties (shown to right) shows a similar difference in the distribution, with a much higher proportion of employment in Montgomery County in more urban area types.

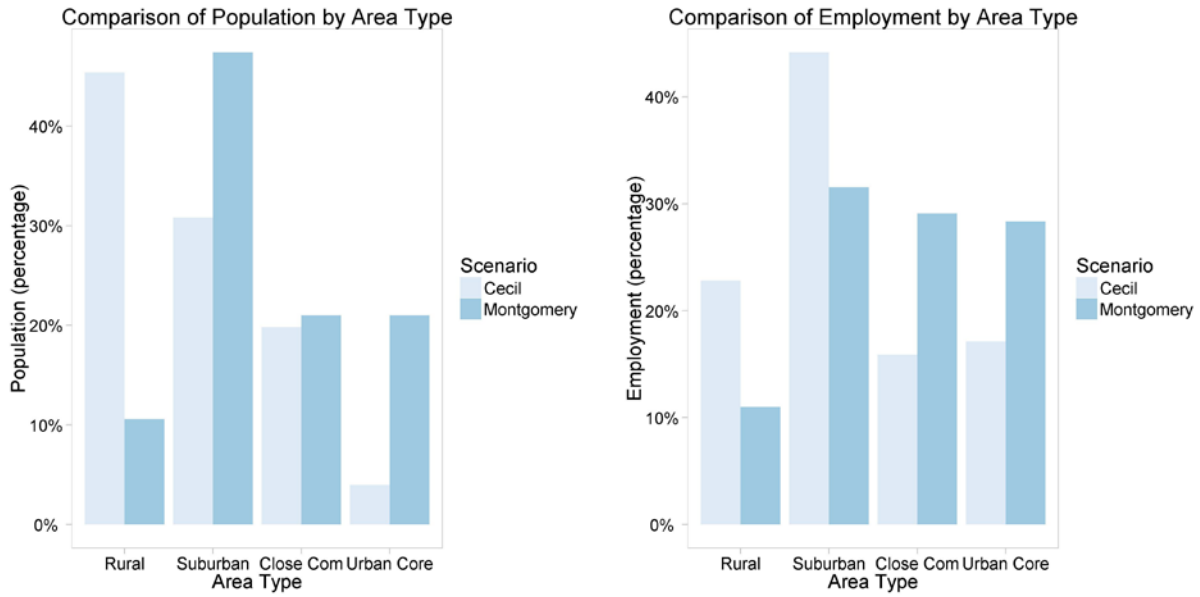


Figure 4-2: Summaries of 2035 Population and Employment by Area Type for Cecil and Montgomery Counties (Percentage of Total County Population and Employment)

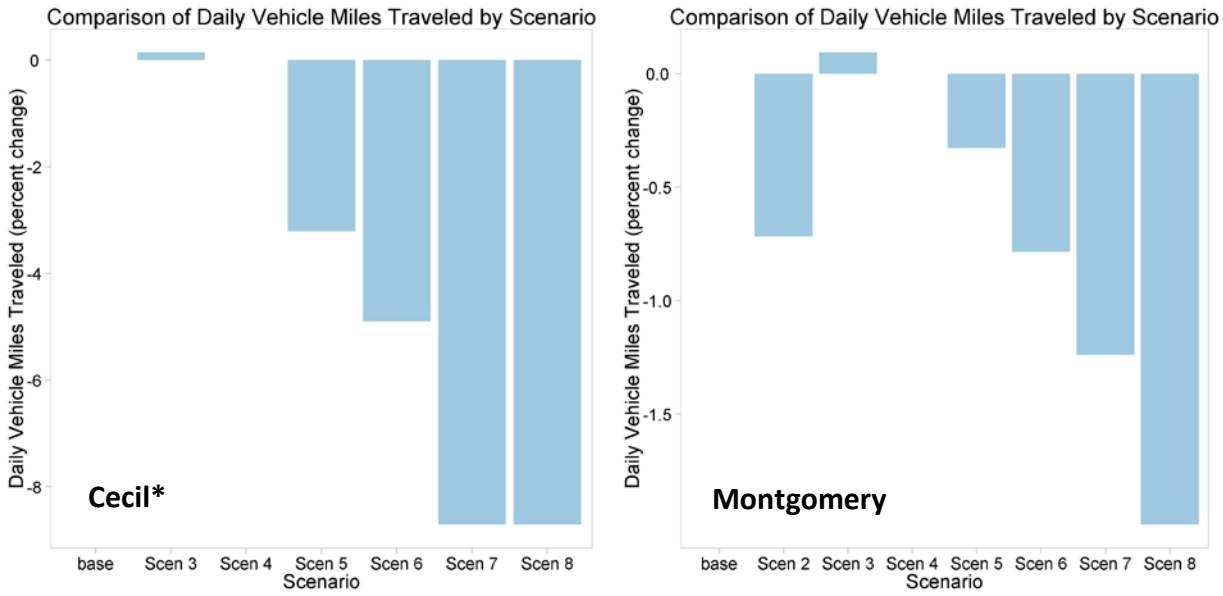
Scenario Testing Results

MDOT provided inputs for the two counties and completed a full set of eight standard scenarios runs for each county. Figure 4-3 compares the changes in daily VMT by scenario for the two counties that were modeled, in the form of an index chart with the base scenario set to zero and the values for other scenarios expressed as percentage changes relative to the base scenario. In the case of Cecil County (to the left), no transit service was modeled and so scenario #2 was not included (and scenario #8 only differs from scenario #7 in its inclusion of additional ITS for incident management of the county's highways).

Cecil County is predicted to have proportionally higher growth than Montgomery County (shown to the right), and so smart growth policies that are implemented between 2005 and 2035 have larger potential effects: Scenario #7, where approximately 30% of the predicted growth in suburban areas is moved to close in communities and urban core area types results in an a reduction of 8% VMT compared to the base scenario. The provision of additional transportation supply in the form of more roads (scenario #3) has relatively little impact on VMT in Cecil County, indicating that its relatively rural and uncongested road system is imposing few constraints on travel.

Montgomery County is relatively more developed than Cecil County and less growth is predicted, so the impacts of reallocating future growth have less overall impact. Scenario #7, where approximately 30% of the predicted growth in suburban areas is moved to close in communities and urban core area types results in a reduction of VMT that is between 1% and 1.5%, a much smaller impact than in Cecil County. Increasing transit services was tested in

scenario #2, and resulted in a daily VMT reduction of over 0.5%. Scenario #8, which tests the combined effect of transit service improvements and smart growth land use policies, resulted in a 2% reduction in daily VMT compared to the base scenario.



*Note – no transit scenario (#2) run in Cecil County

Figure 4-3: Comparison of Percent Change in Daily VMT from the Base by Scenario for Cecil and Montgomery Counties

SmartGAP includes various performance metrics that describe aspects of livability, including the number of traffic accidents and the amount of walking. The number of accident is based on rates that are in terms of accidents per million miles of VMT, so the relative change in each accident severity category tracks the changes in daily VMT shown above. The percentage change in accidents in Montgomery County by accident severity is shown in Figure 4-4. Montgomery County sees a 2% reduction in accidents for scenario #8, which produced the largest reduction in daily VMT. As scenario #3 (increase in transportation supply) leads to an increase in daily VMT it also leads to an increase in accidents. This is only apparent in the injury and property accident severity categories. The number of accidents in each category is calculated as an integer, and since the number of fatal accidents is (thankfully) relatively small, a relatively large change in daily VMT is required to change the number of fatal accidents.

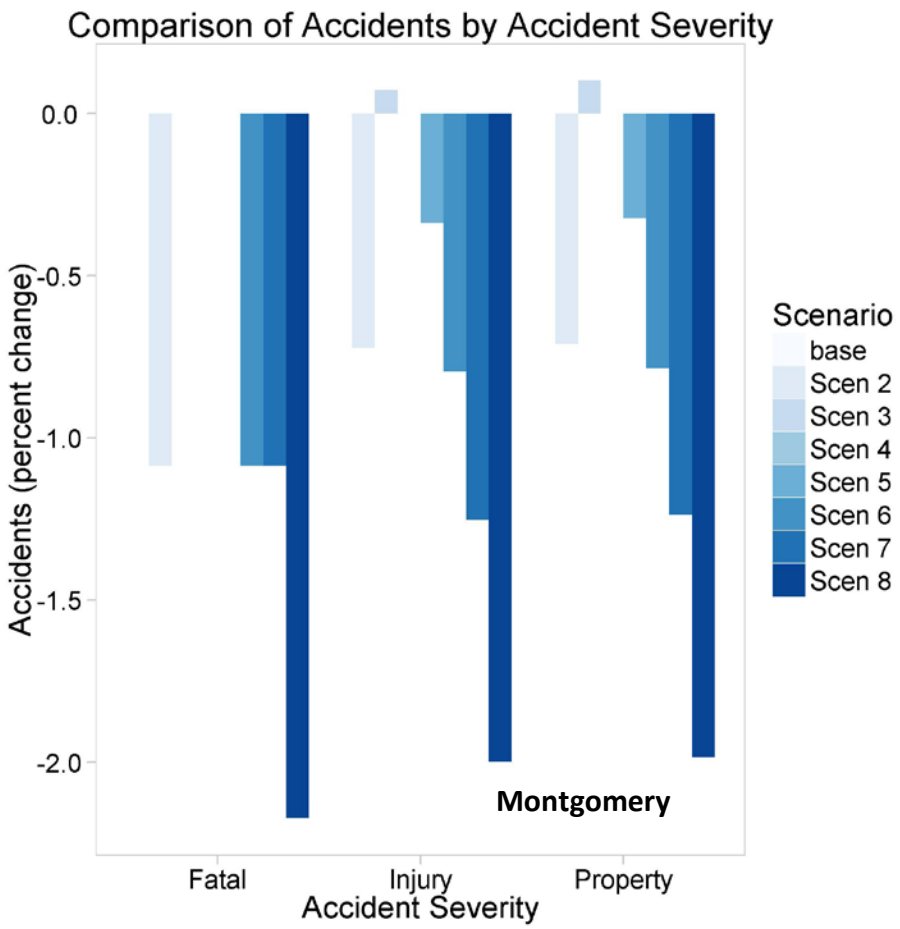


Figure 4-4: Comparison of Percent Change in Accidents by Severity for Standard Scenarios for Montgomery County

The walking metric is the amount of walking above or below a common zero point (based on the expected amount of walking by residents of the suburban TOD place type) that will take place by residents of new housing and employees of new jobs. Therefore, it is only indicative of the effect of newly developed land uses on the people who live and work in them and not on any (possible) secondary effects on walking by residents and employees in existing areas. Figure 4-5 shows a comparison of the walking metric for the full set of standard scenarios for each of Cecil County (to the left) and Montgomery County (to the right). The metric is in term of a proportional change in walking relative to the zero point of development taking place (on average) in the suburban TOD place type. For Cecil County, the base scenario is a general continuance of development in rural and suburban area types, which are in general less walkable than the suburban TOD place type and so the scenario shows in excess of a 10% reduction in walking amongst new residents and workers in the county. For scenarios with the same allocation of future residential and employment development, the metric is the same, indicating that (as designed) it is only sensitive to land use changes and does not measure possible changes in walking that may results from changes in transportation supply. As land use growth is shifted

to more walkable (more urban) place types in scenarios #5, #6, and #7, the amount of walking by new residents and employees increases. In scenario #7, growth is taking (on average) in place types that are more walkable than the suburban TOD place type, and so the walking metric is positive. A comparison between scenario #7 and the base scenario shows around a 15% increase in the amount of walking by new residents and employees increases. The range of the change in the amount of walking between the base scenario and scenario #7 by new residents and employees is similar for Montgomery County, which is expected given a similar shift in the land use allocation. Of note is that all of the scenarios return a positive walking metric, indicating that even in the base scenario with growth allocated in least walkable manner, on average growth is still predicted to take place in place types that are more walkable than the suburban TOD place type.

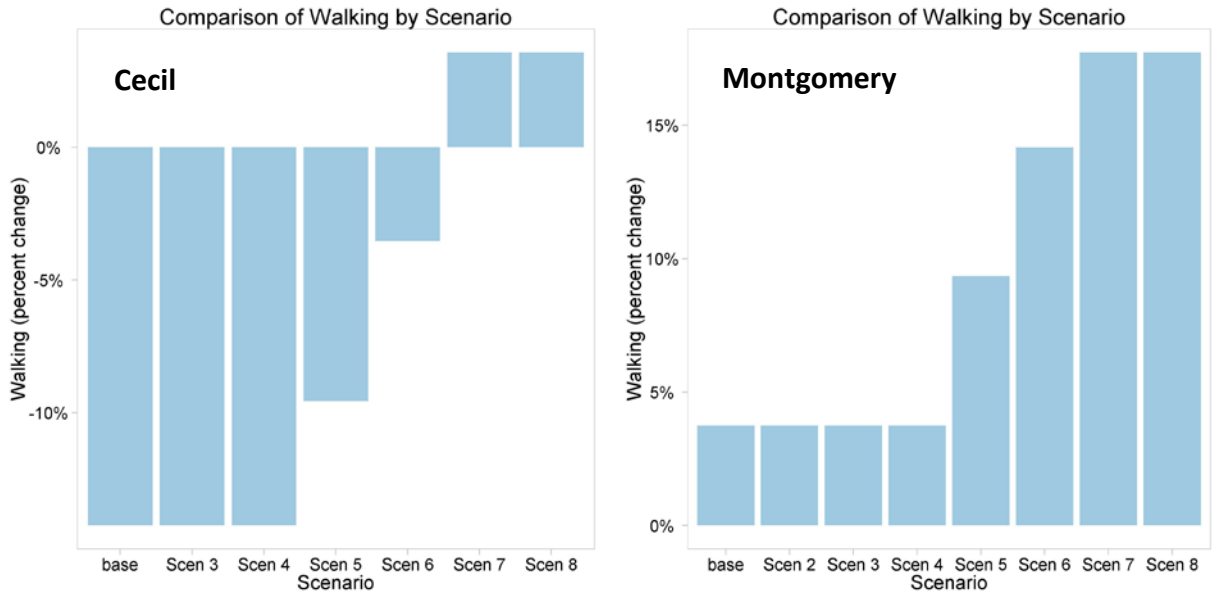


Figure 4-5: Percent Change relative to the Suburban TOD place type in Walking Metric for Cecil and Montgomery Counties

Agency Comments

In addition to providing a complete set of input files for both Montgomery and Cecil counties, MDOT provided additional feedback on SmartGAP. MDOT installed the software locally on a desktop computer and were able to successfully run the demonstration scenarios. Following some assistance, MDOT created input data for the two counties that they chose to study. The Montgomery County implementation, with a population of approximately 1 million, has run times of around 20 minutes, while the much smaller Cecil County only takes a couple of minutes to run. One aspect of the pilot test that caused some difficulty for MDOT staff was receiving software and transmitting results. MDOT's computer network security prevents access to external FTP sites and prevents receipt of zipped files attached to email. MDOT provided other feedback on the pilot tests as well:

- **Software installation.** MDOT found that installation of software is easy as the steps are clearly outlined in the User's Guide.
- **Development of input files.** MDOT also stated that the input file preparation was easy to follow using the descriptions in the User's Guide. For the employment data (employment.csv) input, MDOT recommended included more information to create area specific (say for different counties) employment files. MDOT did find that the input file formatting and naming is very precise and can be difficult to debug if errors are made.
- **Connections with travel demand models.** MDOT recommended that there should be some guidance or methodology described so that regions with travel demand models can use their standard model input/output files for better and easier representation of transportation supply and travel demand.
- **Adjustment and calibration of the model.** MDOT commented that it would be interesting to investigate how to calibrate each of the individual modules and provide guidance on this issue.
- **Overall.** MDOT considered that the SmartGAP software offers a great tool to perform high-level scenario planning work with macroscopic formulations. In terms of applicability, MDOT commented that SmartGAP should act as a good resource for preliminary "what-if" analysis for agencies, particularly smaller MPOs and local jurisdictions without advanced travel demand models, while bigger MPOs and state agencies can use this tool for pre-screening policy scenarios before undertaking extensive travel demand modeling exercises that are resource intensive. SmartGAP can help shortlist a longer list of scenarios to a reasonable number with relatively less effort.

Atlanta Regional Commission

Agency Introduction

ARC is the regional planning agency for a 10-county area in Georgia, which includes the City of Atlanta. ARC also covers a larger, 20-county area for air quality purposes; the ARC Travel Demand Model covers the 20-county area. It is this larger 20 county region that ARC used as the model region for the SmartGAP pilot test. The 20-county area is shown in Figure 4-6.

The ARC 20-county area is a very large region, with a 2010 (base year) population of 5.3 million people and a 2040 (future year) projected population of 8.3 million people. This projection represents population growth of 57%. In 2010, there were 2.1 million jobs in the region, with growth of 68% projected in 2040, giving a total of 3.5 million jobs.

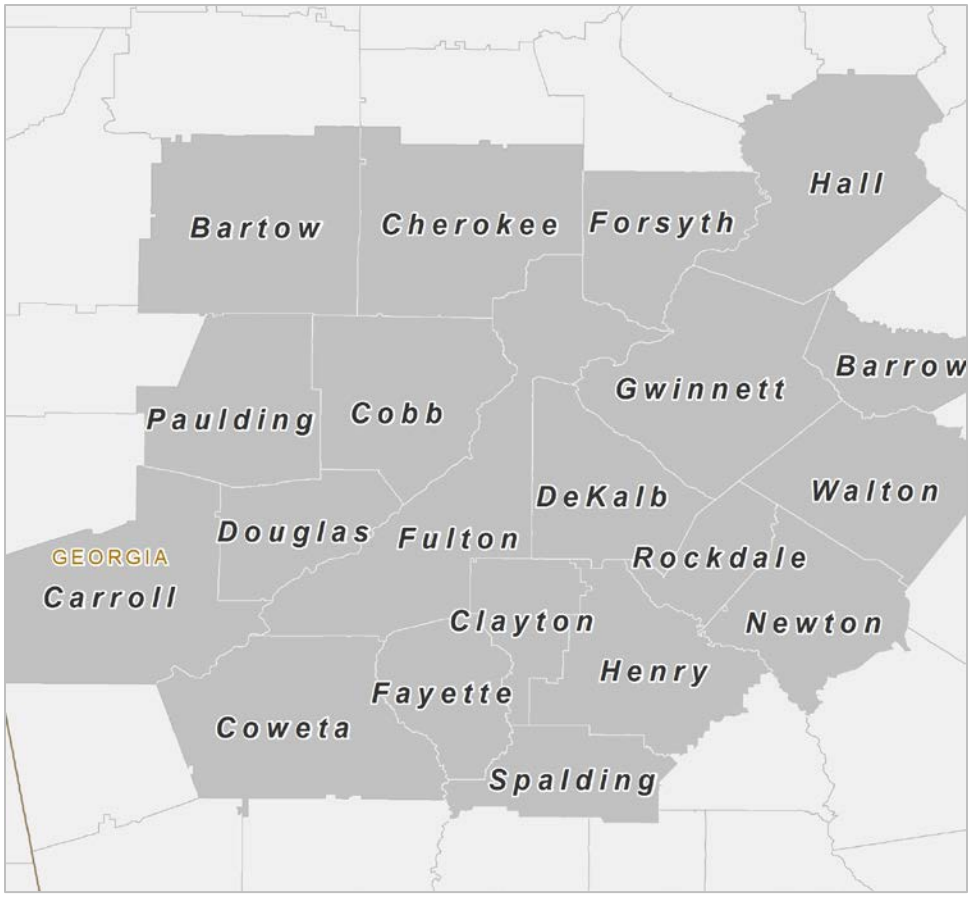


Figure 4-6: ARC 20-county Region Used for Pilot Testing of SmartGAP

Development of Model Inputs

ARC provided a detailed description of their approach to developing the model input data. In general, they followed a somewhat detailed process to derive input data from land use data as presented in their "Unified Growth Policy Map", and from their regional travel demand model. They developed heuristics to align their land use with the 13 place types that SmartGAP uses.

Population and Jobs by Place Type (place_type_existing.csv and place_type_growth.csv) The conversion of land use data to the place type scheme used in SmartGAP involved taking ARC's Unified Growth Policy Map (UGPM) Areas and converting them to the 13 SmartGAP place types.

1. The first step was to allocate the UGPM areas to the four area types used in SmartGAP. The Urban Core area type includes Region Core, Region Employment Centers and Aerotropolis UGPM areas; Close in Community includes Maturing Neighborhoods; Suburban includes Developing Suburbs and Established Suburbs; and Rural includes Rural Areas and Developing Rural.

2. The ARC traffic analysis zone (TAZ) system was overlaid with the area types and the centroid of the TAZ was used to determine its area type.
3. The SmartGAP development type, the other dimension of the place type matrix, which included residential, mixed-use, employment, and TOD development types was determined for each TAZ using the base year percentage of the TAZ's employment in relation to the total of the population and employment in the TAZ. The mix between the employment and employment was used to determine the TAZs development type using the following cut points:
   - Residential: < 33.33%
   - Mixed Use: 33.33 to 66.67%
   - Employment: > 66.67%
4. Only one TAZ was determined to be TOD as a development type, Lindbergh Center, in the Urban Core area type.
5. The combination of the area type and the development type was then used to allocate all TAZs to one of the 13 place types.
6. The 2010 TAZ employment and population totals were summed by the 13 place type and then scaled to total one for both employment and population as called for by the file format for place_type_existing.csv.
7. The population and employment growth amounts between 2010 and 2040 were determined for the 13 place types and were scaled to total 1 for both employment and population as called for by the file format for place_type_growth.csv.

Figure 4-7 shows summaries of 2040 population (on the left) and employment (on the right) by area type for the ARC region base scenario (i.e. their expect future described in their UGPM), as produced by SmartGAP based on the two place type input files. About half of the population is expected to live in suburban areas in 2040, with 40% split between the two denser, more urban area types, and the remainder in rural areas. Employment is more heavily concentrated in the urban core. Figure 4-8 shows similar summaries of 2040 population and employment, this time by development type. The charts indicate the level of mixing of residential and employment locations, with approximately 40% of each land use located in the residential and employment development types respectively, approximately 20% in the mixed-use areas, and 20% in the "opposite" development type (i.e. residential development in employment areas and vice-versa). There is relatively little existing or planning TOD development in the region.

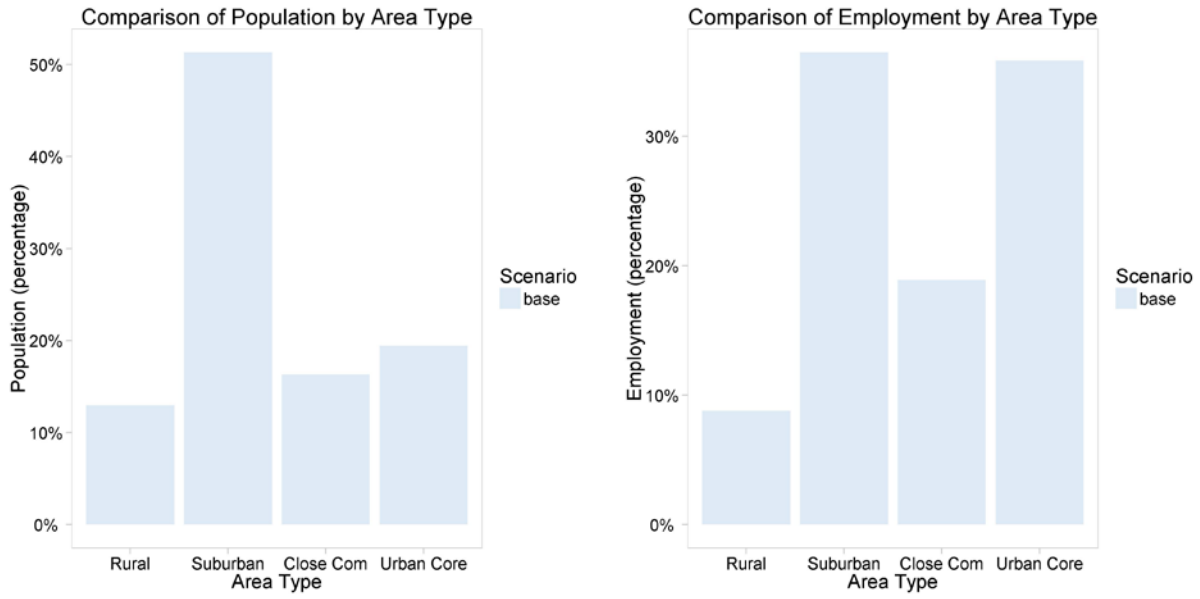


Figure 4-7: ARC Summaries of 2040 Population and Employment by Area Type

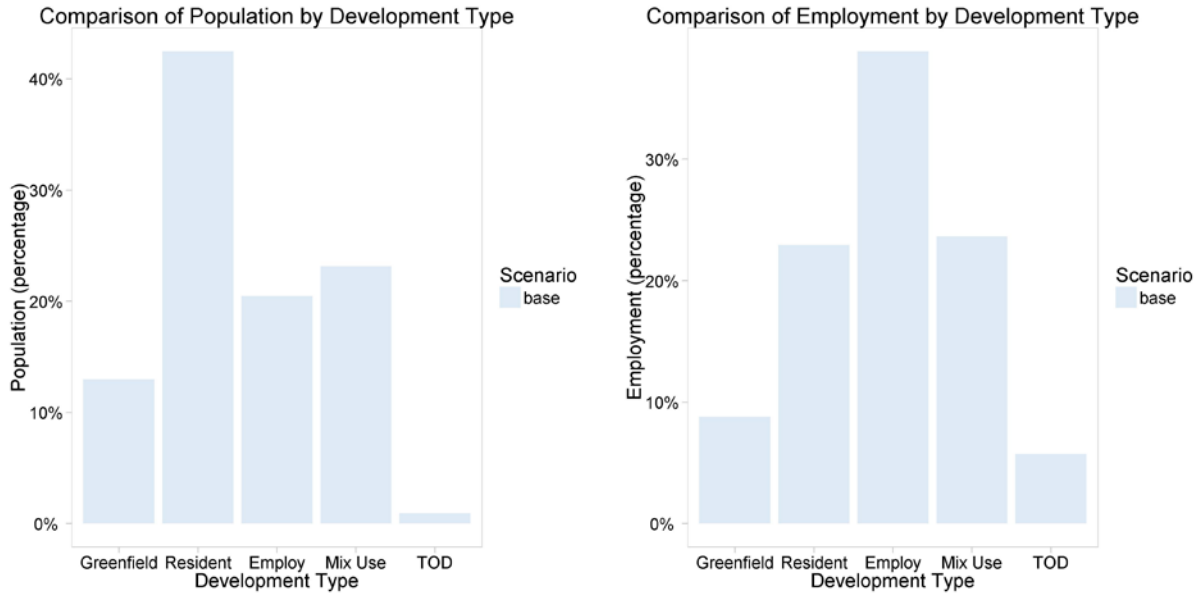


Figure 4-8: ARC Summaries of 2040 Population and Employment by Development Type

Base Daily Vehicle Miles Traveled (base_vmt.csv). This input file includes the total light vehicle daily VMT in the region and the proportion that takes place on freeway and arterial roads. To develop the light vehicle VMT, ARC obtained the single occupant vehicle, high occupancy toll, and drive-to-transit VMT's from the ARC 2010 Plan 2040 Model Summary. These VMTs were summed together and displayed in thousands of miles, as required by the file format of base_vmt.csv. To develop the freeway and arterial percentage of light vehicle VMT, ARC summarized VMT by facility type for from the loaded network TOTAL10 in their travel demand model, and then aggregated it to freeway, arterials, and other roads. The freeway and arterial VMTs were then added and convert to a percentage of the total VMT.

Truck and Bus Vehicle Miles Traveled (truck_bus_vmt.csv). This input file includes the split of VMT by bus and truck that takes place on freeways, arterials, and other roads, and includes the proportion of total VMT in the region that is driven by trucks. The data were developed by ARC using their 2010 Plan 2040 model. To summarize the bus data, ARC used data on transit buses by line joined with the loaded highway network, and followed these steps:

1. Used the network's facility type attribute to create total distance of freeways, arterials and other roads by bus line
2. Computed bus VMT by freeway, arterial and other:
   - Number of Local Buses by Peak = 8 hours * 60/peak headway
   - Number of Express Buses by Peak = 6 hours * 60/peak headway
   - Number of Local Buses by Off Peak = 10 hours * 60/peak headway
   - Number of Express Buses by Off Peak = 2 hours * 60/peak headway
   - If a Local Bus, Total Number of Buses by Line = Number of Local Buses by Peak + Number of Express Buses by Peak
   - If an Express bus, Total Number of Buses by Line = Number of Local Buses by Peak + Number of Express Buses by Peak
   - Total Bus VMT by Line = Total Line Distance * Total Number of Buses by Line
   - Total Bus VMT is the sum of all Total Bus VMT by Line
   - Total Bus VMT by Freeway = Total Bus VMT * (Freeway Mileage / Total Mileage)
   - Total Bus VMT by Arterial = Total Bus VMT * (Arterial Mileage / Total Mileage)
   - Total Bus VMT by Other = Total Bus VMT * (Other Mileage / Total Mileage)

Peak headway is the number of minutes in the peak period divided by the average number of buses in the peak period.

ARC computed truck VMT by freeway, arterial and other roads using the following steps:

1. From the 2010 loaded highway network, Truck VMT by Segment = length of the segment * volume of trucks

2. Summarized all Truck VMT by facility type

   - Truck VMT Freeway % = Truck VMT Freeway / Truck VMT Total
   - Truck VMT Arterial % = Truck VMT Arterial / Truck VMT Total
   - Truck VMT Other % = Truck VMT Other / Truck VMT Total

3. The overall Truck VMT percentage of total VMT was obtained from the ARC 2010 Plan 2040 Model Summary, Truck VMT Percentage = (Commercial Vehicle VMT + Medium Trk VMT + Heavy Trk VMT) / Total Daily VMT

Auto and Transit Trips per Capita (trips_per_cap.csv). This input file contains average number of auto and transit trips per day per person in the region. ARC obtained population, total vehicle trips, and total transit trips from the ARC 2010 Plan 2040 Model Summary, and calculated the two data items as follows:

1. Auto Transit Trips per Capita = Total Vehicle Trips / Population

2. Transit Trips per Capita = Total Transit Trips / Population

Scenario Testing Results

ARC successfully installed the software in a network location, developed input data for their region as described above, ran the eight standard scenarios, and provided a complete set of results for the scenarios. The three scenarios that involved alternative land use assumptions were scenarios #5, #6, and #7. The proportions of population and employment by area type are shown in Figure 4-9. ARC chose to define relatively similar changes between scenarios #5, #6, and #7 in terms of the reallocation of population, with larger differences in the location of employment growth. All three scenarios embody the objective of these test scenarios: to locate increasingly higher proportions of growth to denser and more urban place types.

The direct travel performance metrics presented by SmartGAP include daily VMT, vehicle hours of travel and delay vehicle hours. Figure 4-10 shows daily VMT by scenario, in the form of an index chart with the base scenario set to zero and the values for other scenarios expressed as percentage changes relative to the base scenario. The chart shows that in scenario #2, an increase in transit services leads to a reduction in daily VMT, in this case by a little more than 1%. Scenario #3, where road supply is increased, induces an increase in daily VMT. Scenario #4, where additional highway lane miles are provided with the ITS for incident management, does not affect daily VMT as the ITS policy affects the calculation of policy adjusted congestion, which is after the final calculation of travel demand. Scenarios #5, #6, and #7, show increasingly larger reductions in VMT as more and more growth is located in denser, more urban area types, culminating in an almost 5% reduction in VMT in scenario #7. Combining the land use allocation in scenario #7 with an increase in transit services, gives a VMT reduction in scenario

#8 that approaches 6%. The changes appear to be directionally consistent and reasonable in magnitude.

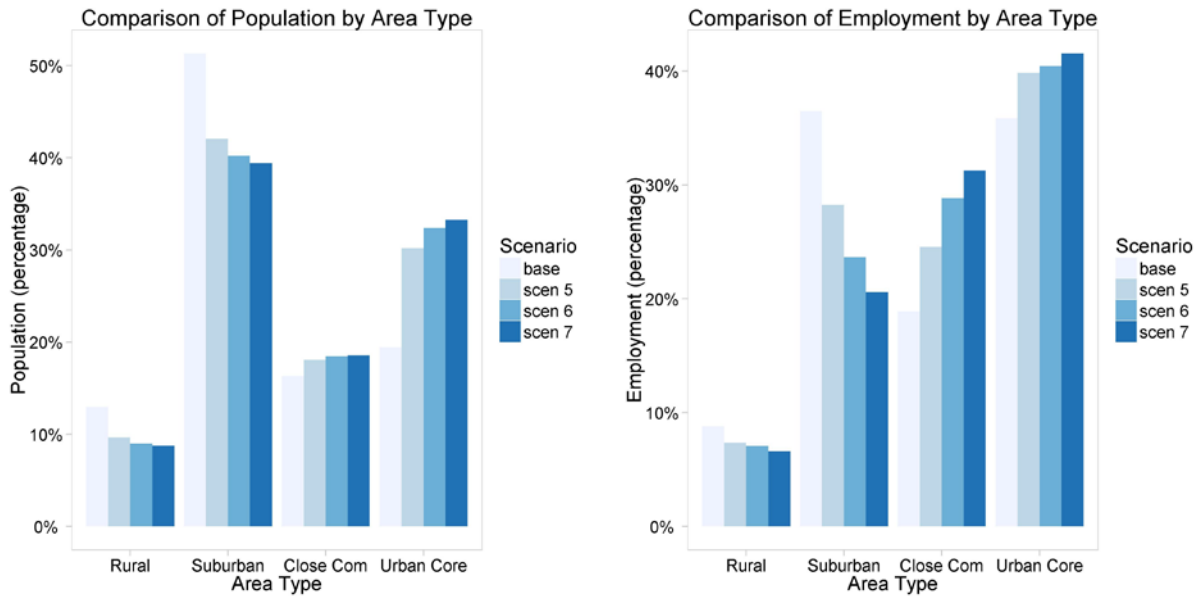


Figure 4-9: ARC Percent of 2040 Population and Employment by Area Type for Base Scenario and Scenarios #5, #6, and #7.

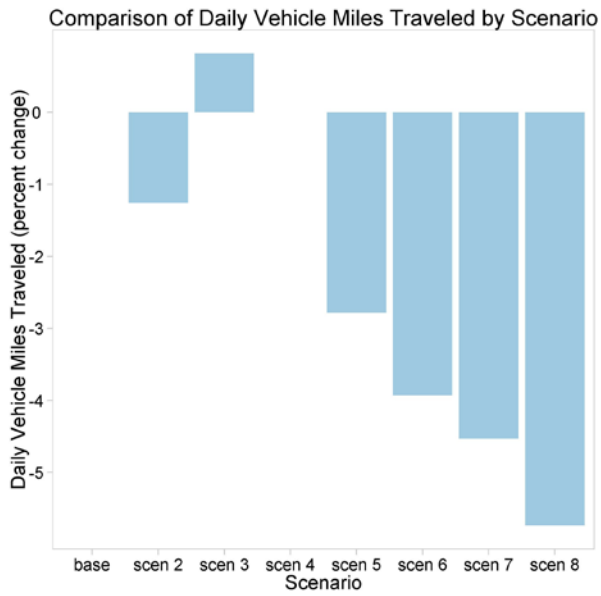


Figure 4-10: ARC Percent Change from the Base of Daily VMT for 8 Scenarios

Figure 4-11 shows both a comparison of changes in total vehicle hours for the eight standard scenarios (to the left) and a comparison of changes in delayed vehicle hours (to the right). Scenario #2 (increase in transit service) and scenarios #5, #6, and #7 (land use growth shifts to more urban areas) shows reductions in vehicle hours that follow the patterns of reductions in VMT. More striking, however, are the changes in scenario #3 (increase in road supply) and scenario #4 (more ITS for incident management). Both scenarios model changes that decrease the effects of congestion, with the first increasing capacity (and while some of that capacity is used up by induced demand, not all of it is) and the second improving traffic flow given the same capacity. In both scenarios, there is a significant reduction in congestion, with an almost 25% reduction in hours of delay in scenario #3 and more than 15% reduction in scenario #4. These translate to overall reduction in vehicle hours of 4% and more than 3%, respectively.

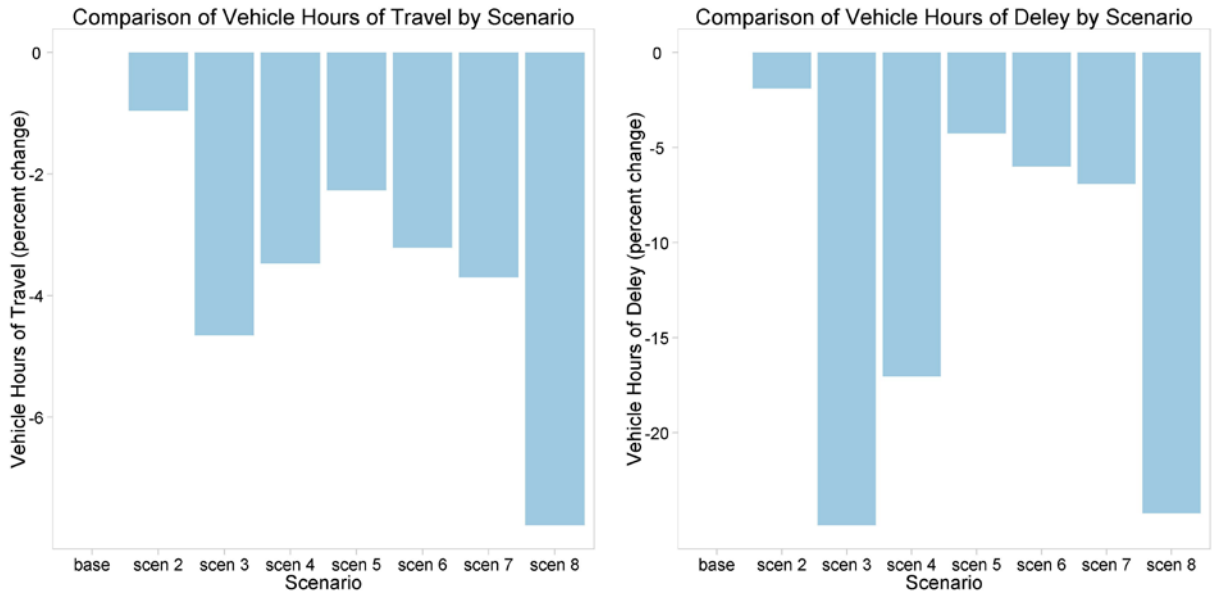


Figure 4-11: ARC Percent Reduction of Vehicle Hours and Delayed Vehicle Hours for by Scenario

Agency Comments

In addition to providing detailed descriptions of their input data development process and a complete set of inputs files and results for the eight standard scenarios, ARC provided some additional feedback on SmartGAP.

- **Input data development.** ARC found some of the input development to be easy and some was more difficult to obtain or calculate. The processes ARC followed to allocate land use to place types and to calculate the VMT by facility type inputs based on travel model inputs were somewhat time-consuming. One of the policy tests (that fell outside of the eight standard scenarios) was travel demand management policies. ARC expressed difficulty in translating their detailed household travel survey results, that categorized work schedules into

many categories, into the simpler categories used to represent compressed work schedules in SmartGAP.

- **Software installation.** ARC faced some initial problems when trying to install R and SmartGAP on a desktop without admin rights, but was able to install R and SmartGAP on a flash drive and copy everything to a folder on a desktop or a server with user rights. ARC was able to install R and SmartGap easily on a server with admin rights.
- **Running the software.** ARC found that the model would not run to completion on a desktop with 2GB of RAM due to insufficient memory, but it completed with no problem when installed a server with more RAM.
- **Software performance.** ARC found that each scenario took approximately 1 hour and 45 minutes to run, and generated approximately 850 MB of data.
- **User's guide content.** ARC commented that the content of the User's Guide was helpful for installing and using the software.
- **Other comments.** ARC found that there are many policies that SmartGAP could test that cannot be evaluated with the current version of their travel demand model

Thurston Regional Planning Council

Agency Introduction

TRPC is the regional council of governments and MPO for Thurston County, Washington, which includes Washington's state capital Olympia. The region the TRPC chose for their implementation of SmartGAP covers the whole of their jurisdiction, which is the single county of Thurston. Thurston County's population in 2010 (the base year used by TRPC) was 250,000 and the projected population in 2040 (the future year used by TRPC) is 425,000, which represents population growth of 69%.The 2010 employment in Thurston County was 130,000, with projected growth by 2040 of 100%. Figure 4-12 shows the location and boundaries of Thurston County.

Figure 4-12: TRPC Region Used for Pilot Testing of SmartGAP

Development of Model Inputs

TRPC developed a complete set of inputs for SmartGAP using local data. They followed a GIS based process very similar to that used by ARC (described above) to develop the existing and future baseline allocation of land uses to place types. The results of the process are shown in Figure 4-13. The distribution of population by area type (to the left) in the base scenario is focused on the suburban area type, which accounts for 65% of the population in 2040, with 20% in rural areas, 10% in close in communities and only around 2% in the urban core. The distribution of employment (shown to the right) is slightly more even across the area types, with around 50% in suburban, 25% in close in communities, and 15% in the urban core. Figure 4-14 shows the distribution of population (to the left) and employment (to the right) by development type. The majority of the population is in primarily residential development types, with the largest proportion of employment (approximately a third) in mixed use areas and slightly smaller proportions in both employment and residential development types.

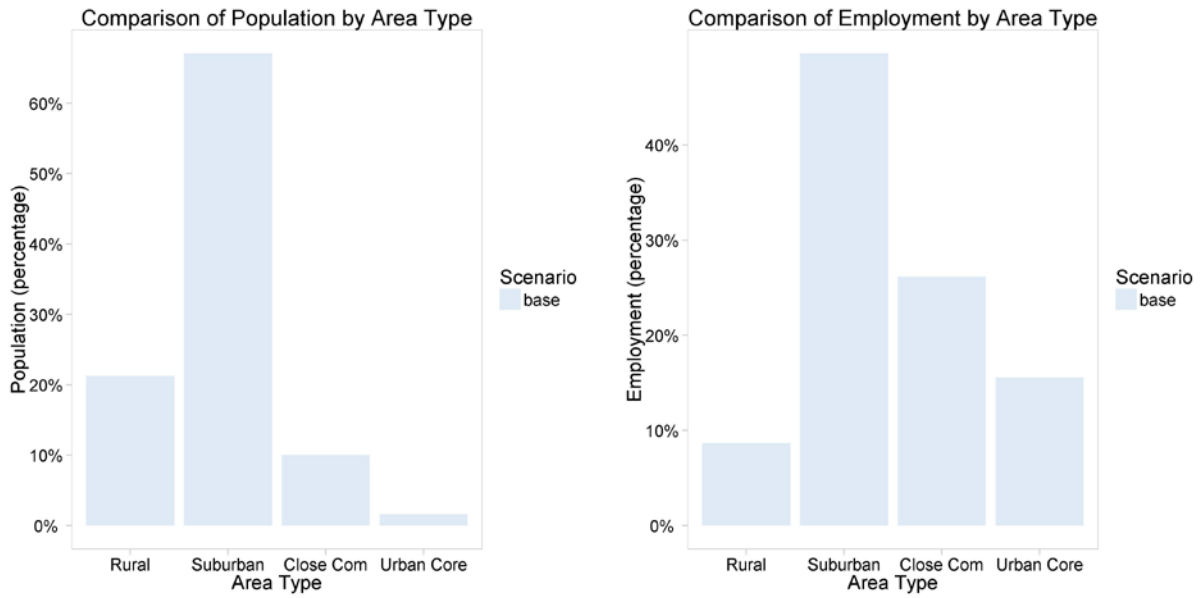


Figure 4-13: TRPC Percent of 2040 Population and Employment by Area Type

TRPC elected to augment the preprocessed employment data that they were provided with (based on County Business Patterns data) with additional records to reflect the employment types that are not covered by those data. Specifically, they added employment in government, which is a very important element of employment in Olympia, the state capital of Washington.

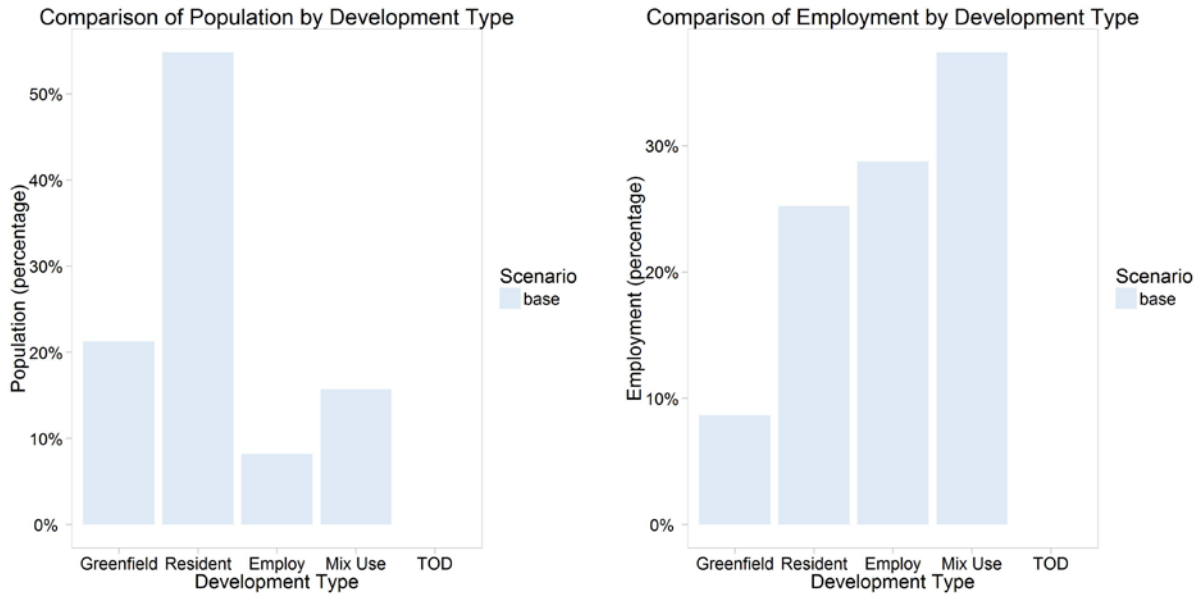


Figure 4-14: TRPC Percent of 2040 Population and Employment by Development Type

Scenario Testing Results

TRPC successfully installed the software in a network location to allow sharing of access amongst several staff, developed input data for their region, ran the eight standard scenarios, and provided a complete set of results for the scenarios. The three scenarios that involved alternative land use assumptions were scenarios #5, #6, and #7. The proportions of population by area type (to the left) and development type (to the right) are shown in Figure 4-15. TRPC chose to reallocate population from the suburban area type to the close in community area type, and from the residential development type to the mixed-use development type. They followed a similar approach to the allocation of employment (except that the reduction was made in the employment development type). TRPC did not allocate any population or employment to the TOD development type.

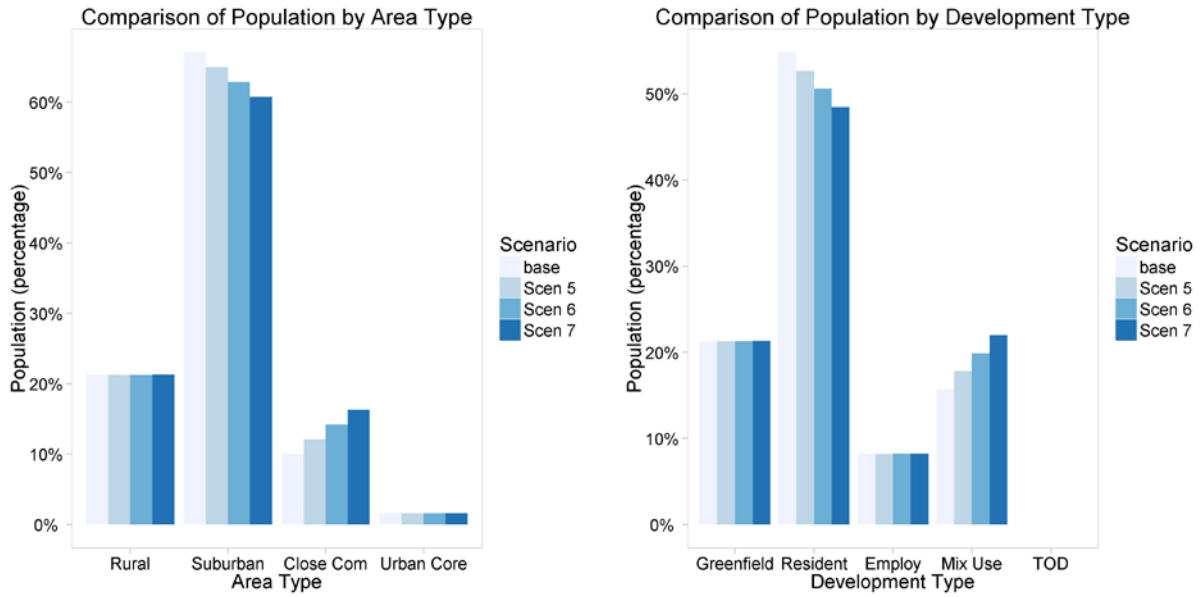


Figure 4-15: TRPC 2040 Population and Employment by Area Type for Base Scenario and Scenarios #5, #6, and #7

Several of the direct travel impacts and the financial and economic impacts that are related to them are only sensitive to land use allocation changes and not to the transportation supply or other policy changes that were tested in the eight standard scenarios. Figure 4-16 shows a comparison of transit trips (to the left) and vehicle trips (to the right) for the base scenario and the three scenarios that include land use changes (scenarios #5, #6, and #7). The transit trip metric increases transit use when more growth is allocated to transit accessible locations (i.e. the close in community area type and mixed-use development type that TRPC allocated more population and employment to). The results show an increase in transit trips of around 3% amongst new residents and employees in scenario #7 relative to the base land use allocation. The vehicle trip metric shows a decrease in the number of vehicle trips made by new residents and employees when more growth is allocated to area types and development types that are more transit accessible and more walkable, as the opportunity to make trips by modes other than car increases. The results show this trend, with scenario #7 showing a reduction in vehicle trips close to 1% relative to the base scenario.

The transit operating costs and capital costs performance metrics are calculated using rates that are proportional, and (as with the transit trip metrics) only measure changes that relate to changes in land use allocations. Therefore, the pattern of changes in costs is intended to follow the same pattern of changes in the number of trips. Figure 4-17 demonstrates that the performance metrics behave as intended.

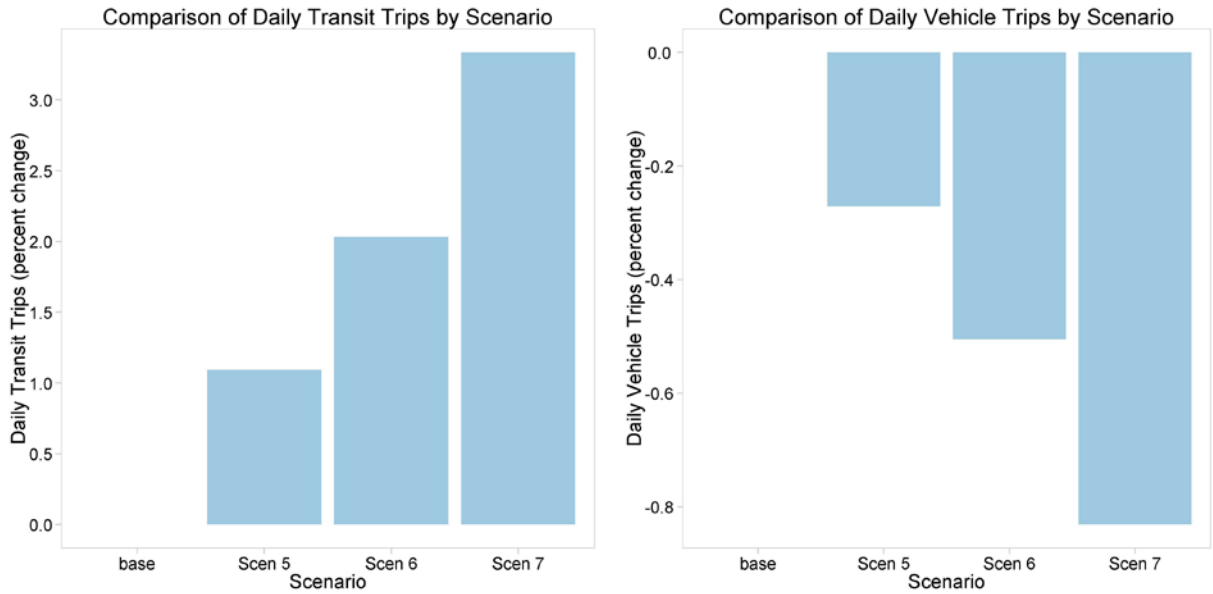


Figure 4-16: TRPC Percent Change Transit and Vehicle Trips for Base and Scenarios #5, #6, and #7

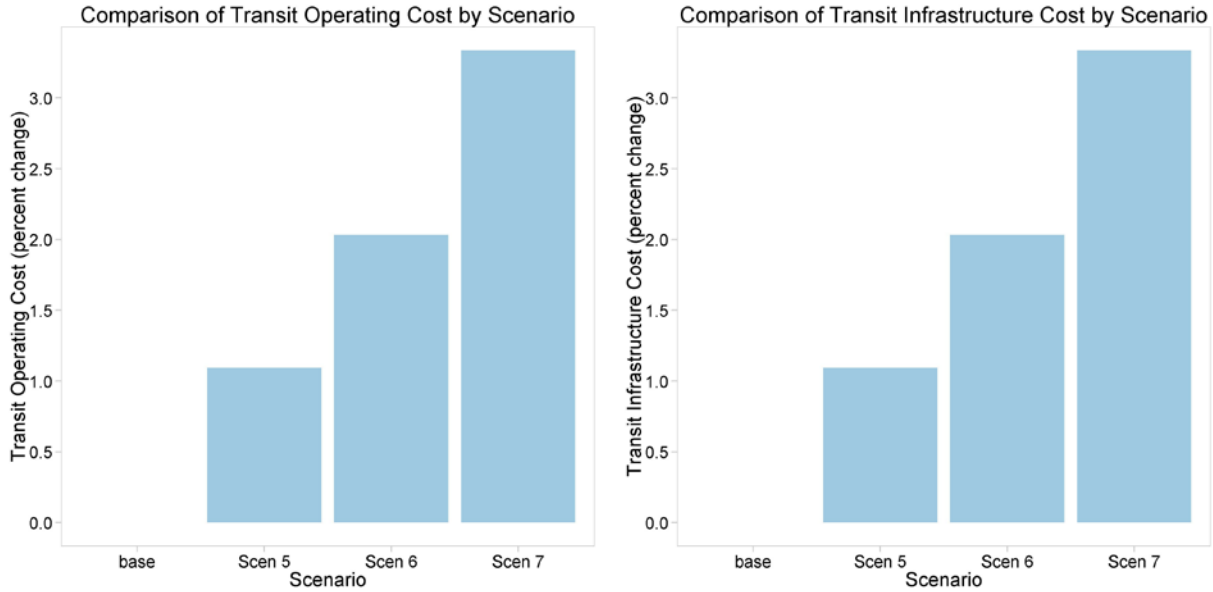


Figure 4-17: TRPC Percent Change Transit Operating Costs and Transit Capital Costs for Base and Scenarios #5, #6, and #7

Agency Comments

In addition to providing a complete set of input files and results for the eight standard scenarios, TRPC provided additional information on their experiences during the pilot tests and feedback on SmartGAP.

- **Software installation.** TRPC installed the software locally and then installed the software in a network location. They were able to successfully run the demonstration scenarios from both locations.
- **Employment data.** TRPC found that the preprocessed County Business Pattern employment data supplied with software does not cover enough of the total employment in their region to be accurate. It omits government employment, which is important in Olympia, the state capitol, and so requires augmentation with additional records to cover omitted employment types.
- **ITS strategy.** TRPC felt that the ITS strategy/policy is difficult to understand and interpret based on its description in the user's guide and its effects on the performance metrics.
- **Software performance.** TRPC found that software is very easy to prepare input tables for and to run, and runs very quickly. For the TRPC implementation of SmartGAP, scenarios take approximately 4 minutes on a relatively new desktop.
- **Software usability.** TRPC reported that they experimented with editing the inputs files in the file system rather through the GUI, but found that this caused some problems due to mistakes or typos in the file causing errors when the model was run. The GUI layout and the legibility of output charts can be affected by long scenario names.
- **Interpretation of results.** TRPC found the distinction between the two types of performance metrics – those that are sensitive to all input changes and those that are only sensitive to land use allocation changes – to be confusing. They found that, when changing only the transportation supply, the comparative output graphs showed no distinction between the scenarios for several of the metrics (which is as designed), but that differences when land use growth was redistributed were much more interesting across all of the metrics.

Test Implementation in Portland

Region Introduction

A fourth implementation of SmartGAP was developed in parallel to the three agency implementations. This implementation, based on the Portland metropolitan region, was used for model testing and to provide a fourth set of results from the standard scenarios. The specific region used for this test implementation is the three-county Portland, Oregon metropolitan area, comprised of all of Clackamas, Multnomah, and Washington counties (shown in Figure 4-18). The three county area had a 2005 (model base year) population of 1.5 million and 2035 projected population of 2.3 million (growth of 50%). Table 4-2 shows the breakdown by County.

Figure 4-18: Portland region Used for Testing of SmartGAP

Table 4-2: Portland Region Population in 2005 and 2035 by County

County	2005	2035	Growth
Clackamas	361,300	552,800	1.53
Multnomah	692,826	968,700	1.40
Washington	489,786	793,100	1.62
Total	1,543,912	2,314,600	1.50

Development of Model Inputs

The majority of the input data were derived from existing sources, such as the inputs to the Oregon statewide implementation of the GreenSTEP model. The data for the three-county metropolitan area were extracted from the complete set of GreenSTEP inputs that cover either each county in Oregon individually or each metropolitan area individually. A simple method was used to develop the place type allocation, with density thresholds used to divide households and employment into the four area types and asserted allocations made to the various development types for testing purposes. This approach for actual implementations is not recommended; the more detailed approach developed by ARC is preferable.

Figure 4-19 shows the distribution of employment (to the left) and population (to the right) by area type for the eight standard scenarios. For both employment and population, the distribution is held static for the first four scenarios and then growth is gradually shifted to towards close in communities and urban core. Figure 4-20 shows zero-based index charts for the same distributions to more clearly show positive and negative changes compared to the base scenario.

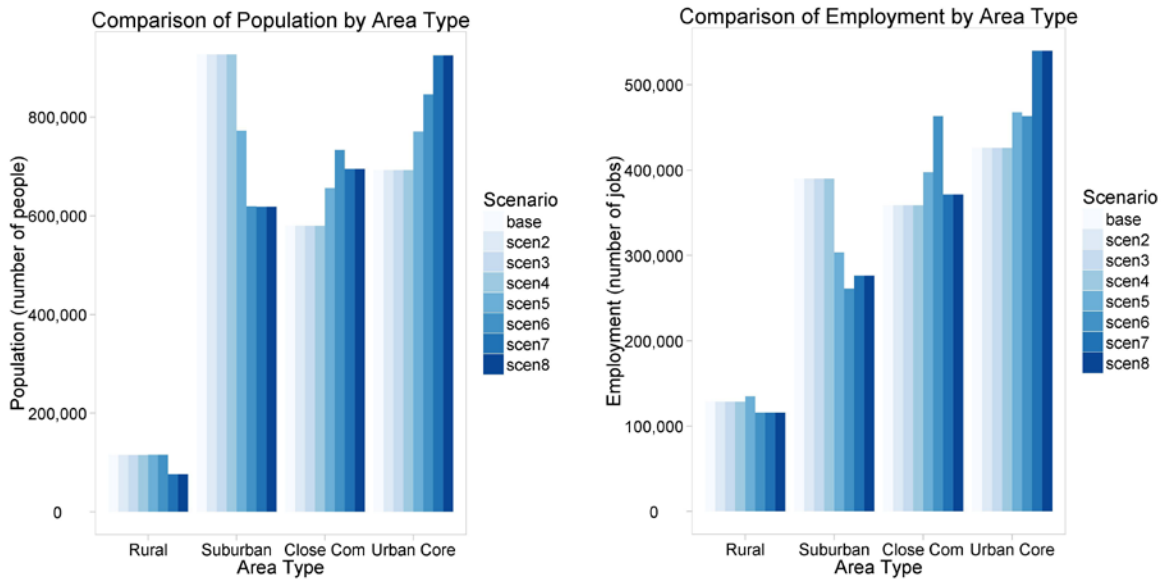


Figure 4-19: Portland 2040 Population and Employment by Area Type for 8 Standard Scenarios

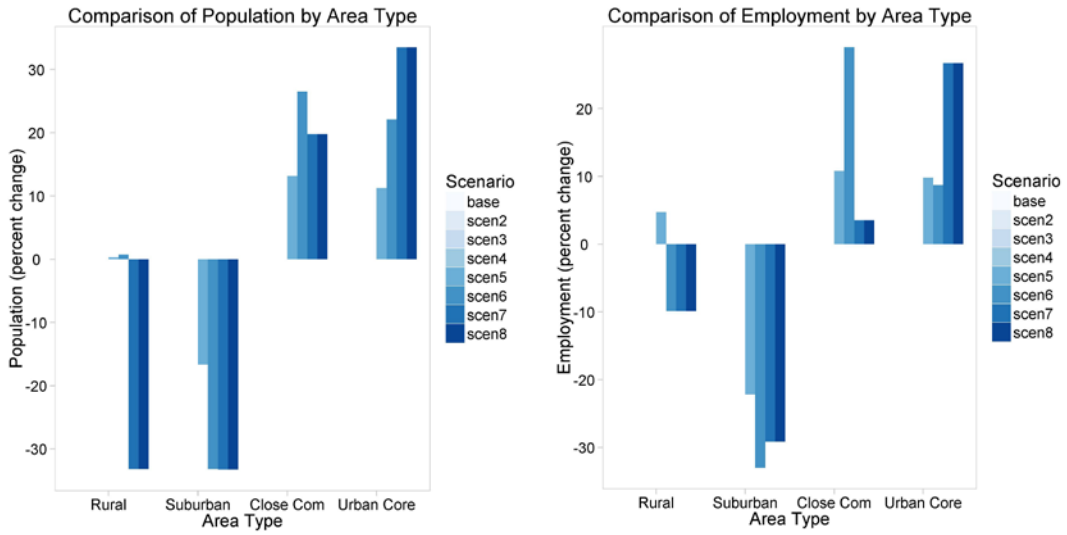


Figure 4-20: Portland Percent Change 2040 Population and Employment by Area Type from the Base for 8 Standard Scenarios

Scenario Testing Results

This section of the report presents the results of the eight standard scenarios for the Portland implementation of SmartGAP and also the results of two additional pricing scenarios that were defined and run. Figure 4-21 shows a comparison of daily VMT across the eight standard scenarios, with a comparison in terms of miles to the left and a zero-based index chart showing percentage changes to the right. The chart in miles shows that there are relatively small variations in total daily VMT across scenarios. The lowest daily VMT is for scenario #8 with the most land use growth focused in urban core and additional transit supply. The highest VMT is from scenario #3, with increased road supply. Given the relatively small variation in total daily VMT across scenarios, the percent change was plotted to show the changes more clearly than the chart to the left that show daily VMT totals. This chart shows that, in comparison to the base:

- Scenario #2, with more transit provided, leads to a decrease in VMT
- Scenario #3, with more highway supply, leads to a small increase in VMT
- Scenario #4, with the addition of ITS for incident management, does not affect VMT (the ITS policy is applied during the final estimation of policy adjusted congestion, after the policy adjusted VMT is calculated)
- Scenarios #5, #6, and #7, which gradually move growth in population and employment to close in communities and the urban core, result in increasingly larger reductions in VMT
- Scenario 8 shows the highest reduction, of 3%, as transit supply is increased and a high proportion of the growth is located in close in communities and the urban core

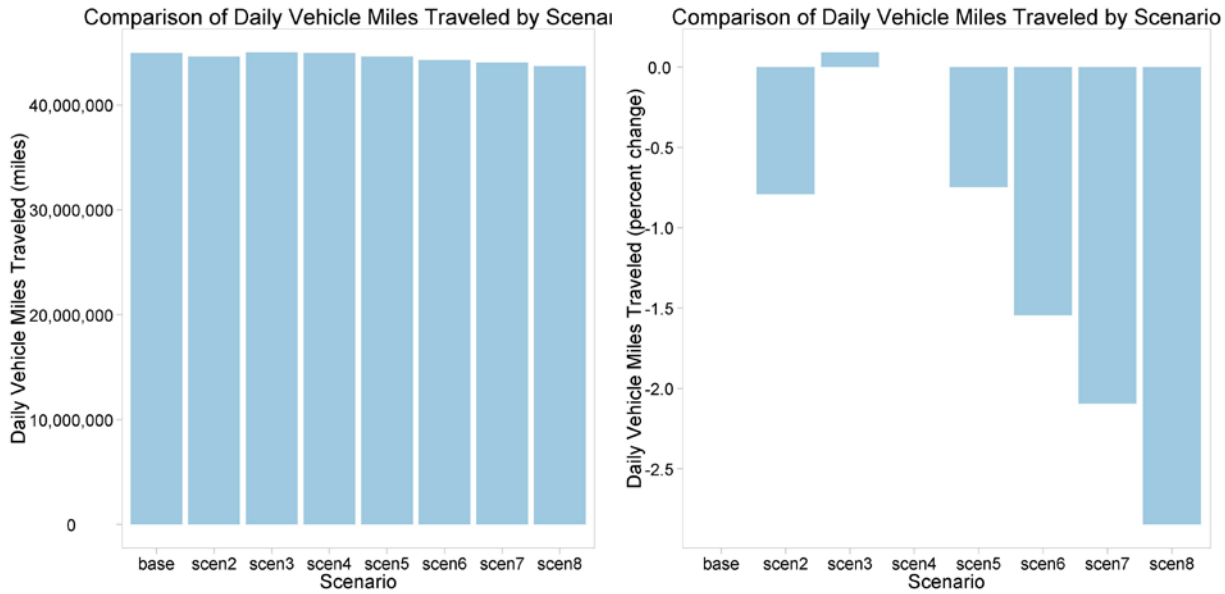


Figure 4-21: Portland Daily VMT by Scenario (Total and Percent Change from Base)

Figure 4-22 shows the effects on congestion (in terms of vehicle hours to the left and delayed vehicle hours to the right) by scenario. The total vehicle hours chart to the left (showing percentage changes relative to the base scenario) shows that scenario #4, where ITS is added to sections of highway, has a large impact on total vehicle hours by reducing non-recurring congestion (ITS is also applied as part of scenario #8). A similar pattern is seen in the chart to the right, as expected, which plot the absolute number of hours of delay due to congestion. The reductions are due to increased transit and denser, more mixed land uses reducing travel demand and to increased road supply increasing capacity, with the strongest effects due to ITS being implement to manage incidents and thus reduce non-recurring congestion.

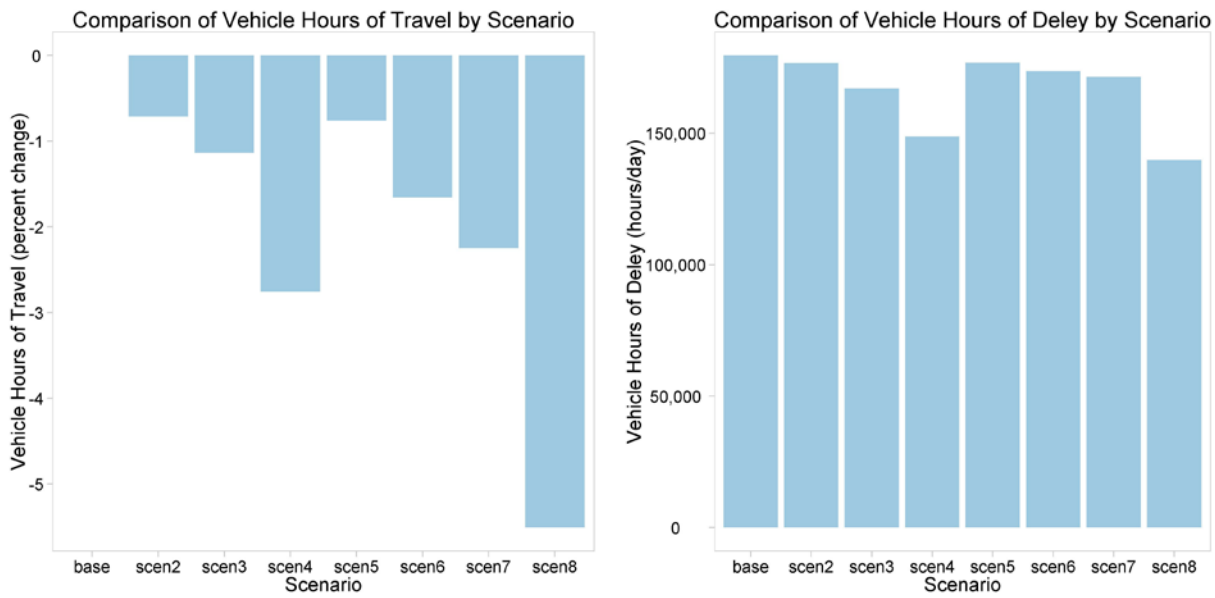


Figure 4-22: Portland Congestion Effects by Scenario (Percent Change from Base and Total)

The transit trips metric reports trips by new residents solely based on land use changes and does not relate to the transit revenue miles supplied as an input. Figure 4-23 shows that transit ridership (to the left) is highest in the urban core, particularly in the scenarios clustering most growth in urban core. The transit operating cost metric develops costs based on forecast usage and, as with the transit trips metric, is not based on the revenue miles supplied. The transit operating cost chart, to the right, shows that the highest operating costs are for the scenarios with growth in the urban core that lead to the highest transit use.

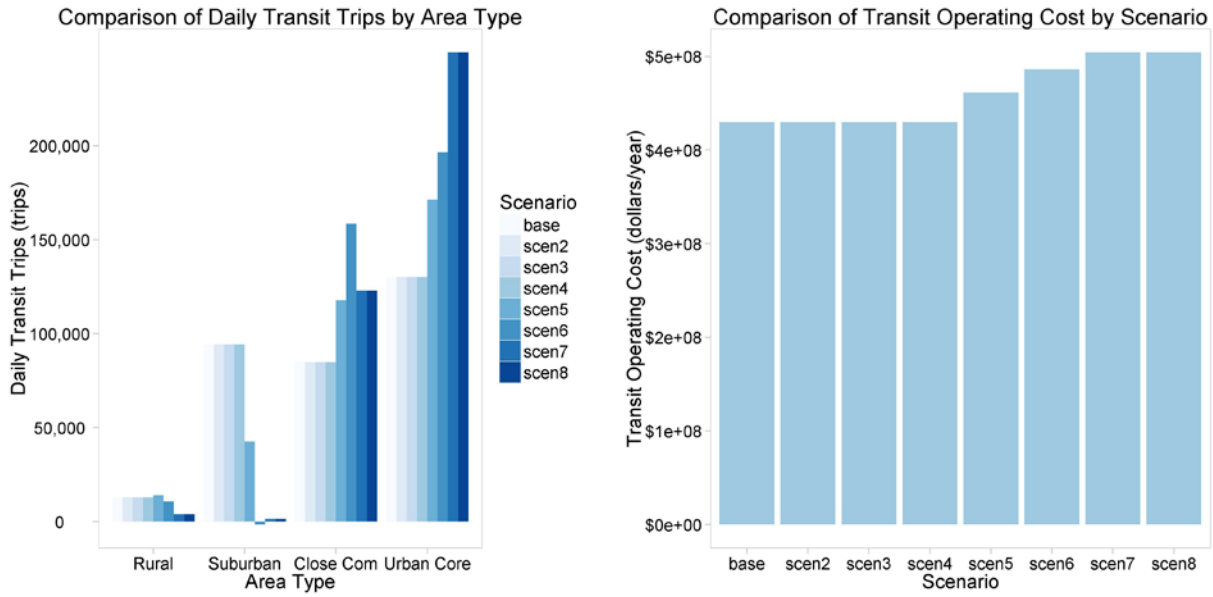


Figure 4-23: Portland Transit Trips and Costs by Scenario

The pattern of reductions in fuel use is affected by both changes in daily VMT and also changes in congestion, as that affects travel speeds and hence fuel economy. GHG emissions are estimated based on fuel use and so the changes in emissions track the changes in fuel consumption. Figure 4-24 shows a comparison of changes in fuel consumption by scenario (to the left) and changes in GHG emissions by area type for the base and scenarios #2, #3, and #4 (to the right). The comparison of fuel consumption shows that congestion reduction through ITS provision has a large impact. The total quantities of emissions by area type only change marginally for the scenarios without redistribution of land uses, reflecting the relatively small percentage changes shown in the fuel consumption results.

In addition to the eight standard scenarios, two pricing scenarios were tested, as defined in Table 4-3. The first of these, scenario #9, increased auto operating cost growth by 25% to test the sensitivity of the model to higher fuel costs. The second test, scenario #10, added a per mile VMT charge at a rate of 10 cents per mile, to test the sensitivity of the model to this form of road pricing.

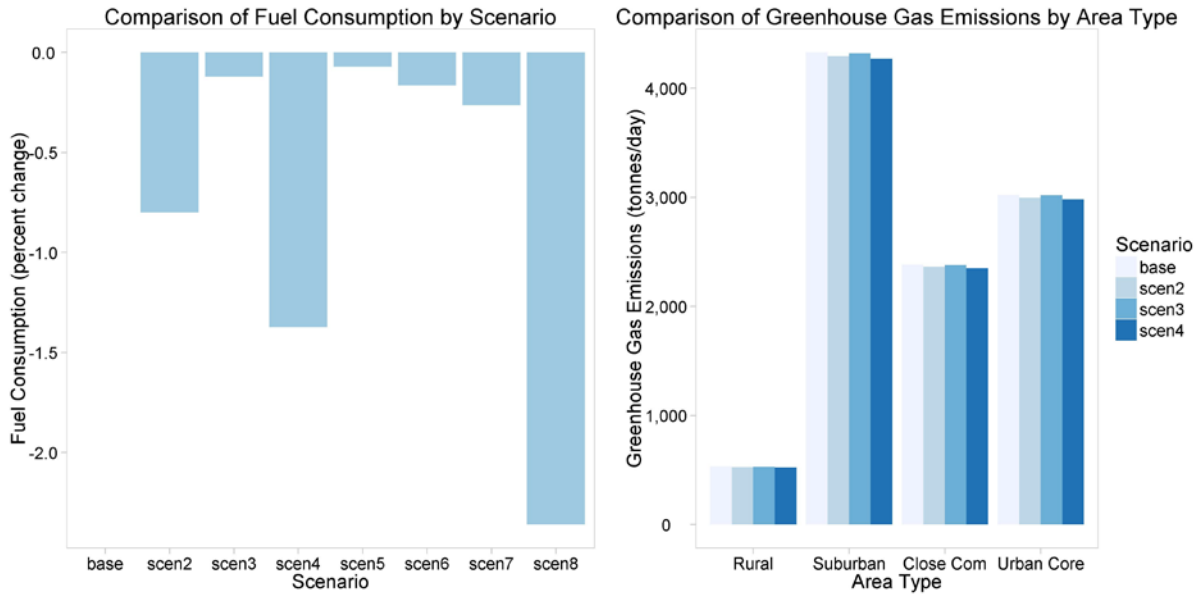


Figure 4-24: Portland Percent Change in Fuel Consumption and Total Greenhouse Gas Emissions by Scenario

Table 4-3: Pricing Scenarios

Scenario	Land Use	Transportation	Policy
#9. Increase Operating Costs	Baseline	Baseline	+ 25% auto operating cost growth
#10. Add VMT Charge	Baseline	Baseline	10 c/mile VMT charge

Figure 4-25 shows results for daily VMT by area type (to the left) and delay vehicle hours by vehicle type (to the right) for the base scenario and the two pricing scenarios. The results show that VMT pricing at this rate (10c/mile), which is the green series in the charts, has a stronger effect than the more modest increase in operating costs (i.e. higher fuel price), which is the blue series in the charts. Although truck VMT is not affected by these pricing policies (as the truck VMT model is only sensitive to regional income changes over time and not to transportation supply or other policy inputs), trucks experience less delay as they benefit from lower traffic levels on the roads. This effect is captured in the chart to the right that shows a reduction in delayed vehicle hours for trucks as well as for light vehicles.

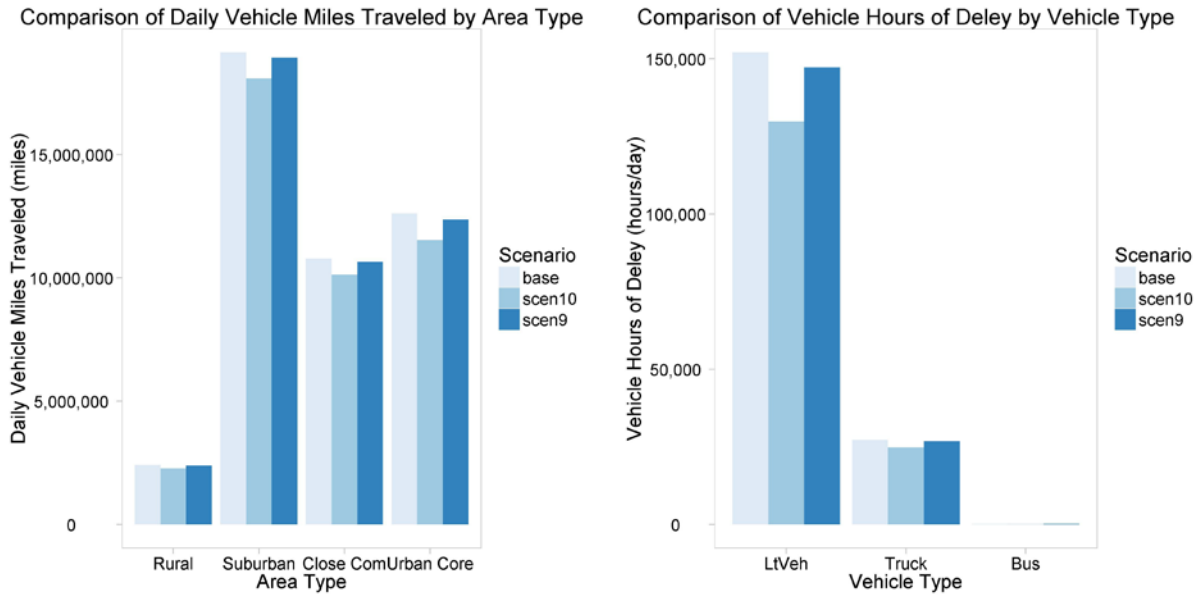


Figure 4-25: Portland Daily VMT and Delay Vehicle Hours for Pricing Scenarios

Research Findings

The model was implemented in Portland and efficiently run the standard scenarios and other scenarios. For the Portland implementation, scenarios took approximately 25 minutes to run on a relatively new desktop. The testing process was useful and led to two rounds of revisions to the model code being released to the pilot test agencies during the course of the pilot test. In general the results of the Portland scenarios appear reasonable and in line with expectations based on the intended sensitivity provided by the model's algorithms.

Summary of Pilot Test Findings

The five implementations of the SmartGAP model by three pilot agencies provided some valuable feedback on the performance and usability of SmartGAP and the supporting user's guide. Each agency provided a set of results and also additional comments. Some common findings are:

- The agencies were all able to install and run the software with relatively little difficulty, although some comments were provided that will assist with the packaging and distribution of the model.
- The performance of the model was good for the smaller agencies, but runtime and hardware (memory) requirements were more onerous for the large implementation of the model by ARC.
- Some of the input data, particularly employment data, was found to need better introduction and discussion in the user's guide. The preprocessed employment data, based on County

Business Patterns data, which was provided to the agencies, requires improvement as it omits certain employment categories.

- Each agency developed an approach, which varied greatly in terms of level of complexity, to allocate their population and housing to place types. The user's guide should include some information on different practical approaches than an agency might follow to develop the place type inputs.
- The results from the five implementations appear to be reasonable and consistent, with varying degrees of sensitivity to the policy changes depending on the levels of growth predicted in a region, the existing distribution of land uses, and the severity of the changes made in the test scenarios.

Table 4-4 provides an overall comparison of the percent change in daily vehicle miles traveled across the five pilot tests completed for all eight scenarios. The greatest reductions in vehicle miles traveled were in Cecil County, Maryland, because it is a rural county with high growth predicted, so smart growth strategies can have a larger impact than in other areas that are already mature. Atlanta also had a higher rate of reduction in VMT, which may be a result of the large size of this region (20 counties) which includes less mature areas of high growth. It should be noted that each agency interpreted the design of the standard scenarios themselves and each incorporated some amount of deviation from the precise scenario definitions, so the comparison presented in the table is illustrative and not a rigorous comparison.

Table 4-4. Comparison of Percent Change from Base in Daily VMT by Scenario for each Pilot Test

Scenario	Cecil County, Maryland	Montgomery County, Maryland	Atlanta Region	Olympia Region	Portland Region
#2	NA%	-0.7%	-1.1%	-0.6%	-0.8%
#3	+0.1%	+0.1%	+0.6%	+0.7%	+0.1%
#4	0%	0%	0%	0%	0%
#5	-3.2%	-0.3%	-2.9%	-0.4%	-0.8%
#6	-5.0%	-0.8%	-4.0%	-0.8%	-1.5%
#7	-9.0%	-1.3%	-4.5%	-1.2%	-2.1%
#8	-9.0%	-1.9%	-5.7%	-1.8%	-2.8%
#9	NA	NA	NA	NA	-1.4%
#10	NA	NA	NA	NA	-6.5%

The findings of the pilot tests supported the recommended enhancements to SmartGAP discussed in this report.

CHAPTER 5. SUMMARY

Research Findings

Initial research on key practitioner information needs provided a framework for evaluation smart growth strategies:

- Most agencies were interested in scenario planning as a strategy for evaluation smart growth.
- Many agencies need coordination, cooperation, and communication with local governments on land use policy, since land use regulations are governed by local governments.
- Agencies want to understand the impacts on performance as a result of induced demand, travel demand management strategy and urban form impacts as well as congestion reduction strategies.

Our research and products were therefore focused on developing a regional scenario planning tool that could be used by land use and transportation planners to provide opportunities for interaction on common goals. The scenario planning tool is able to assess the impacts of various travel demand management, urban form, congestion reduction strategies, as well as induced demand that arises from these.

There were five topics considered in the background research. In each case, research was conducted to identify and clarify well-established relationships that could be used in the evaluation of smart growth strategies. There were also gaps in the research that were identified for each topic. These gaps were also used to define useful capabilities in the SmartGAP software, although not all gaps were completely filled with this first version of SmartGAP.

Table 5-1. Summary of Background Research Relationships and Limitations

Topic	Well-established Relationships	Gaps in Research
Built environment impact on peak auto demand	Impact on daily travel	Impact by time of day
Mobility by mode and purpose	Impact on daily travel	Impact by trip purpose
Induced traffic and induced growth	Capacity expansion on an expanded facility	Route, time of day shifts and mode shifts, induced trips, new destinations, growth shifts; effects of operational improvements, land use plans
Relationship between smart growth and congestion	Localized effects	Macro-level or regional effects
Smart growth and freight	Freight is necessary for population centers	Impacts of loading docks, truck routing, full-cost pricing, freight facilities and crossings, inter-firm cooperation, stakeholder communication

SmartGAP Use

SmartGAP is intended for use by planning agencies that are involved in regional planning activities, such as regional/metropolitan planning agencies, state department of transportations, and local land use planning agencies. If all the agencies that are engaged in regional planning for a particular area were to use the same tool, with similar inputs, then collaboration would be more straightforward and decisions made regarding potential scenarios would be made on a consistent basis.

SmartGAP is designed to be easy to setup and use, so smaller planning agencies with fewer staff resources can make use of the tool. It is also envisioned that larger planning agencies may take advantage of the processing speed and relative ease of use to run multiple scenarios for screening purposes before more complex and time-consuming integrated land use and travel demand forecasting models are needed.

SmartGAP is delivered as a zip file and can be installed simply by unzipping the file to a location on your computer's hard drive. The zip file contains text files scripts, CSV input files, and .Rdata binary files for the models. SmartGAP is coded in R, which is an open source statistical software platform. SmartGAP uses several add-in packages to R, which it downloads automatically the first time it is run.

Future Enhancements to SmartGAP

During the course of the development of SmartGAP and the pilot testing, the TETG and the pilot testing agencies identified potential future enhancements to SmartGAP that could be considered at some point in the future. These were not identified as flaws, or major barriers to the current use of the modeling system, but enhancements that may expand the future usefulness. There were also short term enhancements that were identified and included in the current version of SmartGAP. These longer term enhancements were not possible within the first version of SmartGAP and are summarized here in three main areas:

Model Enhancements

- Expand the freight analysis capabilities to provide sensitivity in the model to freight smart growth strategies.
- Re-estimate models for different regions of the U.S. to recognize regional differences in model parameters. Re-estimate the household income models using more current national data (the current model is based on Oregon Census data from 2000).
- Expand the transit features to recognize different parameters by place type and to calculate transit per employment.
- Expand the modal representation to include other modes, such as taxi.
- Enhance the non-motorized mode features and include pedestrian travel more explicitly.

- Consider housing market response and household budgets as factors in the models that are sensitive to congestion and transportation and land use policies.
- Add residential and commercial building emissions to the existing method of estimating greenhouse gas emissions from transportation sources. Smart growth should have a positive impact on land use greenhouse gas emissions compared to conventional development.
- Add supporting infrastructure costs to the model, such as sewer, schools, local roads, which are needed to support new residential and commercial development. There is available research on this topic that can be used to estimate these costs.
- Include lifecycle costs, such as operations and maintenance, for highway infrastructure.
- Consider adding cost-benefit analysis to the system. For example, what is the return on an ITS investment compared to building new roads. This can currently be done outside the model using the available results, but may be useful to build in as a feature.
- Consider additional ITS policies (in addition to incident management) that could be included in the SmartGAP evaluation.
- Enhance the sensitivity of the performance metrics to transportation supply and congestion by including in the calculations of all the metrics (currently some metrics are calculated based on elasticities that are sensitive only to land use changes).
- Enhance the congestion module with improvements made to GreenSTEP providing more sophisticated support for pricing scenarios by transferring these improvements to SmartGAP.
- Enhance the truck modeling component to allow for sensitivity to policy changes.
- Add additional sensitivity to the model based on employment type (such as the allocation of jobs by industry type).
- Make speed improvements so that larger areas (in particular) can run the model more quickly. This could be achieved by code refactoring or evaluation of a weighted sample of households. L

Graphical User Interface Enhancements

- Replace the data editor window with a more functional and aesthetically improved object.
- Add charting of additional inputs and other calculated variables that are not part of the primary performance metric charting. Add functionality to compare across projects as well as across scenarios.
- Enhance error handling of file naming for inputs and layouts to be more friendly and useful.
- Add a scenario dashboard that can summarize all of the metrics in one view and that allows cross scenario comparisons for multiple metrics at once.

User Information, Data and Access Enhancements

- Provide a linked help system in addition to the user's guide (which is accessible in PDF form in the software).

These enhancements are recorded here to document the future possibilities that were considered, but were outside the original scope for the development of SmartGAP.

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APPENDIX A. PERFORMANCE METRICS AND APPLICATION TOOLS

APPENDIX A. PERFORMANCE METRICS AND TOOLS

LIST OF TABLES

LIST OF FIGURES

The Built Environment's Impacts on Peak Auto Demand

Performance Metrics

There are a variety of performance metrics for evaluating the effect of the built environment's impacts on peak auto demand. This section includes examples of metrics from state transportation departments and MPOs. Recent overviews of performance metrics, from the Pew Center on the States and the Rockefeller Foundation and from the Transportation Research Board's Sustainable Transportation Indicators Subcommittee, are also discussed.

The Florida Department of Transportation (FDOT) utilizes an in-house tool to inform highway expansion planning, and there are several performance metrics by which their tool evaluates projects. As described in *Strategic Investment Tool* (2008), FDOT uses five different Strategic Investment Tool (SIT) measures to evaluate projects: Safety and Security, System Preservation, Mobility, Economic Competitiveness, and Quality of Life.

In FDOT's SIT, Safety and Security is measured by four categories: 1) crash ratio, 2) fatal crashes, 3) bridge appraisal rating, and 4) connection to military bases. System Preservation is rated according to four measures: 1) volume/capacity ratio, 2) truck volume, 3) vehicular volume, and 4) bridge condition. Mobility is scored by nine measures: 1) connector location (evaluating a project based on its proximity to priority hubs and corridors), 2) volume/capacity ratio of a facility, 3) percent share of truck traffic relative to total traffic, 4) average annual daily traffic, 5) segment deficiencies that result in a system gap, 6) projected change in the volume to capacity ratio, 7) interchange operations (used only when evaluating interchanges), 8) bottlenecks and opportunities for grade separation, and 9) daily vehicle hours of delay. Economic competitiveness is measured by four indices: 1) Demographic Preparedness, 2) Primary Sector Robustness, 3) Tourism Intensity, and 4) Supporting Facilities. Quality of Life is assessed according to four measures: 1) land and social criteria (farmland impact, land use, and demographic impact), 2) Geology Criteria (sinkholes, historical site, contamination), 3) Habitat Criteria (conservation preservation, wildlife), and 4) Water Criteria (flood plains/flood control, coastal/marine, special designations, water quality, and wetlands).

The MetroPlan Orlando 2030 *Long Range Transportation Plan* analyzed a smart growth land use scenario that "emphasizes compact development, infill and redevelopment, mixing land uses, improved jobs to housing balance within compact urban travel sheds and configurations that support multi-modal transportation" (2). The effectiveness of this alternative land use strategy was evaluated based on Vehicle Miles Traveled (VMT), Vehicle Hours Traveled (VHT), suburban expansion, and the utilization of commuter rail infrastructure.

For the Delaware Valley Regional Planning Commission's (DVRPC) 2025 long range transportation plan, *Connections: The Regional Plan for a Sustainable Future*, alternative scenarios were compared for a variety of transportation performance metrics, including VMT, vehicle trips, crashes, peak period roadway speed, transit trips, person hours of delay, delay per capita, pedestrian trips, and bicycle trips.

Metro, the Portland area MPO, articulates several transportation-related performance targets in their 2035 *Regional Transportation Plan*. For congestion, the goal is to reduce 2035 vehicle

hours of delay (VHD) by 10 percent relative to 2005. For travel, the goal is to reduce 2035 VMT by 10 percent compared to 2005. Metro is not expected to meet either of these targets. While small reductions in VMT are projected, they do not reach 10 percent. VHD are projected to increase dramatically, far above the target of a 10 percent reduction.

The Washington State Department of Transportation (WSDOT) produces an annual report analyzing highway performance according to various metrics. For example, *The 2010 Congestion Report* describes several metrics for evaluating the performance of the transportation system. System-wide congestion indicators include VMT, VMT per capita, congested lane miles of highway, percent of highway system congested, VHD, and VHD per capita. Corridor-specific congestion indicators include the number of routes where the duration of the congested period improved, the number of routes where average peak travel time improved, and the number of routes where 95 percent reliable travel time improved.

A 2011 report published by the Pew Center on the States and the Rockefeller Foundation provides a high level overview of performance metrics that guide transportation decision-making at the state level. The report, entitled "Measuring Transportation Investments: The Road to Results," focuses on six goals that are both important and widely used across the country. These six goals are Safety, Jobs and Commerce, Mobility, Access, Environmental Stewardship, and Infrastructure Preservation. The performance measures associated with these goals comprise an inventory of the most commonly used metrics for assessing transportation systems in the 50 states and Washington, D.C.:

- Safety: fatalities, injuries, crashes, infrastructure related (hazard index, high crash areas), response to weather emergencies
- Jobs and Commerce: jobs created, freight tonnage or ton-miles or by value, freight travel times/speeds, infrastructure support for freight movement, business access to freight services
- Mobility: congestion/density, delay, travel times/speed, travel time reliability, accident response, transit on-time performance
- Access: access for elderly, disabled and low-income populations, access to multimodal facilities and services, access to jobs and labor, access to non-work activities
- Environmental Stewardship: emissions, fuel consumption/alternative fuels, air quality, water quality, recycling
- Infrastructure Preservation: road condition, bridge condition, remaining life of roads and bridges, rail system condition, transit vehicle condition

Performance metrics can help to chart a community's progress, but they can also serve to entrench the status quo. One example of this is a recent table of metrics recommended by the Transportation Research Board's Sustainable Transportation Indicators Subcommittee. It includes in its "Most Important (Should usually be used)" category the following economic indicator: "Personal mobility (annual person-kilometers and trips) and vehicle travel (annual vehicle kilometers), by mode (non-motorized, automobile and public transport)" (Litman 2010). While it is helpful to monitor the effects of the built environment on trip making, uncritically citing decreased auto trips and VMT as an indicator of economic loss to be guarded against may work against the goals of smart growth.

Application Tools

State DOT Strategies

State DOT methods for addressing smart growth often take the form of a strategy. For example, FDOT's SIT is a methodology "for determining project priority and is applicable only to evaluating and setting priorities for highway capacity expansion projects" (Florida Department of Transportation, 2008). There are three main SIT components: 1) a System Viewer, which provides background data, short and long term plan schedules, and a document library of former studies; 2) an Analyzer, which evaluates performance measures; and 3) a Reporter, which displays results in various formats graphical and interactive interfaces.

The most relevant planning tool on the New York State Department of Transportation (NYSDOT) Smart Growth Program website is a qualitative checklist for the application of smart growth principles to proposed development projects. The eight sections of the NYSDOT Smart Growth Checklist tool include: 1) locating the proposed project near existing infrastructure; 2) providing a range of housing options; 3) protecting open space, farmland, and critical environmental areas; 4) providing a mix of land uses; 5) providing multiple transportation and access choices; 6) designing for walkability and personal interaction; 7) respecting community character; and 8) planning for economic and environmental sustainability. Although the Smart Planning Program is promoted by NYSDOT, its intention is to enable community members to determine "whether a proposed project is likely to contribute to the overall well-being" of their community.

The Pennsylvania Department of Transportation (PennDOT), in its 2010 publication *Improving the Land Use—Transportation Connection through Local Implementation Tools,* states that "Effective comprehensive plan implementation—most specifically within integrated transportation/land use elements—can enhance the function of the overall transportation system by promoting multimodal travel and minimizing the demand for single occupancy trips that congest our system at peak travel times." The following are listed as Applicable Tools for achieving these goals: Access management, site design and roadway standards, traffic operations, zoning for mixed use and density, parking system management, Transit Revitalization Investment Districts, joint municipal zoning ordinances, Urban Growth Areas and rural preservation, and zoning overlays.

Comprehensive Land Use-Transportation Planning Tools

There are a variety of commercially available comprehensive tools for land use-transportation planning. These tools include CommunityViz, Envision Tomorrow, iPLACE^{3}S, INDEX, Urban Footprint, Rapid Fire, MetroQuest, and TREDIS. Additional transportation-land use tools, such as MXD-P, MXD-V, direct ridership models (DRM), best management practices (BMP), and the Southern California Association of Governments (SCAG) TDM Tool, are sensitive to the effect of transportation policies and development scenarios on travel demand. A matrix of the tools and their capabilities (verified by tool providers) is presented in Table A-1. Capabilities are noted by type as well as by scale, depending on their applicability to regions, sub-regions and corridors, or neighborhoods and communities. Please note that the discussion below is supplemented with additional coverage of tool characteristics and capabilities in subsequent topic-specific chapters

(mobility by mode and purpose, induced traffic/growth, and smart growth and congestion topic areas).

These tools typically provide adequate representation of land use data and transportation facilities, as well as the relationship between the built environment and travel demand. Less frequently included in these tools is the ability to reflect demand management, the influence of demand and supply on congestion, or feedback loops for determining induced growth or induced travel. These tools provide a wide range of metrics that is often specific to their area of focus. For example, Urban Footprint produces metrics related to local infrastructure costs, while the DRM estimates transit trips. Additional metrics may be available through customized programming of tools.

Each of these tools has been used by at least a handful of MPOs and/or at a State level to perform interactive smart growth scenario evaluations of a broad array of social, economic and environmental indicators. Many of the tools perform analysis of transportation and other effects, while several (MetroQuest, TREDIS, CommunityViz) serve primarily as visualization platforms for standard transportation modeling. These tools may also be distinguished from one another by the scale at which they operate, the specific data they require and the performance indicators they produce. In terms of scale, the different tools operate at one or more of the following levels:

- Development project or transit station area TOD (micro)
- Corridor/ community (meso)
- County or regional (macro)

Table A-1 identifies the analysis scale and data requirements of each of these application tools. Table A-2 includes the performance metrics that each of application tools will produce. For most prospective users, selection of the most appropriate tool would be a matter of selecting the tool that best addresses the scale(s) of analysis and list of indictors desired and the available data, based on information in the table, as well as logistical questions such as cost, resources required and customer support. The data availability subject is addressed in the table in general terms usually under consideration in smart growth scenario planning and evaluation: the land use aggregation level and unit of analysis, and the extent that the model represents the regional transportation network.

These tables also includes a set of simpler evaluation tools that can be used to selectively produce quick-response indicators of the effects of land use and transportation strategies at various scales on specialized sub-sets of performance metrics:

- MXD-P (project/plan)
- MXD-V (vision/region)
- DRM
- BMP
- SCAG TDM Tool

Table A-1. Capabilities of Planning Tools for Evaluating Interactions between Land Use and Transportation

	Macro Regional												Meso Sub-regional /corridor												Micro Neighborhood/community											
	CV	ET	iP	IN	UF	RF	MQ	TR	MXP	MXV	DRM	BMP	TDM	CV	ET	iP	IN	UF	RF	MQ	TR	MXP	MXV	DRM	BMP	TDM	CV	ET	iP	IN	UF	RF	MQ	TR	MXP	MXV	DRM	BMP	TDM
Land Use Representation																																								
Place-types	▪	▪	▪	▪	▪	▪	▪	▪						▪	▪	▪	▪	▪	▪	▪	▪						▪	▪	▪	▪	▪		▪	▪					
Parcel Based	▪		▪	▪	▪		▪	▪						▪	▪		▪	▪		▪	▪						▪	▪	▪	▪	▪		▪	▪					
Grid-Cell Based	▪	▪		▪	▪		▪	▪						▪	▪		▪	▪		▪	▪						▪	▪		▪	▪		▪	▪					
Census Block	▪	▪		▪	▪		▪	▪						▪	▪		▪	▪		▪	▪						▪	▪		▪	▪		▪	▪					
TAZ	▪			▪			▪	▪						▪			▪	▪		▪	▪						▪			▪				▪					
Major Transport Net Representation																																								
Internal major multi-modal net				▪			▪	▪									▪			▪	▪									▪				▪					
Shares data w network model	▪	▪	▪	▪	▪	▪		▪						▪	▪	▪	▪	▪	▪		▪						▪	▪	▪	▪	▪		▪						
Only local connectivity and transit stations	▪			▪			▪							▪			▪			▪							▪	▪		▪	▪		▪						
Relationships Addressed																																								
Built Environment →Demand	▪	▪	▪	▪	▪	▪	▪	▪		▪				▪	▪	▪	▪	▪	▪	▪	▪	▪	▪				▪	▪	▪	▪	▪		▪			▪			
Demand Mgmt → Demand	▪				▪			▪			▪		▪	▪		▪		▪			▪		▪	▪		▪	▪				▪			▪		▪			▪
Demand+Supply→ Congestion					▪			▪										▪			▪												▪	▪					
Feedback/ Induced Growth							▪	▪												▪	▪																		
Feedback/ Induced Travel								▪													▪																		
Freight								▪													▪																		

Comprehensive, Multi-Issue Land Use Transportation Planning Tools

CommunityViz (CV) Envision Tomorrow (ET) iPLACE^{3}S (iP) INDEX (IN) Urban Footprint (UF) Rapid Fire (RF) MetroQuest (MQ) TREDIS (TR)

Transportation/ Land Use Interactive Effect Tools

MXD-P (project/plan) (MXP) MXD-V (vision/region) (MXV) DRM (DRM) BMP (BMP) SCAG TDM Tool (TDM)

Table A-2. Performance Metrics of Planning Tools for Evaluating Interactions between Land Use and Transportation

	Macro Regional													Meso Sub-regional /corridor												Micro Neighborhood/community											
	CV	ET	iP	IN	UF	RF	MQ	TR	MXP	MXV	DRM	BMP	TDM	CV	ET	iP	IN	UF	RF	MQ	TR	MXP	MXV	DRM	BMP	TDM	CV	ET	iP	IN	UF	RF	MQ	TR	MXP	MXV	DRM	BMP	TDM
Daily Vehicle Trips and VMT	▪		▪	▪	▪	▪			▪	▪				▪		▪	▪	▪	▪	▪		▪	▪				▪		▪	▪	▪		▪		▪				
Daily Transit Trips or Share	▪		▪	▪	▪						▪			▪		▪	▪	▪		▪				▪			▪		▪	▪	▪		▪					▪		
Vehicles by Purpose, Peak	▪				▪				▪	▪				▪				▪		▪		▪	▪				▪				▪		▪		▪				
VHT, VHD, Emissions, Energy	▪		▪	▪	▪	▪			▪	▪				▪		▪	▪	▪	▪	▪		▪	▪		▪		▪		▪	▪	▪		▪		▪	▪	▪		
Traveler Cost	▪				▪	▪		▪						▪				▪	▪		▪						▪				▪								
Development Cost	▪		▪	▪	▪		▪	▪						▪		▪	▪	▪		▪	▪						▪		▪	▪	▪		▪						
Transp. System/Service Cost							▪	▪												▪	▪													▪					
Location Efficiency	▪			▪	▪			▪						▪			▪	▪			▪						▪				▪		▪						
Economy, Prop. Values, Jobs	▪		▪			▪	▪							▪		▪			▪	▪							▪		▪		▪		▪						
Environment and Equity	▪			▪	▪	▪	▪	▪						▪			▪	▪	▪	▪	▪						▪			▪	▪		▪						
Livability, Comm. Character	▪			▪	▪	▪	▪	▪						▪			▪	▪	▪	▪	▪						▪			▪			▪						
Building Energy Use, Emissions	▪					▪								▪					▪								▪												
Building Water Use, Emissions	▪					▪								▪					▪								▪												
Public Health Impacts, Costs	▪					▪								▪					▪								▪												
Local Infrastr.Costs (Capital, O&M)	▪					▪								▪					▪								▪												
Local/jurisdictional revenues	▪					▪								▪					▪								▪												
Land Consumption	▪					▪								▪					▪								▪												
Fiscal Impact	▪													▪													▪												
Resource Usage, Waste Gen.	▪													▪													▪												
Housing Affordability	▪													▪													▪												

Comprehensive, Multi-Issue Land Use Transportation Planning Tools
CommunityViz (CV) Envision Tomorrow (ET) iPLACE^{3}S (iP) INDEX (IN) Urban Footprint (UF) Rapid Fire (RF) MetroQuest (MQ) TREDIS (TR)
Transportation/ Land Use Interactive Effect Tools
MXD-P (project/plan) (MXP) MXD-V (vision/region) (MXV) DRM (DRM) BMP (BMP) SCAG TDM Tool (TDM)

These transportation/ land use interactive effect tools are primarily spreadsheets, some with interactive dashboards, which have been used in local and regional smart growth analysis in various parts of the US. In some cases these tools pivot from baseline analyses produced by more sophisticated analysis models, Their data requirements are much more limited than those of the multi-issue land use transportation planning tools described above.

Travel Demand Models

The California Transportation Commission (2010), in a recent set of guidelines, provides the following summary of travel demand models:

"Travel demand models are statistical and algorithmic attempts to predict human travel behavior. They endeavor to forecast potential outcomes of various transportation scenarios. Travel demand models provide essential information about the region's transportation system operations, conditions and performance and they are used to predict future transportation needs. Typical factors that are included in travel demand models are a region's demographic profile, general plan designations, highway and transit networks, distribution of trips and existing travel patterns including morning and evening peak hour travel demand, trip generation, and split among automobile (Single Occupancy Vehicle and High Occupancy Vehicle), transit, bicycle, and pedestrian modes of travel" (p. 35).

Conventional four-step models remain the most common modeling approach to forecast peak auto demand. A conventional four-step model is based on the individual trip, and is defined by four steps: trip generation, trip distribution, mode choice, and trip assignment. Socio-economic (household and population) data and/or land use data is translated into AM and PM peak period trips on highway networks and daily boardings on transit networks. Without significant enhancements or off-model adjustments, most four-step models cannot adequately produce hourly volumes and hourly speeds (TRB, 2007).

A review of the conventional travel-forecasting process used in California and throughout the U.S. identified a variety of limitations in the model systems regarding smart-growth analysis. DKS Associates et al. (2007), in their assessment of models' smart growth capabilities, describes the current limitations:

"1. Few local jurisdictions in California use models that have sensitivity to smart-growth strategies. Most jurisdictions use models that: (a) lack the capability to estimate transit use or carpooling; (b) do not include representation of walking or bicycling trips; and/or (c) do not allow for variation in vehicle trip rates based on land-use density, mix, or design.

2. Local jurisdictions using Metropolitan Planning Organization (MPO) or Congestion Management Agency (CMA) travel demand models that have "moderate- to high-sensitivity" can capture some of the smart-growth sensitivity, but to what degree is not clear.

3. GIS systems for local jurisdiction land-use and transportation system characteristics are making it possible to bring more information into the Urban Transportation Modeling System (UTMS) modeling process, and that has the potential to increase smart-growth sensitivity. This includes parcel-level land-uses and GIS layers for street systems, bicycle routes, sidewalks,

topography, environmentally sensitive areas, etc. GIS systems are also facilitating the application of supplemental methods such as I-PLACE^{3}S and INDEX (DKS Associates et al., 2007).

Because of the current lack of smart-growth sensitivity in many models, research has been conducted to develop supplemental tools to provide the missing sensitivity. Over the past 15 years, a series of studies have used cross-sectional analyses of variations in travel patterns for zones in major metropolitan areas. These research efforts have documented how four key factors influence the rate of vehicle use per capita" (DKS Associates et al., 2007).

"The four key factors are often referred to as the "4Ds." They include:

- Density – population and employment per square mile
- Diversity – the ratio of jobs to population
- Design – pedestrian environment variables including street grid density, sidewalk completeness, and route directness
- Destinations – accessibility to other activity concentrations expressed as the mean travel time to all other destinations in the region

Research that resulted in the 4Ds characteristics also produced estimations of "elasticities" regarding vehicle travel per capita with respect to changes in each of the 4D variables. These elasticities have been used in a variety of application tools to assess the potential vehicle travel reduction benefits of smart-growth land-use strategies" (DKS Associates et al., 2007).

The DKS Study defines three ranges of modeling improvement regarding sensitivity to smart growth strategies, ranging from low sensitivity to high sensitivity (DKS Associates et al., 2007). Among the high-sensitivity models are those commonly referred to as tour- or activity-based models. Activity-based models are more sensitive to transportation policies, such as pricing, parking, or demand management, than trip-based models. This sensitivity arises from linking travel together over the course of the day in such a way that a policy that influences a round trip (such as the cost of parking at the destination) will be sensitive to all aspects of that round trip.

The California Transportation Commission (CTC) concludes as follows:

"Additional research and development attention is being directed to tour/activity-based modeling, an approach which is believed to be a significant advance over the traditional trip-based modeling approach. Tour/activity-based models better recognize the complex interactions between activity and travel behavior. These models require more information on travel activity, particularly travel time, focusing on the trip chains and the sequences of activities in the chain, and need more detailed data on person and household travel characteristics. These models also require significant time investments in data assembly and model development and resources, which are major challenges typically best addressed by the largest MPOs. Because of these formidable challenges, only a handful of major MPOs across the country are in the relatively early stages of tour/activity-based model development and/or implementation. The mainstream and the state-of-the-practice in travel demand modeling still remains the traditional 4-step trip-based models. However, there are significant add-ons and enhancements to this approach that

can improve land use/transportation assessment capabilities" (California Transportation Commission, 2010).

Examples from the CTC of significant add-ons and enhancements for assessing land use/transportation interaction include post-processing model outputs where models are insensitive to certain policies or factors (such as the Ds) and including feedback loops that account for the effects of congestion on mode choice, induced demand, and induced growth (California Transportation Commission, 2010).

The recent TRB meta-analysis of advanced travel forecasting practices points out that SACOG selected an activity-based model, in part, due to its anticipated advantages in documenting how the built environment affects travel decisions. The structure of four-step models can sometimes hinder the meaningful comparison of alternative land use scenarios at associated with finer-grained changes. SACOG's activity-based model was able to demonstrate, for one particular large development, how a denser development option produced less VMT than an alternative spread option. This approach could presumably extend to peak hour congestion comparisons as well (TRB, 2010).

Travel Demand Models and Post-Processing

Given the dearth of empirical evidence on smart growth and peak travel, large-scale, regional forecasting models might be the best framework available for tracing the travel-demand impacts and congestion (reducing or inducing) effects of smart growth. Still, most large-scale models fail to capture the trip-reducing benefits of smart growth (Cervero, 2006). Four-step models were never meant to estimate the travel impacts of neighborhood-scale projects or development near transit stops. Their resolution tends to be too gross to pick up fine-grained design and land-use mix features of neighborhood-scale initiatives like new urbanism and TOD. For these and other reasons, it is often necessary to "post-process" initial estimates to reflect more recent empirical evidence. Differences between the do-nothing versus do-something (i.e., smart growth) scenarios are the best gauge of traffic congestion impacts.

Post processing normally involves pivoting off of four-step model outputs, using elasticities to account for effects (such as those of land-use variables) not specifically accounted for in models. Post-processing has been used to fine-tune generic model estimates to reflect local conditions (Fehr & Peers, 2005), assess alternative regional growth scenarios involving jobs-housing balance (Kuzmyak, 2006), and predict daily traffic for land use and transportation options along proposed multi-modal corridors (Fehr & Peers, 2004). In the case of the planned Legacy Parkway west of Salt Lake City, elasticities from national research on "Traveler Responses to Transportation System Changes" were used to pivot off of four-step forecasts to refine estimates (Kuzmyak et al., 2003).

One of the more notable examples of post-processing was to study the travel impacts of redeveloping the Atlantic Station site in central Atlanta (Walters et al., 2000). The Atlanta region's nonconformity with federal clean air standards held up progress on the project by freezing federal financial assistance for supporting improvements, including a pedestrian bridge to a nearby subway station. The developer argued that a mixed-use infill project near rail transit would yield air-quality benefits by housing population that would otherwise live less centrally,

and be more car-dependent. Consultants hired to estimate the travel impacts of the Atlantic Steel proposal quickly realized that the four-step model was not up to the task. Thus, four-step model outputs were post-processed. Studies from the San Francisco Bay Area (Cervero and Kockelman, 1997), metropolitan Portland (Lawton, 1998) that found the 3 Ds -- density, land-use diversity, and pedestrian-friendly designs -- reduced vehicle trip rates and VMT were used to adjust trip-generation and mode-choice estimates. Through these modifications, the proposed Atlantic Steel location was estimated to reduce future travel by as much as 52 percent compared to a greenfield location. Post-processing results were pivotal in EPA's decision to give the Atlantic Steel project a green light.

Some of the major shortcomings of post-processing approaches include:

- Most adjustments are made only for the residential production end of trips, and do not take into account the effects of what is happening at the destination end – which obviously must affect the choice of destination (where that is an option) as well as choice of mode to access the destination (more alternatives to balanced 4Ds locations, higher costs of driving/parking, less need for a car while at the site).
- Some post-processors estimate only change in VMT, which makes it virtually impossible to ascertain what is happening on the surrounding road network.
- Even those post processors that estimate changes in trips by mode (in addition to VMT) lack the capacity to account for what destinations in the trip table are being affected.
- Most models do not differentiate between work and non-work trips, which appear to be affected by different sociodemographic and land use characteristics and at different magnitudes.
- None of the post-processor approaches differentiate travel by time of day.

As a result of the above, the adjustments made through the post-processor models miss a large part of the behavioral construct through which smart growth impacts travel choice. In general, it is anticipated that the predicted benefits are much less than would happen in reality.

Mobility by Mode and Purpose

Performance Metrics

Although they do not typically differentiate by trip purpose, a growing number of transportation agencies have formulated performance metrics for multiple modes of travel. FDOT developed the Quality/Level of Service Handbook in 2009 based on the *2000 Highway Capacity Manual* (HCM), Transit Capacity and Quality of Service Manual (TCQSM), Bicycle LOS Model, and Pedestrian LOS Model. The Bicycle LOS model evaluates roadway segments and requires a variety of data including average daily traffic, percent heavy vehicles, number of lanes of traffic, posted speed limit, total width of pavement, on-street parking presence and occupancy, outside lane width, pavement condition, and presence designated bike lane. The Pedestrian LOS model evaluates the width of the outside lane, the width of the shoulder, presence of on-street parking, presence and type of buffer between the walk and a roadway, buffer width, presence of a sidewalk, sidewalk width, traffic volumes, peak hour factor, number of travel lanes, and average

speed. Although each of the methodologies makes use of the LOS A-F scales, the meaning of A-F is not consistent across the modes.

Smart Mobility 2010, produced by the California Department of Transportation (Caltrans) includes several smart mobility goals, including reliable mobility and location efficiency. Metrics for reliable mobility include travel times and costs by mode between representative origins and destinations, the day-to-day range of travel time variability between representative origins and destinations, and mode-specific assessments of the quality of service (multi-modal LOS). Metrics for location efficiency include supporting sustainable growth through compliance with regional performance standards; percentage of trips within a corridor or region occurring by high occupancy transit vehicle; households located 30 minutes by transit from employment, 20 minutes by car from employment, and walking distance from schools; and the weighted travel time and cost between trip producers and attractors.

The Denver Regional Transportation District's *Quality of Life Study (2008)* provides another example of mobility metrics by mode. Under the objective of improving travel choices and accessibility, several mode-specific measures are listed. Transit measures include access and egress mode, population within walking distance of transit, employment within walking distance of transit, miles of rapid transit facilities, revenue hours of ADA service, and transit revenue hours. Auto metrics include park-and-ride capacity and utilization. Bicycle metrics include bike-on-bus usage, station bicycle access. Pedestrian metrics include station pedestrian access.

Application Tools

There is a small field of emerging tools for measuring performance by mode and trip purpose, including the 2010 Highway Capacity Manual, I-PLACE^{3}S, and Urban Footprint. Recent federal research into multimodal LOS (NCHRP 3-70) has resulted in publication of a proposed set of methodologies to analyze LOS for auto, transit, bicycle, and pedestrian modes in the *2010 Highway Capacity Manual* (HCM) (TRB, 2010b). The study conducted video laboratories and field surveys involving the general public from four urban areas and then developed a LOS model for each of the four modes (auto, transit, bicycle, and pedestrian). The models were calibrated and validated to observed data and were found to match the public's perception better than the *2000 HCM*. The method provides an integrated LOS modeling system where changes to a single variable can be quickly evaluated for their effect on each modal LOS.

I-PLACE^{3}S is a model that uses real-time GIS to analyze and display the results of different land use scenarios. An option is available in I-PLACE^{3}S to apply the 4Ds (density, diversity, design, and destinations) to estimate travel behavior based on land use change. Specifically, I-PLACE^{3}S can measure how different land use scenarios for a given travel network can affect travel behavior indicators such as VMT, vehicle trips per household, and mode choice, based on the 4D factors. I-PLACE^{3}S reports percent change indicators that include transit and bike/walk shares.

Urban Footprint uses GIS to create and evaluate physical land use-transportation investment scenarios. The model defines future scenarios through a common set of "Place Types," a range of development types and patterns that varies from higher density mixed-use, to single-use zones. Physical and demographic characteristics associated with the "Place Types" are used to

evaluate each scenario's impacts. The model produces travel behavior output metrics that include vehicle miles traveled, non-auto mode share, and related travel metrics.

The MXD tool, mentioned in the tools summary (Table A-1) uses hierarchical modeling to estimate walking and transit use (for external trips) from mixed-use development (Ewing 2011). Walking share of external trips is related to three types of D variables – diversity, destination accessibility, and demographics. Transit use share of external trips is related to measures of design, destination accessibility, distance to transit, and demographics.

Travel Demand Models

The modeling discussion in Chapter 3 alluded to the limitations of current models to accurately reflect built environment characteristics. Similar limitations are evident in addressing the relationship between the built environment and the tendency to drive vs. walk vs. bike vs. use transit. In response, a fifth D, Distance to Rail Transit, has been used to more accurately estimate transit use based on the built environment and other locally-specific determinants of rail patronage (DKS Associates et al., 2007). Many four-step models do not model walking or bicycle travel, which makes it difficult to evaluate smart growth policies including transit-oriented development (TRB, 2007). Within the past 10 years, however, more MPOs have incorporated bicycling and walking in to the modeling scheme, by introducing a high degree of spatial resolution (i.e., smaller traffic analysis zones that reflect meaningful walking distances) (TRB, 2007).

Tour/activity-based models offer potential advantages in forecasting mobility by mode and purpose. For example, "Trip-chaining allows mode choice to consider the context of the trips. For example, transit must be available in both the departure and return period for it to be available, so there is an advantage to having a tour-based model that considers the level-of-service in both directions" (TRB, 2010a, p. 39).

Induced Traffic and Induced Growth

Performance Metrics

The standard metrics used to gauge the degree of induced demand impacts are: (a) percent growth in traffic attributed to induced demand over a defined time line; and (b) elasticities of changes in travel demand as a function of changes in capacity, speed, or built-environment attributes, measured over the short-, intermediate-, or longer terms.

Percent growth in traffic attributed to induced demand. Studies of impacts at the project level, which could be a specific road improvement or a specific smart-growth strategy, typically compare observed traffic counts either along a facility or within a defined impact zone to what would have been expected had the change not occurred. Expected volumes under the "null" might be based on trend extrapolation, travel-demand forecasts, or comparisons to a "control" corridor, facility, or neighborhood. Thus, if 10,000 ADT is recorded in a surrounding neighborhood prior to a TOD, and two years after the TOD opening an ADT of 14,000 is recorded yet only 12,000 ADT is forecasted (based on trend projections and accounting for the trips generated by the TOD itself), then the share of additional traffic attributable to the TOD is assumed to be 50 percent – [(14,000 – 12,000)/(14,000 – 10,000)] = 0.50, or 50%.

One problem with some before-and-after project-level analyses is they fail to sort out diverted trips from latent trips in gauging induced demand. Additional, if matched-pair comparisons are conducted (e.g., comparing ADT trends in a TOD versus an otherwise comparable non-TOD setting), it is virtually impossible to find nearly identical projects in terms of income profiles, transit provisions, levels of regional accessibility, and other determinants of travel.

Elasticities as a function of changes in capacity, speed, or built-environment attributes. By establishing a statistical relationship between travel outcomes and a "stimuli" or "intervention", be it a road expansion or a smart-growth strategy, an elasticity can be measured of a general form:

Elasticity = [(% change in Travel Demand attributable to induced traffic) /
(% change in Intervention, as measured in speed, density, etc.). *(5.1)*

The tricky part of this formula is the numerator – separating out changes in traffic that can be assigned to induced traffic or growth impacts. This is normally done within an econometric framework involving the use of time series data and multiple regression methods to associate changes in travel demand to changes in the intervention, controlling for other factors (e.g., gasoline prices; transit service levels; unemployment rates) that influence travel over time. Mathematically, the elasticity derived from a regression model might appear as the beta coefficient (β) for a log-log model or the beta coefficient multiplied by the ratio of means – $\beta * (\bar{X} / \bar{Y})$ – for a linear model (also known as a mid-point elasticity).

The ability to attribute induced demand impacts over time hinges on the ability to introduce a lag structure in the predictive model. If, for example, the influences of higher densities on VMT are thought to be negative in the near term however some of these impacts might be eroded over the long term, then a distributed lag model might be introduced with the following form:

$$Y_t = f\,(D_t, D_{t-1}, D_{t-2}\ldots, D_{t-k}, C_t) \qquad (5.2)$$

where Y = VMT; D = density; C = control variables; t = time series data point. These models normally assume that lag effects taper according to an exponential function, with the strongest influences occurring immediately and impacts attenuating during longer lag periods (Hansen and Huang, 1997; Noland and Cowart, 2000; Fulton et al., 2000; Cervero and Hansen, 2002; Cervero 2002; Cervero, 2003). If higher densities are assumed to initially depress VMT (say over years 0 to year 2) and that some of these benefits erode thereafter (say from year 3 to year k), then the model should estimate negative coefficients on D_t, D_{t-1}, D_{t-2}, and positive but smaller coefficients on D_{t-3} to D_{t-k} (assuming the net impact of densities over the long run is a diminution of VMT). To the degree a distributed lag model is estimated using a log-log model structure, then the net induced demand impact of higher densities, adjust for a rebound effect, would be the sum of the marginal coefficients across all lagged express of the variable D.

Application Tools

No standard, widely accepted kitbag of tools has emerged for estimating induced demand impacts of highway or transit improvements, much less for gauging the second-order, rebound impacts of smart-growth strategies. In the absence of such tools, the simplest approach to adjust for possible erosion of the traffic-reducing impacts of smart growth is to borrow from the experiences of others. As reviewed in this section, however, the compendium of empirical experiences in this area is quite slim and for many specific initiatives, be they neighborhood-level TOD or regional-scale jobs-housing balance, non-existent.

The best empirical numbers on possible second-order impacts of changes in the built environment are for the "diversity" dimensions of the 3Ds (Cervero and Kockelman, 1997) or 5Ds (Ewing and Cervero, 2001, 2010) – that is, mixed land uses. The direct traffic-reducing impacts of mixed land uses are typically accounted for in the "internal capture" factor, which according to the Institute of Transportation Engineer's (ITE) *Trip Generation* manual is generally a small number, on the order of 3 to 5 percent of total generated trips (Ewing et al., 2001). A recent analysis of six U.S. regions with mixed-use suburban activity centers found an internal capture rate of 18 percent, which in combination with non-automobile external trips by walking or transit meant "a total of 29 percent of the trip ends generated by mixed-use development put no strain on the external street network and should be deducted from ITE trip rates for stand-alone suburban developments" (Ewing et al., 2011).

NCHRP Report 684 (NCHRP, 2011) provides an improved methodology to estimate how many internal trips will be generated in mixed use developmetns – trips for which both the origin and destination are within the development. The methodology estimates morning and afternoon peak period trips to and from six specific land use categories: office, retail, restaurant, residential, cinema, and hotel. The 684 methodology is intended to be utilized at the project level and would therefore not be well-suited to the MPO and state-level of analysis employed in SmartGAP.

Using simple factor methods (more formally, sometimes called "post-processing"), one can make a plausible, empirically informed adjustment of internal captures accounting for the induced demand impacts of suburban, mixed-use development. Ascribing to the 18 percent internal capture factor of Ewing et al. (2011) and the recent finding of Sperry et al. (2010) that in the suburbs of Dallas that around 26 percent of internal trips are induced, one could adjust the internal capture figure to account for second-order induced travel effects downward to 13.3 percent – $[(0.18) * (1 – 0.26)] = 0.133$.

By way of example, assume a suburban mixed-use activity center with the following land-use program is proposed: (1) 300 apartment units; (2) 50,000 square feet of general office space; (3) 100,000 square feet retail shopping center; and (4) 10,000 square feet health club/fitness center. The estimated trip generation impacts and the post-processing adjustments for both internal capture and induced demand effects could proceed as follows:

Step 1: Trip generation calculation for each land use

Based on the 2008 ITE *Trip Generation* manual rates (Table A-2), the sum-total of trips generated by these four land uses, ignoring possible trip-reducing benefits from their co-presence, is 7,219 daily trips and 669 trips during the P.M. peak hour.

Table A-3 ITE Trip Generation Rates by Land Use Code

Land Use (ITE code)	Land Use Proposal	ITE Vehicle Trip Generation Rates		Total (unadjusted) Generated Trips	
		Weekday	PM Peak	Weekday	PM Peak
Apartments (220)	300 DU	6.65/DU	0.62/DU	1,995	186
General office (710)	50KSF	11.01/KSF	1.49/KSF	551	75
Shopping center (820)	100KSF	42.94/KSF	3.73/KSF	4,294	373
Health/fitness club (492)	10KSF	37.93/KSF	3.53/KSF	379	35
TOTAL				7,219	669

Source: ITE Trip Generation Manual (2008)

Step 2: Internal capture adjustment

Based on the recent findings of Ewing et al. (2011) that around 18 percent of total vehicle trips generated by such mixed-use developments are captured internally, the second step involves simply adjusting these estimates down by 18 percent, assuming the same internal-capture rate applies in the weekday and PM peak alike:

Weekday trips: 7,219 * (1-0.18) = 5,920

PM peak trips: 669 * (1-0.18) = 549

Step 3: Induced demand adjustment

Based on the recent findings of Sperry et al. (2010) that around 26 percent of trips that are internally captured for such mixed-used developments are newly generated, or induced, trips, a third step adjustment could be:

Weekday trips: 7,219 * { 1 - [(0.18)*(0.26)]} = 6881

PM peak trips: 669 * { 1 - [(0.18)*(0.26)]} = 638

In sum, the initial estimate using ITE unadjusted rates is 7, 219 weekday and 669 PM peak trips. Accounting for internal capture lowers the estimates to 5,290 weekday and 549 PM peak trips. A third round of adjustments that accounts for possible induced demand impacts brings these figures up slightly to 6,257 weekday and 580 PM peak trips.

One could argue for even further refinements to reflect the traffic impacts of mixed-use development. Some of the traffic going to the shopping center might be pass-by trips, such as motorists pulling over on a whim to do pick up a few items. The ITE manual recommends a pass-by adjustment of 34 percent for shopping centers (ITE code 820). Thus a reasonable adjustment would be to take 34 percent of generated trips off the top of estimates for shopping centers – i.e., 2,832 trips = [(4,292 * (1 - .34)], though caution should be exercised because ITE's pass-by adjustment rates were derived from a small number of observations. Also, from the Ewing et al. (2011) study, 11.5 percent of trips produced by mixed-use centers were external trips made by walking or public transit. Mode split adjustments might reduce some of the generated trip estimates by this figure as well, particularly among trips made by residents of the 300 apartment units.

State DOT Strategies

Through various methods, state DOTs have attempted to measure induced travel and induced growth. The Utah Department of Transportation (UDOT) employed an approach for measuring induced demand in response to a legal challenge from an environmental group regarding the suitability of the Wasatch Front Regional Council (WFRC) travel demand model for analyzing highway expansion (Schiffer et al., 2005). Sensitivity tests were conducted that held the following constant between future base and future base with the highway: land use, auto ownership, trip generation, trip distribution, mode choice, and traffic assignment. The highway network was the only component of the WFRC travel demand model that was changed. The sensitivity test produced performance metrics and helped derive elasticities by region and by facility. The study concluded that the WFRC model was sensitive to changes in the highway network. The addition of highway capacity lead to higher VMT, lower VHT, increased driving speeds, and lower transit ridership. Elasticities were more influenced by trip distribution than mode choice or highway assignment, and elasticity values fell within the range found in the literature review.

FDOT provides guidance on determining induced growth in *Community Impact Assessment: A Handbook for Transportation Professionals* (2000). Three categories of induced growth related to transportation are identified: 1) "projects serving specific land development," 2) "projects that would likely stimulate complementary land development," and 3) "projects that would likely influence regional land development location decisions" (7-5). The handbook observes that the first two categories are easily predictable. For the third, a checklist approach is favored over a land use modeling approach, which would be more data intensive and costly. The checklist "provides guidance toward a general conclusion on growth inducement potential through systematic consideration of common market factors applied by real estate investors when making

a development or purchase decision" (7-5). This tool is based on *NCHRP Report 403: Guidance for Estimating the Indirect Effects of Proposed Transportation Projects* (1998).

Travel Demand Models

Travel demand models are commonly used to predict the demand for transportation services, as described above. More sophisticated models will include some form of feedback loop to provide traveler reaction to the state of the network and will redistribute trips based on the feedback outputs. Advanced travel demand models include feedback loops to take into account the effects of corridor capacity, congestion and bottlenecks on mode choice, induced demand, travel speed and emissions (California Transportation Commission, 2010).

Wegener's land use-transport feedback cycle is one representation of these interactions based on activities and accessibilities (TRB, 2010a). According to this representation, land use (which accounts for population and employment) drives activities; activities rely on the transportation system; the transportation system determines accessibility; and accessibility influences land use. Simulating feedback loops between transportation and land use improves the logical consistency of model forecasts.

TRB Special Report 288, *Metropolitan Travel Forecasting: Current Practice and Future Direction*, summarized the limitations of many current travel demand models with regard to induced traffic and induced growth. Since four-step models are not behavioral in nature, they cannot evaluate time shifting of travel in congested networks (TRB, 2007). Four step models are also limited in their ability to represent land use allocation, trip generation, and traffic assignment (Schiffer et al., 2005). Land use allocation methods do not consistently account for accessibility effects. Latent demand is not typically considered as part of trip generation. Traffic assignment routing may not be sensitive to the impact of queuing. Furthermore, the shortcomings of four-step models are often amplified under congested traffic conditions. When static models use base-year travel behavior parameters for future horizon scenarios, they do not account for the tendency of traffic congestion to shift the share of daily trips occurring during the peak (Schiffer et al., 2005).

The Spreadsheet Model for Induced Travel Estimation (SMITE) is a sketch planning model designed by FHWA that uses travel demand model outputs to compare the costs of induced travel with the net societal benefits of highway capacity expansion (DeCorla-Souza and Cohen, 1998). After estimating a diversion of traffic from arterials to the freeway, SMITE applies elasticities that relate decreases in travel time to increases in travel demand. User benefits are estimated based on conventional FHWA cost-benefit analysis procedures. External environmental and social costs per VMT are based on user-provided estimates.

The Surface Transportation Efficiency Analysis Model (STEAM) is another FHWA model that uses outputs from travel demand models (FHWA, 1997). STEAM was developed to estimate the affect of regional transportation projects on mobility and safety at both corridor and system-wide levels. STEAM allows users to produce metrics by user-defined districts. It also addresses the benefits of increased accessibility resulting from transportation investments by estimating the affect of decreased travel time on employment availability.

Relationship Between Smart Growth and Congestion

Performance Metrics

Evaluating the effectiveness of Smart growth design on traffic congestion is a multi-step process, as illustrated in the Phoenix and Prince George's County examples above. One must first examine the vehicle traffic stream and ascertain the degree to which a subject development (or collection of developments) is contributing to that traffic stream. This cannot be credibly done by simply measuring traffic levels on links or at intersections in the immediate proximity of the development(s), but requires methods and metrics that can attribute the impacts to source.

Methods and metrics that can serve this purpose are:

- Traffic volumes on individual network links or intersections by time of day and direction.
- Proportion of those volumes comprised of trips with a relationship to the study area (both origin and destination, or either origin or destination within the study area) vs. the proportion that are entirely pass through.

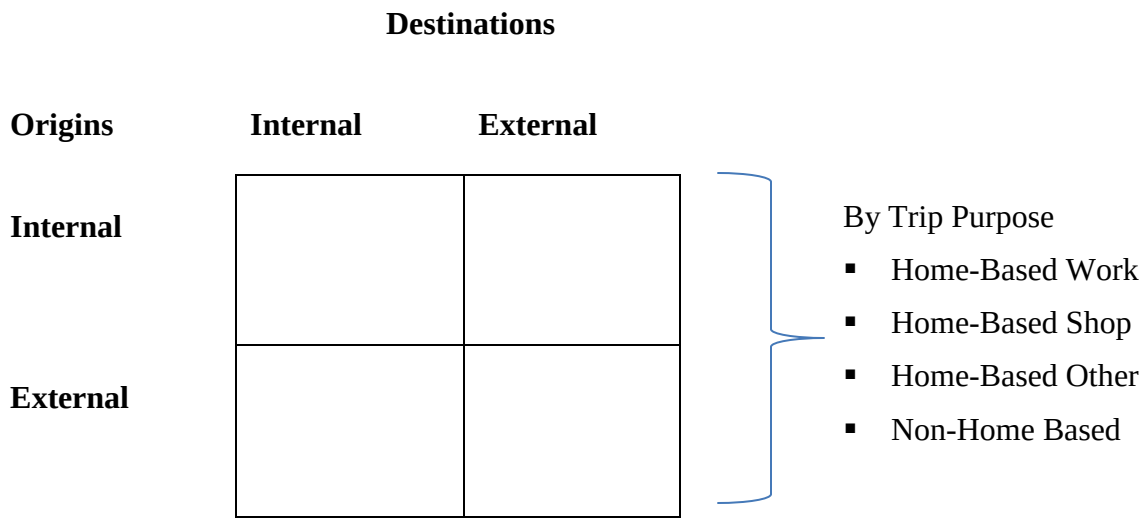
The through traffic share is an important indicator of the subject area's impact on traffic. If a traffic level of service standard is violated, it is important to ascertain the portion of the volume leading to the violation that is outside the control of the subject area. Short of expensive travel surveys, the only practical way to estimate these proportions is through "select link" analyses with the regional travel model. By attempting to associate the traffic volumes on a given link with the TAZ-to-TAZ trip movements that have been assigned to that link, it is possible to estimate the proportions of internal vs. through traffic. Unfortunately, as traffic assignment routines in travel forecasting models have become more and more complex, with many iterations before achieving an equilibrium assignment, this leads some practitioners to question the accuracy by which origin of these trips can be identified. Still, through traffic identification is a critical variable, and a select link approach is arguably better than any other available technique (other than origin-destination type studies, which are generally cost infeasible.)

The second set of performance metrics correspond to the structure and performance of the subject area itself. The measures in this group include the following:

- Rates of internal trip capture
- Mode split
- Average trip lengths
- VMT production

A useful framework for approaching this assessment is similar to the approach described above to attribute traffic contributions on identified roadway segments. The framework offers important insight from analyzing a breakdown of key trip market segments. This can be done by manipulating trip table data by trip purpose from the local travel model into the simple construct pictured in Figure A-1.

Figure A-1. Framework of Trip Market Segments



If this compilation is done for each of the primary trip purposes shown, the following useful metrics can be obtained:

- First, the proportion of total trips of each type that are retained within the area (Internal-Internal), vs. those made to external destinations (Internal-External). If the area has strong smart growth characteristics, it should retain a high proportion of its trips, particularly for non-work travel.
- The modal share for each trip purpose for those trips originating in the subject area. If the area has good smart growth characteristics, a high percentage of the Internal-Internal trips should be made by walking, biking or local transit; for trips made outside the area, a high percentage should be made by transit, multi-passenger vehicle (reflected in vehicle occupancy), or bicycling.
- The average trip length for trips that originate in the subject area should be shorter than average, reflecting that more trips are made locally because of attractive opportunities and good connectivity. Combined with less auto use, this should result in lower household and per capita VMT rates for these areas.
- For trips made to the area (External-Internal), the indicators should show a high percentage of trips arriving by transit, multi-passenger vehicle (occupancy higher), or bicycle/walk. The compact, well-designed nature of the receiving area should make alternative modes attractive and efficient, and also lead to a high percentage of internally-captured non-home based trips.

Application Tools

It is acknowledged that conventional TAZ-based travel forecasting models are poorly suited to estimate the effects of smart growth land patterns on travel behavior. The structure is simply too coarse to capture the effects of density, diversity and design on household and individual travel decisions, which operate at the "walking scale" of the traveler's environment. These characteristics strongly affect choice of destination, mode, linking of trips, number of vehicles

owned, etc., but are outside the resolution of the TAZ. To get at these characteristics, it is necessary to engage other tools that incorporate the characteristics directly – the D's models such as I-PLACE^{3}S, INDEX and Envision described earlier – or to look forward to the new generation of activity-based or tour-based models that operate at a much finer level of resolution (parcels or points). It is also necessary to use tools that incorporate or are sensitive to 4Ds measures of built environment in order to evaluate or optimize the overall efficiency of a smart growth design.

Nevertheless, for many of the broad measures of impact described above, a great deal of useful information can be derived from analysis of trip table data and traffic assignment results. In many cases it is more about asking the right questions and properly massaging the data than having the exact right tool, per se.

The Prince George's and Phoenix examples illustrate how conventional tools and data can be used more effectively to address the smart growth vs. traffic congestion question. An illustration of what such an analysis can convey is pictured in Figure C-2 used in the Prince George's study. This setup is for the US 1 North corridor, one of the six earlier- described case study sites. To portray travel flows within the county and in connection with the broader Washington DC region, the county itself was subdivided into 16 internal districts (not including the 6 case study areas) and 10 external districts representing surrounding counties and the District of Columbia. Individual traffic analysis zones (TAZs) were then aggregated into these districts, and trip tables reflecting person trips and trips by mode for four primary purposes (work, shopping, other home-based, non-home based) were for the system of 6 activity centers + 16 internal districts + 10 external districts, or a 32 x 32 analysis universe. The internal districts are denoted as I-1, I-2, etc. in Figure 6-4, while the external districts are denoted as E-1, E-2, etc. Pulling data from the respective trip tables for this district-level setup, it can be seen that only 18% of trips that originate in the study zone remain within the zone, meaning that 82% travel outside, the largest shares to Montgomery County (E-2) and northern Prince George's County (I-1). Since this is much more of an employment area than a residential area, only 40,700 trips originate in the area, while 104,300 come to the area from the outside.

This is not a particularly transit oriented area. It does not have a Metrorail station, though there is a MARC commuter rail station, and there is limited walkability in the area. Thus we see that the primary transit use is for work (HBW) travel, which accounts for 23.5% of the 9% of daily trips that originate in the area, and 10.4% of the 33% of HBW trips which are made to the area. Transit use for all other purposes is less than 2%. Regrettably, walk/bike data were not available for this analysis, though given the design, few trips would be expected.

Figure C-3 provides additional insight on the nature of trips made by residents in relation to the presumed Smart Growth design. It shows that only 10% of resident work trips are made to destinations within the study area, which is not particularly uncommon except that this is a jobs-rich setting where a higher live-work rate might be expected. A high percentage of shopping trips are made internally, which is a desirable result of smart growth design, and attributable to the rich retail environment, with a study area ratio of 1.51 retail jobs per household (compared with 0.32 County-wide). However, only 19.6% of home-based other and 16.4% of non-home based trips are made within the study area, suggesting that the purposes associated with these types of trips are not well served by the design of the corridor. The relative lack of large

concentrations of identifiable locations for these trips suggests that they are scattered widely about the surrounding region.

Figure A-2. 2030 Daily Traffic Flows in US 1 North Corridor

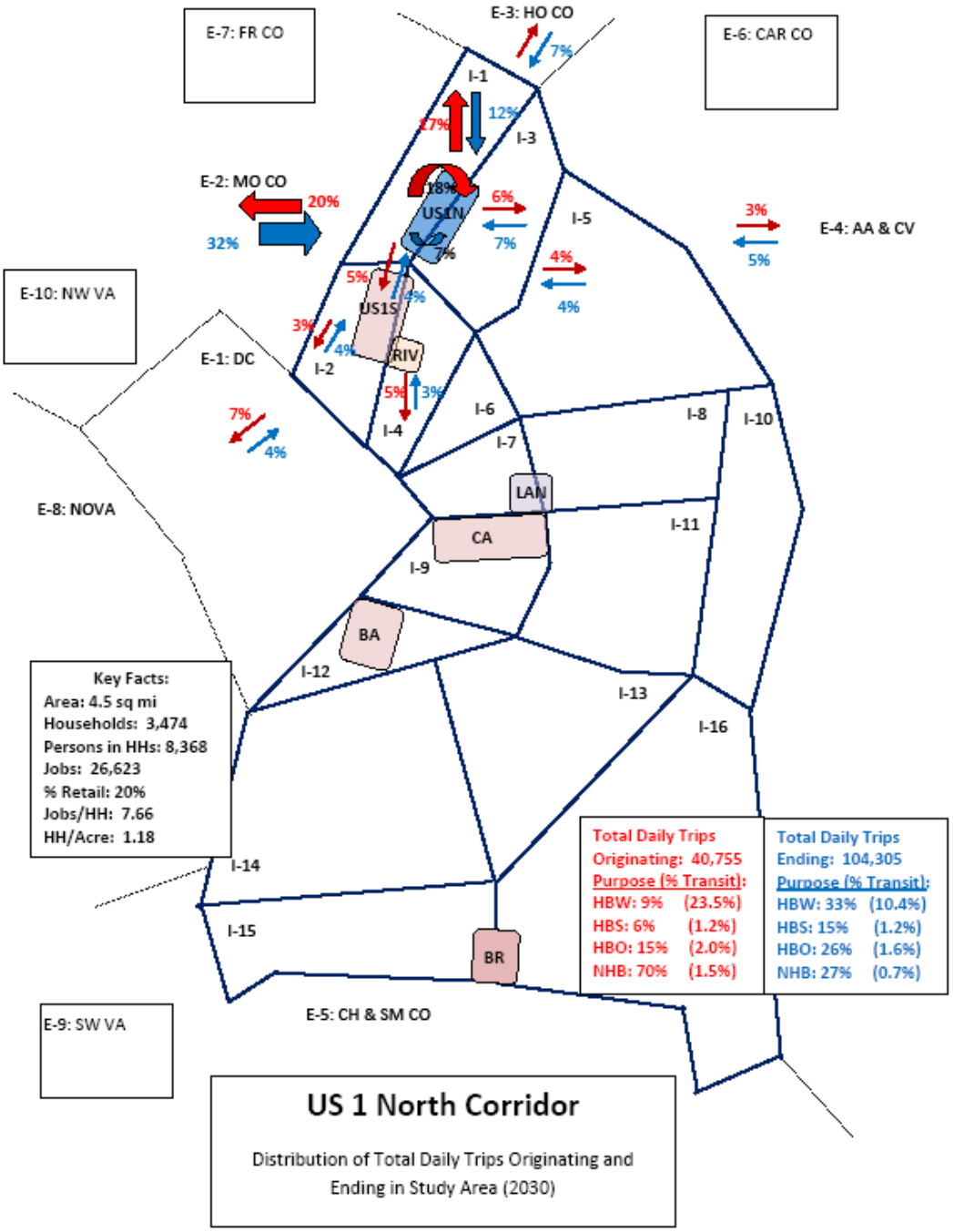
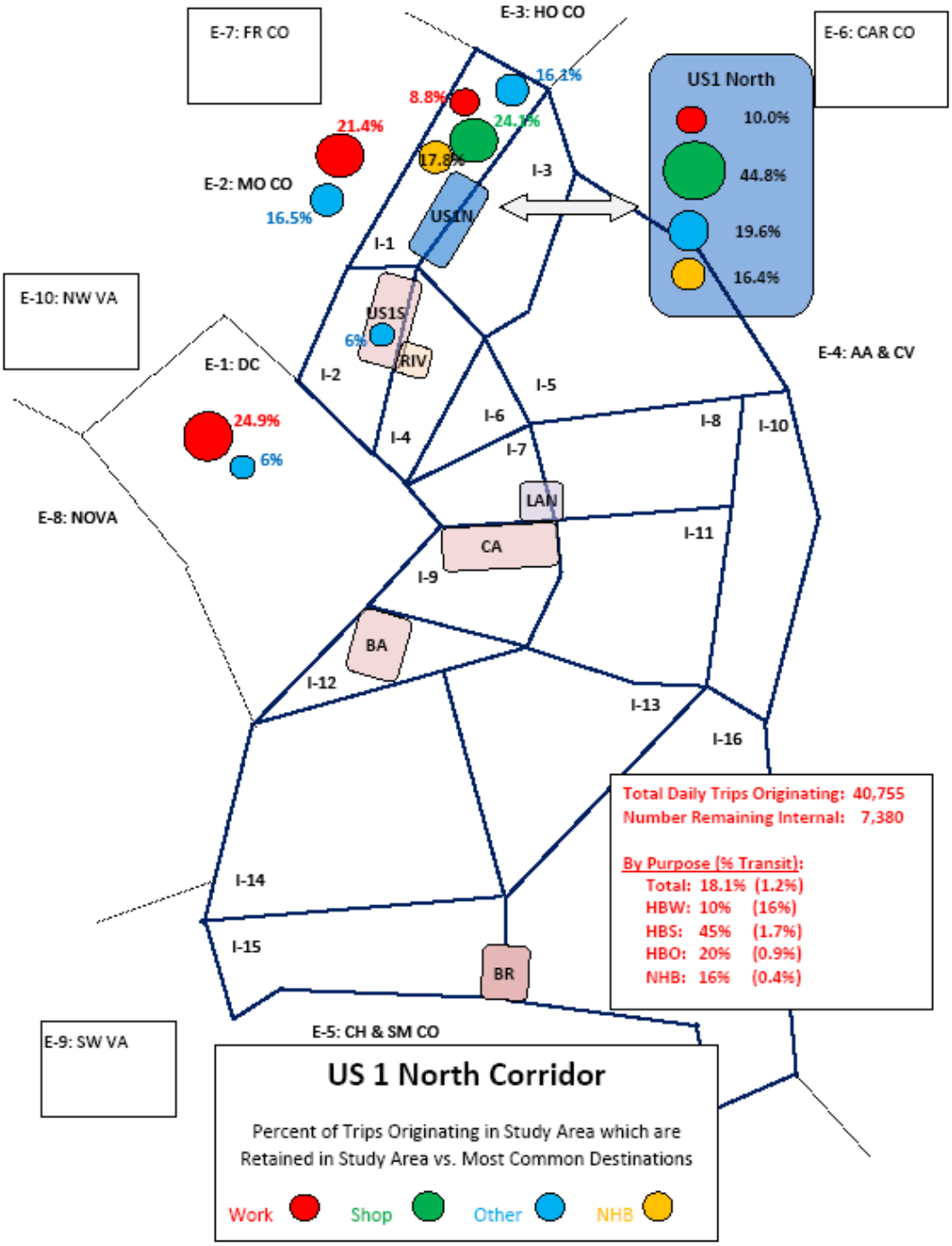


Figure A-3. Internal Capture Analysis for US 1 North Corridor



Such an analysis clearly tells a story that this particular development area is well short of what would be considered adequate Smart Growth performance: Too few trips retained internally, far too few trips by transit from or to the area, and certainly very little use of transit for non-work travel or work travel that is not downtown-oriented.

While the diagrams and performance indicators shown were generated "manually," it would probably not be difficult to create software that would extract these relationships and create the visual elements automatically. GIS tools can be programmed to portray relationships in this manner, and some modeling software packages (such as TransCAD) actually incorporate such features in their structure and can be programmed for other custom output functions. This includes showing actual traffic conditions and congestion levels on network facilities.

New tools are emerging that will contain much more of the desired capability to address land use impacts in the local and regional context. A major shortcoming among even the conventional 4Ds models has been the ability to accurately account for pedestrian and bicycle travel. This is due both to the issue of modeling scale, but also reflects not having the functional relationships that are necessary to estimate non-motorized travel demand. The reason this is important is that the ultimate measure of efficiency of a smart growth designed community is in how much it encourages walking and biking for basic travel. If walking and biking are viable alternatives, they can serve as a substitute for auto trips, provide improved access to and from transit, and allow both residents and visitors to travel between non-home based locations without relying on a car. NCHRP Project 08-78 is currently focused on developing such a modeling capability, which can be used to estimate bicycle and pedestrian demand at the community or corridor level, for regional planning and policy analysis, and for local bike/ped network design and prioritization (Renaissance Planning Group et al., 2011). The proposed tools should be capable of not only guiding the development of effective smart growth designs, but accounting for the subsequent effect on traffic levels on local and regional facilities.

Smart Growth and Freight Traffic

Performance Metrics

As used in Lemp and Kockelman (2009a), Zhou et al. (2009), Tirumalachetty and Kockelman (2010), Kakaraparthi and Kockelman (2010), and many other papers and reports, the most common method for regional-scale modeling is simulation, at one point in time or over 20+ year horizons (after including land use models), across various policy scenarios (e.g., congestion pricing, highway expansions, urban growth boundaries, higher gas prices, and purposeful shifting of job and household locations). Simulations can be disaggregate – at the level of individual households and businesses, for example, or in aggregate (at the level of TAZs). Zone counts generally number 1000 or more, and link counts over 10,000 for regions of 1 million-plus population.

Network assignment of traffic in such model almost exclusively relies on static assignment (where a link's congestion cannot impact upstream links), since dynamic user equilibrium applications require far more detail and longer run times (and stronger assumptions about route choices and the evolving nature of trip tables over the course of a day). Models are estimated based on disaggregate travel records (by households and businesses), and sometimes calibrated

based on observed network data. Inventories of job, population and land use patterns are significant activities for planners that support such models, with data generally applied at the zone level.

Metrics for such regional-scale models include regional VMT, VHT, and tons of emission (by type) per modeled travel day (typically a weekday). They regularly include average volume-to-capacity ratios and speeds (by broad time-of-day categories) for the network (though such values are generated at the link level). Kockelman and teammates also regularly provide measures of *welfare* (using monetized differences in logsums between the base case and alternative scenarios), in order to provide more substantive information than simple travel metrics. For example, travel time savings are not always a good indicator of social benefits. Land use patterns and access can be key to meeting traveler needs. Examples of this include Lemp and Kockelman (2009a) and Gulipalli and Kockelman (2008), who described spatial and demographic relationships in welfare changes under road pricing and other scenarios for Texas regions. Lemp and Kockelman (2009b) offer a detailed examination of how such values can be computed, using rigorous nested logit examples.

Of course, modelers can also examine particular O-D pairs in detail – their travel times and costs before and after a system change (see, e.g., Gulipalli and Kockelman [2008]). They can seek to quantify the effects of system changes on travel time *reliability and crash counts*, and value these changes (along with traveler welfare, emissions, and policy costs) using engineering accounting (e.g., net present valuation versus base case values to produce *benefit-cost ratios*), as in Fagnant et al. (2011). Kockelman and teammates are finalizing a Project Evaluation Toolkit (PET) that quickly anticipate travel patterns by using constrained maximum entropy techniques and existing or anticipated link-flow inputs, and then pivoting (via incremental logit functions and elastic trip-making equations for all O-D pairs) to each scenario's estimated trip table. The PET provides a variety of comprehensive project impact scores (e.g., internal rates of return and B/C ratios, including their distributions over a series of random simulations, to reflect uncertainty in model parameters and inputs). But PET does so without detailed link systems (e.g., 300 links) or land use information. Coming versions may allow for planners to input their own, more detailed models' outputs, for PET estimation of project values and overall scores. Such details would allow for PET evaluation of multiple land use scenarios, once paired with an appropriate travel demand model.

In a study of Seattle freight, PSRC (2009) staff identified the following performance metrics for characterizing commercial vehicle activities: value of travel time savings and reliability, vehicle and facility operating and capital costs, revenues and jobs, access to freight-trip generators (e.g., ports and businesses), emissions rates and costs per ton of pollutant, accident rates and costs, and value of network redundancy (in case of emergency, resurfacing, or other incidents that impact access times). Many of these are already included in the PET described above, though the Toolkit generally assigns generic values to all truck types, rather than allowing for industry- and/or firm-specific variations.

Other metrics of interest to this work are inputs to the modeling process, particularly those characterizing the transport *network, land use patterns and system behavior*. They include free-flow and modeled speeds, link-performance functions (travel time versus demand parameters), signal phasing, and delays. They also include the balance and mix of land uses, using simple or

sophisticated accessibility indices, entropy equations, and other functions, around points of interest (e.g., homes and businesses), routes of interest, and/or zones.

Application Tools

The *Regional Freight Plan* developed by Portland's Metro in 2010 includes a chapter on developing a freight strategy toolkit. Freight planning goal categories include system planning for efficient freight mobility and access; system management to increase network efficiency; better public understanding of freight issues; freight-sensitive land use planning; and strategic transportation investments.

Decision-making tools in the *Washington State 2010-2030 Freight Rail Plan* released by the Washington State Department of Transportation lists the following tools that can be used in modal selection of freight infrastructure: a benefit/cost calculator; a legislative priority matrix; a project management assessment matrix; a user benefit levels matrix; project evaluations; and decision documentation.

The DVRPC has published freight planning guidelines as part of their Municipal Implementation Tool series. This 2010 document entitled *Freight Transportation* articulates a goal of focusing goods movement in designated corridors. To achieve this goal, the DVRPC makes several recommendations to cities, including: improve the links between freight-related transportation and land use, concentrate freight growth in industrial centers, create freight villages with contiguous freight land uses, and advance access management.

The New Jersey *Comprehensive Statewide Freight Plan* from 2007 concludes that more data and tools are needed for a proper analysis of the freight system. The summary recommendations state that, "The development of improved data and analysis tools could help determine where it is best to target infrastructure improvement to mitigate current and forecast congestion" (12-14). It also recommends the development of a multimodal tool that would be used "to gain a better understanding of the relationship among improvements in capacity, travel times, and reliability at points, corridors, and Interstate routes (or freight lanes) and the impacts on freight movements as part of the overall logistics supply-chain" (12-14).

Key Findings and Recommendations

Performance Metrics

Our research on performance measures proven most effective in comprehensive smart growth and transportation system planning include metrics designed to operate at three important levels: a) transportation specific indicators, b) metrics that indicate the effectiveness of the regional and local integration of transportation and land use, and c) higher-level metrics that capture the effects of land use and transportation decisions on a "triple bottom line" of economic, environmental and societal impact.

Higher-order metrics are particularly noteworthy when evaluating smart growth benefits. Compared with uncontrolled growth, smart growth development patterns would produce the following savings nationally (TCRP 2000):

- 188,305 reduction in local road lane miles, and related savings of $109.7 billion
- Lower local fiscal impact of $4.2 billion
- Reduced property development cost of $420 billion or 6.6%
- Personal savings related to reduced VMT (auto + bus) of 4.9 million VMT or $24 billion

We identify the following as key metrics that address the effects of smart growth on transportation capacity needs as measured in terms of pure engineering assessment of traffic volume-to-capacity relationships and resulting congestion, as well as the higher-level objectives States and regions are now using to envision and plan their future balance of infrastructure and land use with respect to economic, environmental and social goals and return on investment:

Transportation Metrics

- Daily Vehicle Trips and VMT
- Daily Transit Trips or Share
- Vehicles by Purpose, Peak Periods
- VHT, VHD, Emissions, Energy
- Adequate Crossing Time and Intersections
- Right-of-Way Allocation to all Modes (e.g. Complete Streets)
- Multi-modal Level-of-Service

Integrated Transportation/Land Use Metrics

- Traveler Cost
- Development Cost
- Transportation System/Service Cost
- Location Efficiency
- Economy, Property Values, Jobs
- Environment and Equity
- Livability, Community Character

Higher-Order Metrics

- Economic and Social Value of Induced Traffic over Short and Long Terms
- Public Health Impacts and Costs
- Local Infrastructure Costs (Capital, O&M)
- Building Energy Use and Emissions
- Building Water Use and Emissions
- Local/jurisdictional revenues

- Land Consumption
- Fiscal Impact
- Resource Usage and Waste Generation
- Housing Affordability
- Storm Water Management

Our consideration of application tools in the next section addresses whether each of the available tools is capable of producing the above list of metrics.

Application Tools

Current Modeling Practice

Most MPOs and State DOTs use sophisticated modeling tools to forecast the effects of land use and transportation systems and policies on future traffic levels and the need for roadway capacity expansion. All of the modeling processes contain the following basic elements:

- Socio-economic and land use forecast – projected future population and employment and land use for every sub-area of the region
- Trip generation estimate – the number and purposes of trips that will occur as a result of the future land use
- Trip distribution – the destinations and lengths of each generated trip
- Mode choice – whether each trip will occur by single-occupant automobile, carpool, transit, walking or biking
- Route Assignment – what paths with the auto and transit trips follow to reach their destinations and what volumes of traffic will result on each street and highway segment and what ridership on each transit line
- Capacity Analysis – the resulting levels of congestion throughout the roadway and transit networks and resulting travel speeds and delays
- Travel performance measures – the levels of travel, regional mobility, transportation system performance expressed, for example, as vehicle miles travelled, vehicle hours of delay, congestion levels and air quality emissions.
- Multi-dimensional performance – the effects of the land use patterns and transportation system conditions on an array of socio-economic and environmental indicators specified to reflect regional, state and federal objectives, such as livability, cost benefit and return on investment.

Within this basic analysis framework, the degree of modeling sophistication varies depending on the size, complexity, and resources of the region. Smaller MPOs often use simpler four-step models that perform basic trip generation, distribution, mode choice and route assignment to prepare information for the evaluation of travel performance and multi-dimensional regional objectives.

Larger MPOs are beginning to adopt more sophisticated activity based models to perform forecasting at a more refined and policy-oriented level. Some of the most advanced of the activity-based models are reaching the level of specificity to adequately address transportation and land use interactions at the localized level needed to capture the effects of smart growth on travel demand. However, these models are very complex and resource intensive and even the largest and most advanced MPOs find it challenging to respond to growing demands from decision-makers and the public on the subject of smart growth and its effects.

The demand for more responsive models emerges from the desire of planners and decision-makers to perform interactive scenario evaluations in a public setting and the desire to capture the effects of both regional and community-level smart growth concepts on a diverse set of regional goals and concerns. These demands require models that are highly responsive, transparent, stable and sufficiently fine-tuned to capture the effects of both local and regional land use and transportation decisions on levels of travel and accessibility and consequential economic, environmental and societal effects. Models employed by MPOs for evaluating regional transportation investments are, for the most part, too slow and macro-scale to address these needs. Standard, and even advanced, regional models take many hours of processing time to produce results and/or operate at a macro regional scale, too insensitive to capture the critical effects of local land use patterns and transportation choices.

Smart Growth Evaluation Tools

At least a dozen options have emerged to address the need for tools that are responsive to smart growth policies and interactive enough to inform planning processes that involve high levels of engagement with decision-makers and the public. They include:

- Simple spreadsheets to address a sub-set of planning factors and performance measures
- Sophisticated GIS tools that allow scenario planning at the land use parcel level and produce a large variety of performance indicators
- Tools that provide a visual interface "dashboard" for presenting the results of a set of analyses performed on the full MPO models in advance of the planning sessions.

Of the comprehensive, multi-issue land use transportation planning tools, the most well known and commonly used (and shown on Table A-1 and Table A-2) are:

- CommunityViz
- Envision Tomorrow
- INDEX
- iPLACE^{3}S
- MetroQuest
- Rapid Fire / Urban Footprint
- TREDIS

Each of these tools has been used by at least a handful of MPOs and/or at a State level to perform interactive smart growth scenario evaluations of a broad array of social, economic and environmental indicators. Many of the tools perform analysis of transportation and other effects, while several (MetroQuest, TREDIS, CommunityViz) serve primarily as visualization platforms for standard transportation modeling. These tools may also be distinguished from one another by the scale at which they operate, the specific data they require and the performance indicators they produce. In terms of scale, the different tools operate at one or more of the following levels:

- Development project or transit station area TOD (micro)
- Corridor/community (meso)
- County or regional (macro)

The table also indentifies a set of simpler evaluation tools that can be used to selectively produce quick-response indicators of the effects of land use and transportation strategies at various scales on specialized sub-sets of performance metrics:

- MXD-P (project/plan)
- MXD-V (vision/region)
- DRM
- BMP
- SCAG TDM Tool

These transportation/land use interactive effect tools are primarily spreadsheets, some with interactive dashboards, which have been used in local and regional smart growth analysis in various parts of the US. In some cases these tools pivot from baseline analyses produced by more sophisticated analysis models, Their data requirements are much more limited than those of the multi-issue land use transportation planning tools described above.

With respect to the primary purpose of the SHRP2 C16 research and capacity building effort, a most critical question in tool selection, is the question of which tools are capable of addressing the underlying relationships that measure the effects of smart growth on transportation system capacity needs. Table C-1 also indicates which of the core relationships each of the available application tools address. While most of the application tools address the effects of built environment on daily travel demand, and about half address the effects of travel demand management on amounts of travel, **a critical finding of this first phase C16 analysis is that few of the available tools address the effects of:**

- The relationship between peak travel demand and network supply (capacity) on congestion
- Congestion and accessibility on induced growth or induced travel
- Freight demand and urban form on system capacity needs
- No single application tool addresses all three factors at any analysis scale.

Information Gaps and Limitations of Current Practice

Performance measures and metrics to evaluate the effects of smart growth on transportation system capacity needs should be compatible with and integrated with the metrics used for the broad range of regional and local transportation planning, such as MPO Regional Transportation Plans. Metrics should operate at three basic levels: a) transportation specific indicators, b) metrics that indicate the effectiveness of the regional and local integration of transportation and land use, and c) higher-level metrics that capture the effects of land use and transportation decisions on a "triple bottom line" of economic, environmental and societal impact. Examples of transportation-specific indicators include VMT and VHD. Integrated land use and transportation metrics include location efficiency and induced travel impacts, livability and community character. Higher order metrics include public health impacts, housing affordability and fiscal impacts.

Models used by MPOs and DOTs are too macro-scale to fully address the effects of smart growth on trip reduction and the complexities of location-specific congestion and needed remediation. Regions with sufficient resources can fine-tune their models and add policy sensitivities through "activity-based" formulations and can analyze congestion and infrastructure needs through more detailed and sophisticated tools such as dynamic traffic assignment and simulation. However, most regions lack the resources to achieve these goals in the short or medium term. Furthermore, the resulting highly sophisticated models would not achieve the other goals cited by the agency representatives as important for smart growth scenario planning: a) the capability to perform quick response visioning and scenario analysis, and b) the ability to scale effectively between the local, corridor and regional levels of analysis for effective communication with local governments and sub-regional agencies and the public.

While there are at least a dozen application tools that have been successfully used as stand-alones or to supplement regional travel models for scenario planning and production of travel, socio-economic and environmental indicators, few of the available tools address the effects of:

- The relationship between peak travel demand and network supply (capacity) on congestion
- Congestion and accessibility on induced growth or induced travel
- Freight demand and urban form on system capacity needs
- No single application tool addresses all three factors at any analysis scale.

In conclusion, subsequent tasks of the C16 work effort will need to address the means through which to overcome the lack of sound and transferrable knowledge on the phenomenon of induced travel, the effects of smart growth on peak travel generation, and the effects of network connectivity on infrastructure capacity needs, as well as the lack of application tools presently equipped to address these issues.

APPENDIX B. SMART GROWTH AREA PLANNING TOOL DOCUMENTATION

APPENDIX B. SMART GROWTH AREA PLANNING TOOL (SMARTGAP) DOCUMENTATION

LIST OF TABLES

LIST OF FIGURES

Overview

Sources

Some of the models contained in SmartGAP were derived from work developed from other sources and brought together in this implementation. The primary sources were identified in the description for each model and include the following:

- Greenhouse Gas Statewide Transportation Emissions Planning (GreenSTEP) Model Documentation (November, 2010) prepared by Brian Gregor of the Oregon Department of Transportation, Transportation Planning Analysis Unit
- Freight Activity Microsimulation Estimator (FAME) project conducted by Amir Samimi, Kouros Mohammadian, and Kazuya Kawamura from the University of Illinois at Chicago for the National Center for Freight, Infrastructure, Research and Education (CFIRE) at the University of Wisconsin-Madison and the Illinois Department of Transportation
- Highway Economic Requirements System (HERS) model developed for the FHWA in 2005
- National Transit Profile in the National Transit Database
- US DOT's National Transportation Statistics
- Texas Transportation Institute's annual Urban Mobility Report

The urban form models were developed originally for SmartGAP and estimated from the National Household Travel Survey data.

Glossary of Variables used in the Models

Table B-1 presents a glossary of variables used in all the models for reference. These are sorted alphabetically by variable name.

Table B-1: Variables used in SmartGAP Models

Description	Variable Name
Number of Persons per Household Age 0-14	Age0to14
Number of Persons per Household Age 15-19	Age15to19
Persons age 15-19 interacted with vehicles per driver	Age15to19:VehPerDrvAgePop
Number of Persons per Household Age 20-29	Age20to29
Persons age 20-29 interacted with log of population density	Age20to29:LogDen
Number of Persons per Household Age 30-54	Age30to54
Persons age 30-54 interacted with log of population density	Age30to54:LogDen
Persons age 30-54 interacted with vehicles per driver	Age30to54:VehPerDrvAgePop
Number of Persons per Household Age 55-64	Age55to64
Persons age 55-64 interacted with log of population density	Age55to64:LogDen
Persons age 55-64 interacted with vehicles per driver	Age55to64:VehPerDrvAgePop
Number of Persons per Household Age 65+	Age65Plus
Persons age 65+ interacted with log of population density	Age65Plus:LogDen

Description	Variable Name
Dummy variable if household is in the Midwest region	Census_rMidwest
Dummy variable if household is in the Southern region	Census_rSouth
Dummy variable if household is in the Western region	Census_rWest
Children Dummy Variable, Second City Area Type	Children_City
Children Dummy Variable, Rural Area Type	Children_Rural
Children Dummy Variable, Suburban Area Type	Children_Suburban
Children Dummy Variable, Town Area Type	Children_Town
Couple No Kids Dummy Variable, Second City Area Type	CoupleNoKids_City
Couple No Kids Dummy Variable, Rural Area Type	CoupleNoKids_Rural
Couple No Kids Dummy Variable, Suburban Area Type	CoupleNoKids_Suburban
Couple No Kids Dummy Variable, Town Area Type	CoupleNoKids_Town
Number of driving age persons	DrvAgePop
Freeway lane miles per 1000 persons	Fwylnmicap
Household Income ($1000s), Second City Area Type	Hhinc_City
Household Income ($1000s), Rural Area Type	Hhinc_Rural
Household Income ($1000s), Suburban Area Type	Hhinc_Suburban
Household Income ($1000s), Town Area Type	Hhinc_Town
Total annual household income in dollars	Hhincttl
Household income interacted with persons ages 15-19	Hhincttl:Age15to19
Household income interacted with persons ages 30-54	Hhincttl:Age30to54
Household income interacted with persons ages 55-64	Hhincttl:Age55to64
Household income interacted with household vehicles	Hhincttl:Hhvehcnt
Household income interacted with population density	Hhincttl:Htppopdn
Household income interacted with log of population density	Hhincttl:LogDen
Household income interacted with daily VMT	Hhincttl:LogDvmt
Household income interacted with log of household size	Hhincttl:LogSize
Household income interacted with elderly populations	Hhincttl:OnlyElderly
Household income interacted with transit revenue miles	Hhincttl:Tranmilescap
Household income interacted with urban mixed use area	Hhincttl:Urban
Household income interacted with urban mixed use area	Hhincttl:Urban
Number of persons per household	Hhsize
Number of vehicles in the household	Hhvehcnt
Census tract population density in persons per square mile	Htppopdn
Population density interacted with freeway lane miles	Htppopdn:Fwylnmicap
Population density interacted with household vehicles	Htppopdn:Hhvehcnt
Population density interacted with elderly populations	Htppopdn:OnlyElderly
Population density interacted with transit revenue miles	Htppopdn:Tranmilescap
Population density interacted with urban mixed use area	Htppopdn:Urban
Natural log of the Census tract population density	LogDen
Log of population density interacted with log of daily VMT	LogDen:LogDvmt
Log of population density interacted with log of household size	LogDen:LogSize
Log of population density interacted with urban mixed use area	LogDen:Urban
Log of daily vehicle miles traveled	LogDvmt

Description	Variable Name
Natural log of annual household income	LogIncome
Log of persons per household	LogSize
Log of household size interacted with log of daily VMT	LogSize:LogDvmt
Log of household size interacted with urban mixed use area	LogSize:Urban
When all persons in the household are over 65 years old	OnlyElderly
Elderly populations interacted with freeway lane miles	OnlyElderly:Fwylnmicap
Elderly populations interacted with transit revenue miles	OnlyElderly:Tranmilescap
Only Elderly Dummy Variable, Second City Area Type	OnlyElderly_City
Only Elderly Dummy Variable, Rural Area Type	OnlyElderly_Rural
Only Elderly Dummy Variable, Suburban Area Type	OnlyElderly_Suburban
Only Elderly Dummy Variable, Town Area Type	OnlyElderly_Town
Average per Capita Income (Power Transform)	PowPerCapInc
Singleton Dummy Variable, Second City Area Type	Singleton_City
Singleton Dummy Variable, Rural Area Type	Singleton_Rural
Singleton Dummy Variable, Suburban Area Type	Singleton_Suburban
Singleton Dummy Variable, Town Area Type	Singleton_Town
Annual transit revenue miles per person	Tranmilescap
Transit revenue miles interacted with freeway lane miles	Tranmilescap:Fwylnmicap
Transit revenue miles interacted with urban areas	Tranmilescap:Urban
Transit revenue miles per capita interacting with households in an urban mixed-use area	Tranmilescap:Urban
Household is in an urban mixed-use area	Urban
Urban mixed use areas interacted with freeway lane miles	Urban:Fwylnmicap
Urban mixed use area interacted with log of population density	Urban:LogDen
Urban mixed use area interacted with log of daily VMT	Urban:LogDvmt
Persons age 20-29 interacted with vehicles per driver	VehPerDrvAgePop:Age20to29
Persons age 65+ interacted with vehicles per driver	VehPerDrvAgePop:Age65Plus
Households with no vehicles	ZeroVeh

Note: Some variables are interacted with other variables to include effects from a combination of these variables. For example, household income is interacted with urban mixed use areas to show that there will be more zero-vehicle households with one driving age person in the household in urban mixed use areas as income increases.

Census regions (http://www.eia.gov/emeu/mecs/mecs2002/census.html) are defined by Census divisions and states (Table B-2), as follows: a Census Division is a geographic area consisting of several States defined by the U.S. Department of Commerce, Bureau of the Census; and the States are grouped into four regions and nine divisions.

Table B-2. Census Regions, Divisions, and States

Region	Division	States
Northeast	New England	Connecticut, Maine, Massachusetts, New Hampshire, Vermont, and Rhode Island
	Middle Atlantic	New Jersey, New York, and Pennsylvania
Midwest	East North Central	Illinois, Indiana, Michigan, Ohio, and Wisconsin
	West North Central	Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, and South Dakota
South	South Atlantic	Delaware, District of Columbia, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia, and West Virginia
	East South Central	Alabama, Kentucky, Mississippi, and Tennessee
	West South Central	Arkansas, Louisiana, Oklahoma, and Texas
West	Mountain	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming
	Pacific	Alaska, California, Hawaii, Oregon, and Washington

Area types are defined in the NHTS data in the "Hthur" urban/rural variable in Appendix Q of the 2001 NHTS Users Guide (http://nhts.ornl.gov/2001/usersguide/UsersGuide.pdf). Density was converted into centiles, that is, the raw numbers (persons per square mile) were translated into a scale from 0 to 99:

- "Rural" (centiles 19 and less) based on density
- "Small town" (centiles 20 to 39) based on the density
- Population centers were defined if a route through the 8 neighboring cells could be constructed in which the density of successive cells was decreasing or equal.
- Population centers with centiles greater than 79 were designated "urban."
- Other centers were classified as "second cities."
- "Suburban" areas of the population centers were defined, using both the cell density and the cell's density relative to the population center's density.

Household and Firm Models

Household Age Models

The household age model uses a synthesis process that is commonly used in travel modeling to enumerate a set of household records from county-level estimates of population by age. The households are described in terms of the number of people in each of six age groups ((0 – 14, 15 – 19, 20 – 29, 30 – 54, 55 – 64, 65+). The aim of the synthesis process is to capture both the overall characteristics of the population, such as average household size, and also the range of those characteristics, such as the distribution of household sizes.

The probability distribution linking the population by age data with household membership is obtained from PUMS data. The PUMS data were coded into household types based on the number of people in each of the six age groups. Some simplifications were made to represent only the more common household structures in the PUMS data – which still accounted for 99% of all households in PUMS data – by limiting the number of people in the 0-14 age

group to a maximum of four and in older age groups to a maximum of two. Households with only people in the 0-14 age group were filtered out of the PUMS data. The household type summary was converted to a probability of a person in a given age group being in each specific household type. Since a household is often comprised of several people, applying the probabilities to each age group create multiple different estimate of households by type. Gregor (2011) explains the computational process used in the synthesis process to account for this:

"An [iterative proportional fitting] IPF process was used to reconcile the household type estimates and create a consistent set of households. The first control for the IPF process is to match the population forecasts by age category. The second control is to create a consistent forecast of the number of households of each type. Each iteration is comprised of the following steps:

1. Persons of each age group are allocated to households by type by applying the calculated probabilities to the number of persons in each age category.

2. The persons allocated by household type are converted to households by type by dividing persons in each age category and type by the corresponding persons by age for that household type. For example, 100 persons of age 0 – 14 allocated to household type 2-0-0-2-0-0, implies 50 households of that type.

3. The result of step #2 will be several conflicting estimates of the number of households of each type. The method used to resolve the differences in the estimates is the "mean" method that chooses the average of the estimates.

4. The resolved number of households for each type computed in step #3 is multiplied by the corresponding number of persons in each age group to yield an estimate of the number of persons by age group and household type.

5. A new table of household type probabilities for each age group is computed from the step #4 tabulation.

6. The sum of persons by age group is calculated from the results of step #4 and subtracted from the control totals of persons by age group to determine the difference to be reallocated.

7. The person differences are allocated to household types using the probabilities calculated in step #5.

These steps are repeated until the difference between the maximum number of households and the resolved number of households computed for every household type is less than 0.1 per cent or until a maximum number of iterations (default 100)." (Gregor, 2011, pp. 12-13)

Household Income Models

The household income model is a regression model that estimates household income based on the number of people in each group in the household size and the average per capita income for the region. The regression model's coefficients were estimated using Census PUMS

data and are shown in Table B-3. The dependent variable is a power transform of income, with an exponent of 0.4, following the observed distribution of the PUMS income data. The average per capita income is also power transformed with the same exponent. The effect on income of additional household member initially increases with age, peaks in the 30-54 age group, where people's earning power and labor force participation typically peaks), and then declines for the older age groups.

Table B-3: Household Income Model

Description	Coefficients	Estimate
Average per Capita Income (Power Transform)	PowPerCapInc	0.792567
Number of Persons per Household Age 0-14	Age0to14	-1.008610
Number of Persons per Household Age 15-19	Age15to19	0.938870
Number of Persons per Household Age 20-29	Age20to29	7.740331
Number of Persons per Household Age 30-54	Age30to54	15.190270
Number of Persons per Household Age 55-64	Age55to64	13.149690
Number of Persons per Household Age 65+	Age65Plus	8.410674

Applying a regression model does not recreate the variability in incomes observed in the data, and therefore a random variable is added to the model's predictions (drawn from a standard normal distribution). Figure B-1 shows that, with this term added, the model closely replicated the distribution of income observed in the PUMS data (Gregor, 2011, pp. 16-20).

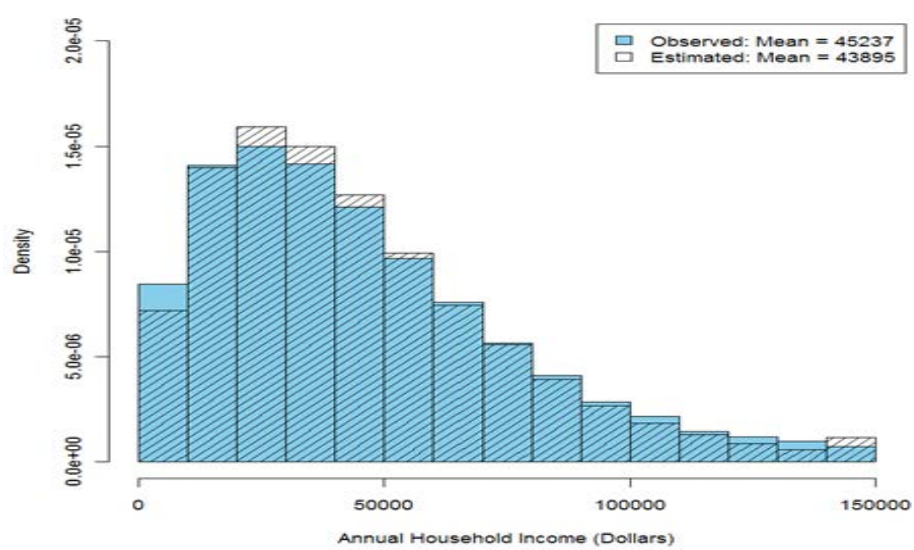


Figure B-1: Distribution of Observed and Adjusted Modeled Household Incomes

Firm Size Models

In the firm size model, county-level estimates of employment by size of business for each industry are transformed into a set of firm records where each firm is defined by the number of employees in each of eight size categories in the firm (1-19; 20-99; 100-249; 250-499; 500-999;

1,000-2,499; 2,500-4,999; and over 5,000 employees) and by its industry. The firm size model synthesizes the individual firms by enumerating the county level summaries. The county-level estimates of employment by size of business and industry were obtained from County Business Pattern data (http://www.census.gov/econ/cbp/) (Samimi et al, 2010).

Sources

The household age and income models were adapted from the Greenhouse Gas Statewide Transportation Emissions Planning (GreenSTEP) Model Documentation (November, 2010) prepared by Brian Gregor of the Oregon Department of Transportation, Transportation Planning Analysis Unit and the subsequent Energy and Emissions Reduction Policy Analysis Tool Model Documentation (draft August 2011) prepared by Resource Systems Group for the Federal Highway Administration.

The firm size model was adapted from the Freight Activity Microsimulation Estimator (FAME) project conducted by Amir Samimi, Kouros Mohammadian, and Kazuya Kawamura from the University of Illinois at Chicago for the National Center for Freight, Infrastructure, Research and Education (CFIRE) at the University of Wisconsin-Madison and the Illinois Department of Transportation and the subsequent application of this model as part of the Tour and Supply Chain Modeling for Freight in Chicago project conducted by Resource Systems Group for the Federal Highway Administration.

Urban Form Models

Household Allocation to Urban Form

The purpose of these models is to allocate synthesized households to different types of urban form. These include the type of area where the household or firm resides (urban core, close in community, suburban, rural), the population and employment density (persons per square mile) of the Census tract where the household or firm resides, and the urban form characteristics of the Census tract where the household or firm resides (urban mixed-use vs. other). The synthesized households and firms are placed into 13 place types, defined by four area types:

- **Urban Core –** includes high density commercial developments (primarily)
- **Close in Community –** includes medium density commercial and medium density residential developments
- **Suburban –** includes low density residential areas (primarily) and low density commercial development
- **Rural –** includes Greenfield developments only

And five types of development:

- **Residential –** primarily located in suburban areas, but can also occur in close in community and urban core areas

- **Commercial –** located in urban core areas (primarily) but also found in close in communities and suburban areas, but in lower densities
- **Mixed-Use –** found in urban core and close in community areas (primarily) but can also be found in suburban areas
- **Transit Oriented Development (TOD)**
- **Greenfields –** only occurs in rural areas

The 13 place types are derived from three area types (urban core, close in community and suburban) and four development patterns (residential, commercial, mixed-use, and transit oriented development) plus the rural/greenfields place type.

The household allocation model is comprised of the following elements:

- **Area type model -** a multinomial logit model to predict the probability that a household will reside in each of the area types based on their household income and a set of variables describing the household type.
- **Model calibration algorithm -** an algorithm that adjusts the allocation probabilities so that the overall allocation of households matches the growth by place type input for the scenario.
- **Area type allocation -** a Monte Carlo simulation to allocate each household to a specific area type based on the calibrated probabilities from the previous step.
- **Development type allocation** - a proportional allocation process (based on the development type proportions for the scenario) to allocate households to a development type within each area type.
- **Population density calculation -** a draw from an observed distributions of population densities to assign a specific population tract density to each household, based on their area and development type.

Area Type Model

The 2001 National Household Travel Survey (NHTS) provides a dataset which allows us to identify relationships between demographic data and allocation of households to various area types. A multinomial logit model estimated using the NHTS dataset predicts the probability that a household will reside in each of the area types based on their household income and a set of variables describing the characteristics of the household.

The model predicts the area types defined in the NHTS data in the "Hthur" urban/rural variable, a post processed variable that was added to the NHTS dataset by Claritas, Inc., and is described in Appendix Q of the 2001 NHTS Users Guide (http://nhts.ornl.gov/2001/usersguide/UsersGuide.pdf). "The classification that is reflected in the urban/rural variable is based on population density, but not just the density of a specific geography, but the density in context of its surrounding area, or "contextual density". To establish this classification, the United States was divided into a grid to reduce the impact of variation in size (land area) of census tracts and block groups. Density was converted into

centiles, that is, the raw numbers (persons per square mile) were translated into a scale from 0 to 99:

- "Rural" (centiles 19 and less) based on density
- "Small town" (centiles 20 to 39) based on the density
- Population centers were defined if a route through the 8 neighboring cells could be constructed in which the density of successive cells was decreasing or equal.
- Population centers with centiles greater than 79 were designated "urban."
- Other centers were classified as "second cities."
- "Suburban" areas of the population centers were defined, using both the cell density and the cell's density relative to the population center's density." (US DOT, 2001)

At the stage in the overall model process that the area type model is applied, the population has been synthesized and the household income model has been applied. Therefore, the variables that are available to predict the area type that the household will probably live in are household size, the ages of household members, and household income. In addition, various household structure variables can be constructed to describe the household, such as "singletons" (households that comprise one person of working age). The distributions of these variables were found to be related to the area type where households in the NHTS dataset lived.

Figure B-2 shows how household size distributions are different in each of the five area types defined in the NHTS. Household size skews lowest in the more urbanized area types (second city and urban), and skews highest in the least urbanized area types (rural and town). Suburban falls in between these two extremes. Figure B-3 shows how the distribution of

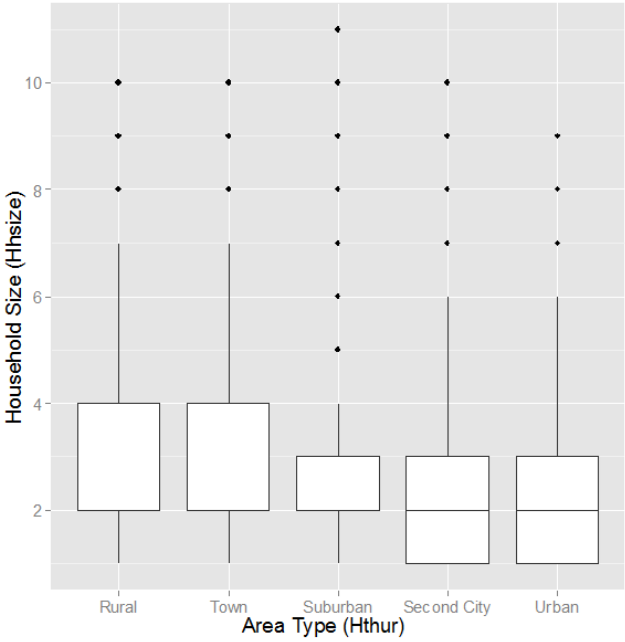


Figure B-3: Distribution of Household Size for each Area Type

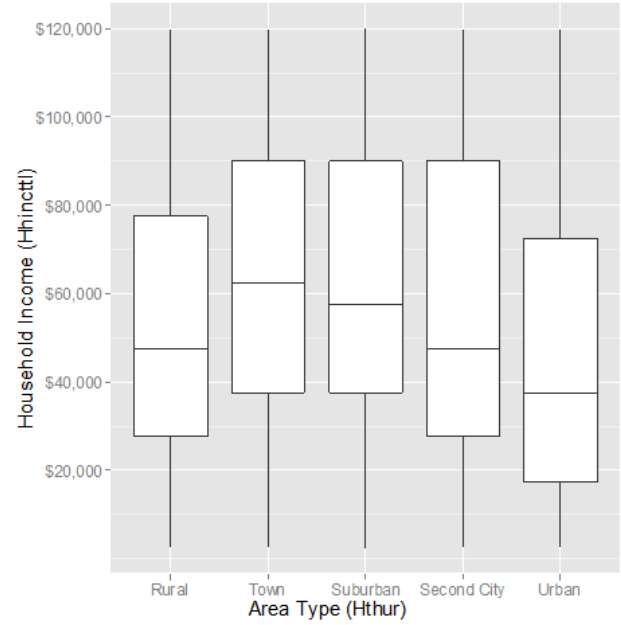


Figure B-2: Distribution of Household Income for each Area Type

household income varies across the five area types. The urban area type is notable as having the lowest median income, with the highest median incomes in suburban and town area types, with second city and rural areas in between.

Several household structure variables were constructed based on the household size and age variables developed in the household synthesis model. They were developed to segment the household population in to several approximately equal parts (and so are mutually exclusive) based on factors that theoretically affect travel behavior (e.g. presence of children in the household, presence and number of working age adults). The variables are:

- Singletons: Households that are made up of one person of working age
- Couple No Kids: Households that are made up of two people of working age
- Children: Households that include children
- Only Elderly: Households where all household members are 65 years old or older

Table B-4 shows the variation in area type distribution among households in the four different area types. The "singleton" households are the group most heavily skewed towards residence in urban areas. The "couple no kids" group is relatively evenly distributed by area type, as is the "only elderly" groups, with the highest proportions in rural and second city area types respectively. The "children" group is the group most heavily skewed away from urban areas. The household income variable (specific in thousands of dollars) also follows the trend shown above, with the probability of residence in areas other than urban increasing as income increases, and particularly for suburban and town area types.

Table B-4: Variation in Area Type Distribution by Household Structure Variable

Area Type	Singleton	Couple No Kids	Children	Only Elderly
Urban	25%	19%	23%	19%
Second City	16%	21%	27%	21%
Suburban	14%	22%	28%	17%
Town	10%	23%	33%	17%
Rural	10%	25%	32%	16%
Total	100%	100%	100%	100%

Table B-5 shows the coefficients on the area type multinomial logit model. The model was estimated using 19,527 observations, one for each metropolitan area household in the 2001 NHTS (with some screening of data to remove some incomplete records).

The model specification includes alternative specific constants for four of the five area types, with the urban area type as the base alternative specified without a constant. Membership of each of the four household groups is coded as a set of dummy variables of four of the five area types; again, the urban area type is used as the base alternative. The values of the coefficients reflect the trend shown above. For example, the values for singletons are all negative relative to the implicit zero value of urban and the values for children are all positive relative to the implicit zero value of urban.

In order to apply the model, the differences between the area types described in the Hthur variable in the NHTS and the area types used in this model must be reconciled. The translation implemented in the application is straightforward:

- Urban Core = Urban
- Close in Community = Second City
- Suburban = Suburban
- Rural = Rural and Town

The area type model as estimated will allocate households to the area types in similar overall proportions to those seen in the NHTS sample that was used to estimate the model (with some differences based on for example average income for the scenario). However, it is important for the allocation process to conform to the growth distribution by place type entered as an input to the scenario. This means that the allocation must be adjusted. This is achieved using an iterative calibration process, during which the alternative specific constants in the model are adjusted until the overall allocation matches the target distribution by place type. During each iteration, the modeled and target area type shares are compared and the alternative specific constants for each area type are adjusted by a value of natural log (target share/modeled share).

Sources

The urban form models were developed specifically for this project using place types that were initially developed for the Smart Growth Transect and further refined by the Caltrans Smart Mobility project and combined with place types from Reconnecting America. The models were developed using the National Household Travel Survey collected by the U.S. Department of Transportation.

Table B-5: Area Type Model

Description	Variable	Estimate	T-Stat
Alternative Specific Constant, Second City Area Type	ASC_City	-1.07	-13.6
Alternative Specific Constant, Rural Area Type	ASC_Rural	-1.43	-13.9
Alternative Specific Constant, Suburban Area Type	ASC_Suburban	-0.348	-5.7
Alternative Specific Constant, Town Area Type	ASC_Town	-0.903	-13.0
Singleton Dummy Variable, Second City Area Type	Singleton_City	-0.284	-3.3
Singleton Dummy Variable, Rural Area Type	Singleton_Rural	-1.07	-8.2
Singleton Dummy Variable, Suburban Area Type	Singleton_Suburban	-0.505	-7.7
Singleton Dummy Variable, Town Area Type	Singleton_Town	-0.872	-10.9
Children Dummy Variable, Second City Area Type	Children_City	0.119	1.5
Children Dummy Variable, Rural Area Type	Children_Rural	0.0962	0.9
Children Dummy Variable, Suburban Area Type	Children_Suburban	0.00304	0.1
Children Dummy Variable, Town Area Type	Children_Town	0.119	1.8
Couple No Kids Dummy Variable, Second City Area Type	CoupleNoKids_City	0.0824	1.0
Couple No Kids Dummy Variable, Rural Area Type	CoupleNoKids_Rural	0.0908	0.9
Couple No Kids Dummy Variable, Suburban Area Type	CoupleNoKids_Suburban	-0.0725	-1.1
Couple No Kids Dummy Variable, Town Area Type	CoupleNoKids_Town	-0.0918	-1.3
Only Elderly Dummy Variable, Second City Area Type	OnlyElderly_City	0.347	4.1
Only Elderly Dummy Variable, Rural Area Type	OnlyElderly_Rural	-0.347	-2.9
Only Elderly Dummy Variable, Suburban Area Type	OnlyElderly_Suburban	0.13	1.9
Only Elderly Dummy Variable, Town Area Type	OnlyElderly_Town	0.0623	0.8
Household Income ($1000s), Second City Area Type	Hhinc_City	0.00708	9.5
Household Income ($1000s), Rural Area Type	Hhinc_Rural	0.00123	1.2
Household Income ($1000s), Suburban Area Type	Hhinc_Suburban	0.0123	20.8
Household Income ($1000s), Town Area Type	Hhinc_Town	0.0128	19.2

Number of observations = 19,527
Number of parameters = 24
Intial log likelihood = -31,427.49
Final log likelihood = -28,212.36
Rho square = 0.102

Vehicle Models

Vehicle Ownership

The vehicle ownership model is a two stage model that estimates the number of vehicles owned by each household in the synthesized population. The first stage of the model allocates households to one of four categories based on the ratio of vehicles to driving age people in the household, using a series of binomial logit models: (1) Zero vehicles, (2) Fewer than one vehicle per driving age person, (3) One vehicle per driving age person, and (4) More than one vehicle per driving age person. The second part of the model identifies the actual number of vehicles for category 2 and category 4 households. The independent variables in the models include freeway supply, transit supply and urban type variables (Gregor, 2011, p. 31).

Zero-Vehicle Models

Table B-6 to Table B-8 show the models for households with zero vehicles, which are segmented into three groups based on the number of driving age people in the household (one, two, and three or more (Gregor, 2011, p. 32). Some variables are interacted with other variables to include effects from a combination of these variables. For example, household income is interacted with urban mixed use areas to show that there will be more zero-vehicle households with one driving age person in the household in urban mixed use areas as income increases. This will counteract the negative coefficient on household income for zero-vehicle households and add to the positive coefficient on households in an urban mixed use area. It can explain the phenomenon that some higher income households will choose to live in urban mixed use areas without a car as a lifestyle choice.

Table B-6: Zero-Vehicle Household Models - One Driving Age Person in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	-0.683
Total annual household income in dollars	Hhincttl	-0.00011
Census tract population density in persons per square mi	Htppopdn	0.00011
Annual transit revenue miles per person	Tranmilescap	-0.0362
Household is in an urban mixed-use area	Urban	1.03
Household income interacted with population density	Hhincttl:Htppopdn	9.06E-10
Household income interacted with transit revenue miles	Hhincttl:Tranmilescap	0.00000095
Household income interacted with urban mixed use area	Hhincttl:Urban	0.0000197
Population density interacted with transit revenue miles	Htppopdn:Tranmilescap	0.000000963
Population density interacted with urban mixed use area	Htppopdn:Urban	-0.0000551
Population density interacted with freeway lane miles	Htppopdn:Fwylnmicap	-0.000119
Transit revenue miles interacted with freeway lane miles	Tranmilescap:Fwylnmicap	0.0577

Table B-7: Zero-Vehicle Household Models - Two Driving Age Persons in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	-1.43
Total annual household income in dollars	Hhincttl	-0.0000679
Household income interacted with population density	Hhincttl:Htppopdn	1.42E-09
Household income interacted with elderly populations	Hhincttl:OnlyElderly	-0.0000355
Population density interacted with transit revenue miles	Htppopdn:Tranmilescap	0.00000185

Table B-8: Zero-Vehicle Household Models - Three or More Driving Age Persons in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	-3.49
Total annual household income in dollars	Hhincttl	-0.000049
Census tract population density in persons per square mi	Htppopdn	0.0000972
Household income interacted with population density	Hhincttl:Htppopdn	7.31E-10
Transit revenue miles interacted with freeway lane miles	Tranmilescap:Fwylnmicap	0.0755

More Drivers than Vehicles Models

The models are segmented into three groups defined by the number of persons of driving age in the household: one driving age person, two driving age persons, three or more driving age persons. Table B-9 to Table B-10 show the models for households with more drivers than vehicles.

Table B-9: <1-Vehicle per Driving Age Person Household Models - Two Driving Age Persons in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	-0.263
Total annual household income in dollars	Hhincttl	-0.0000459
Census tract population density in persons per square mi	Htppopdn	0.0000565
When all persons in the household are over 65 years old	OnlyElderly	1.74
Household income interacted with population density	Hhincttl:Htppopdn	1.19E-09
Household income interacted with transit revenue miles	Hhincttl:Tranmilescap	0.000000334
Household income interacted with elderly populations	Hhincttl:OnlyElderly	0.00000936
Population density interacted with transit revenue miles	Htppopdn:Tranmilescap	-0.00000143
Population density interacted with urban mixed use area	Htppopdn:Urban	-0.0000475
Population density interacted with elderly populations	Htppopdn:OnlyElderly	-0.0000271
Transit revenue miles interacted with urban areas	Tranmilescap:Urban	0.0295
Elderly populations interacted with transit revenue miles	OnlyElderly:Tranmilescap	-0.0129

Table B-10: <1-Vehicle per Driving Age Person Household Models - Three or More Driving Age Persons in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	0.934
Total annual household income in dollars	Hhincttl	-0.0000183
When all persons in the household are over 65 years old	OnlyElderly	5.21
Household income interacted with transit revenue miles	Hhincttl:Tranmilescap	0.000000166
Household income interacted with urban mixed use area	Hhincttl:Urban	0.0000131
Household income interacted with elderly populations	Hhincttl:OnlyElderly	-0.00012
Population density interacted with urban mixed use area	Htppopdn:Urban	-0.0000489
Population density interacted with transit revenue miles	Htppopdn:Fwylnmicap	0.0000893
Urban mixed use areas interacted with freeway lane miles	Urban:Fwylnmicap	-0.689

Equal Drivers and Vehicles Models

The models are segmented into three groups defined by the number of persons of driving age in the household: one driving age person, two driving age persons, three or more driving age persons. Table B-11 to Table B-13 show the models for households with one vehicle for each driving age person in the household.

Table B-11: One-Vehicle per Driving Age Person Household Models - One Driving Age Person in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	0.622
Annual transit revenue miles per person	Tranmilescap	0.0233
Household income interacted with population density	Hhincttl:Htppopdn	1.13E-09
Household income interacted with transit revenue miles	Hhincttl:Tranmilescap	-0.000000276
Household income interacted with elderly populations	Hhincttl:OnlyElderly	0.0000072
Population density interacted with transit revenue miles	Htppopdn:Tranmilescap	-0.00000166
Population density interacted with urban mixed use area	Htppopdn:Urban	-0.0000454
Population density interacted with transit revenue miles	Htppopdn:Fwylnmicap	0.0000408
Elderly populations interacted with transit revenue miles	OnlyElderly:Tranmilescap	-0.00776

Table B-12: One-Vehicle per Driving Age Person Household Models - Two Driving Age Persons in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	0.153
Total annual household income in dollars	Hhincttl	0.00000579
Census tract population density in persons per square mile	Htppopdn	0.0000402
Household is in an urban mixed-use area	Urban	-0.381
When all persons in the household are over 65 years old	OnlyElderly	-0.554
Household income interacted with population density	Hhincttl:Htppopdn	2.41E-10
Household income interacted with urban mixed use area	Hhincttl:Urban	0.00000818
Household income interacted with elderly populations	Hhincttl:OnlyElderly	0.00000711
Population density interacted with transit revenue miles	Htppopdn:Tranmilescap	-0.00000179
Population density interacted with urban mixed use area	Htppopdn:Urban	-0.0000494

Table B-13: One-Vehicle per Driving Age Person Household Models - Three or More Driving Age Persons in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	-1.28
Total annual household income in dollars	Hhincttl	0.00000791
Census tract population density in persons per square mile	Htppopdn	-0.0000576
Household income interacted with population density	Hhincttl:Htppopdn	5.38E-10
Transit revenue miles interacted with urban areas	Tranmilescap:Urban	-0.0204

Fewer Drivers than Vehicles Models

The models are segmented into three groups defined by the number of persons of driving age in the household: one driving age person, two driving age persons, three or more driving age persons. Table B-14 to Table B16 shows the models for households with more drivers than vehicles.

Table B-14: >1-Vehicle per Driving Age Person Household Models - One Driving Age Person in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	-1.75
Total annual household income in dollars	Hhincttl	0.0000161
Census tract population density in persons per square mile	Htppopdn	-0.0000567
When all persons in the household are over 65 years old	OnlyElderly	-1.02
Population density interacted with transit revenue miles	Htppopdn:Tranmilescap	-0.00000119
Population density interacted with urban mixed use area	Htppopdn:Urban	0.0000453
Urban mixed use areas interacted with freeway lane miles	Urban:Fwylnmicap	-0.946
Elderly populations interacted with freeway lane miles	OnlyElderly:Fwylnmicap	1.11

Table B-15: >1-Vehicle per Driving Age Person Household Models - Two Driving Age Persons in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	-1.96
Total annual household income in dollars	Hhincttl	0.00000757
Freeway lane miles per 1000 persons	Fwylnmicap	0.764
When all persons in the household are over 65 years old	OnlyElderly	-0.665
Household income interacted with population density	Hhincttl:Htppopdn	5.78E-10
Population density interacted with transit revenue miles	Htppopdn:Tranmilescap	-0.00000127
Population density interacted with urban mixed use area	Htppopdn:Urban	0.0000287
Population density interacted with transit revenue miles	Htppopdn:Fwylnmicap	-0.000156
Transit revenue miles interacted with urban areas	Tranmilescap:Urban	-0.0227

Table B-16: >1-Vehicle per Driving Age Person Household Models – Three or More Driving Age Persons in Household

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	-1
Census tract population density in persons per square mile	Htppopdn	-0.000301
Annual transit revenue miles per person	Tranmilescap	-0.0129
Household income interacted with population density	Hhincttl:Htppopdn	2.21E-09

Vehicle Type Models

The light truck model predicts the vehicle type – autos or light trucks – for each vehicle in each household. The model is a binary logit model that was estimated using NHTS data. In application, the model is calibrated to match input regional light truck proportions (Gregor, 2011, p. 84). Table B-17 shows the model's coefficients and statistics for the western Census region.

"The model includes both a population density and logged population density term. Plots of the relationship between population density and light truck ownership showed there to be a nonlinear relationship. The relationship with population density is approximately linear at higher densities while the relationship with the log of population density is approximately linear at lower population densities." (Gregor, 2011, p. 85)

Table B-17: Light Truck Type Model (western Census region)

Description	Variable	Estimate
Total annual household income in dollars	Hhincttl	0.0000106
Number of vehicles in the household	Hhvehcnt	0.375
Household is in an urban mixed-use area	Urban	-3.74
Natural log of the Census tract population density	LogDen	-0.174
Household income interacted with household vehicles	Hhincttl:Hhvehcnt	-0.00000377
Population density interacted with household vehicles	Htppopdn:Hhvehcnt	0.00000878
Population density interacted with urban mixed use area	Htppopdn:Urban	-0.0000549
Urban mixed use area interacted with log of population density	Urban:LogDen	0.445

As it is important to match current, past and forecast light truck proportions, the model calibrates to input light truck proportion for the region by iteratively adding a constant to the model in the application.

Vehicle Age Model

The vehicle age model assigns an age (vintage) to each vehicle for each household. This allows the model to capture effects such as variations in vehicle age by household income. Higher income households tend to own newer vehicles (Figure B-4), which is important as vehicle age affects fuel economy, and hence fuel expenditures. The model is based on the observed joint and marginal distributions of automobiles and light trucks by age and household income from NHTS data, and is calibrated to match a state's vehicle age distribution using an IPF procedure (Gregor, 2011, p. 87). A Monte Carlo process is used to draw from these joint distributions to select an age for each vehicle (Gregor, 2011, p. 88).

If the Monte Carlo process is run without a fixed seed, each run will produce different results. Figure B-5 and Figure B-6 show the results of 20 runs the auto and light truck vehicle age model respectively for the NHTS western region survey households. The model runs describe a band of results that are consistent with the survey values (Gregor, 2011, p. 89).

Once each vehicle is identified as an auto or light truck and has an age, it is assigned with the average fuel efficiency for that vehicle type and model year. Fuel efficiencies are measured in gasoline equivalent gallons (i.e. energy content of a gallon of gasoline) and are averaged across fuel types. Model users can vary future fuel economy values. The vehicle model also shares household VMT among a household's vehicle using a Monte Carlo process to draw from a distribution of annual miles traveled by vehicles in NHTS data (Figure B-7). "The random assignment of mileage proportions to vehicles assumes that households do not optimize the use of their vehicles to minimize fuel use." (Gregor, 2011, p. 95)

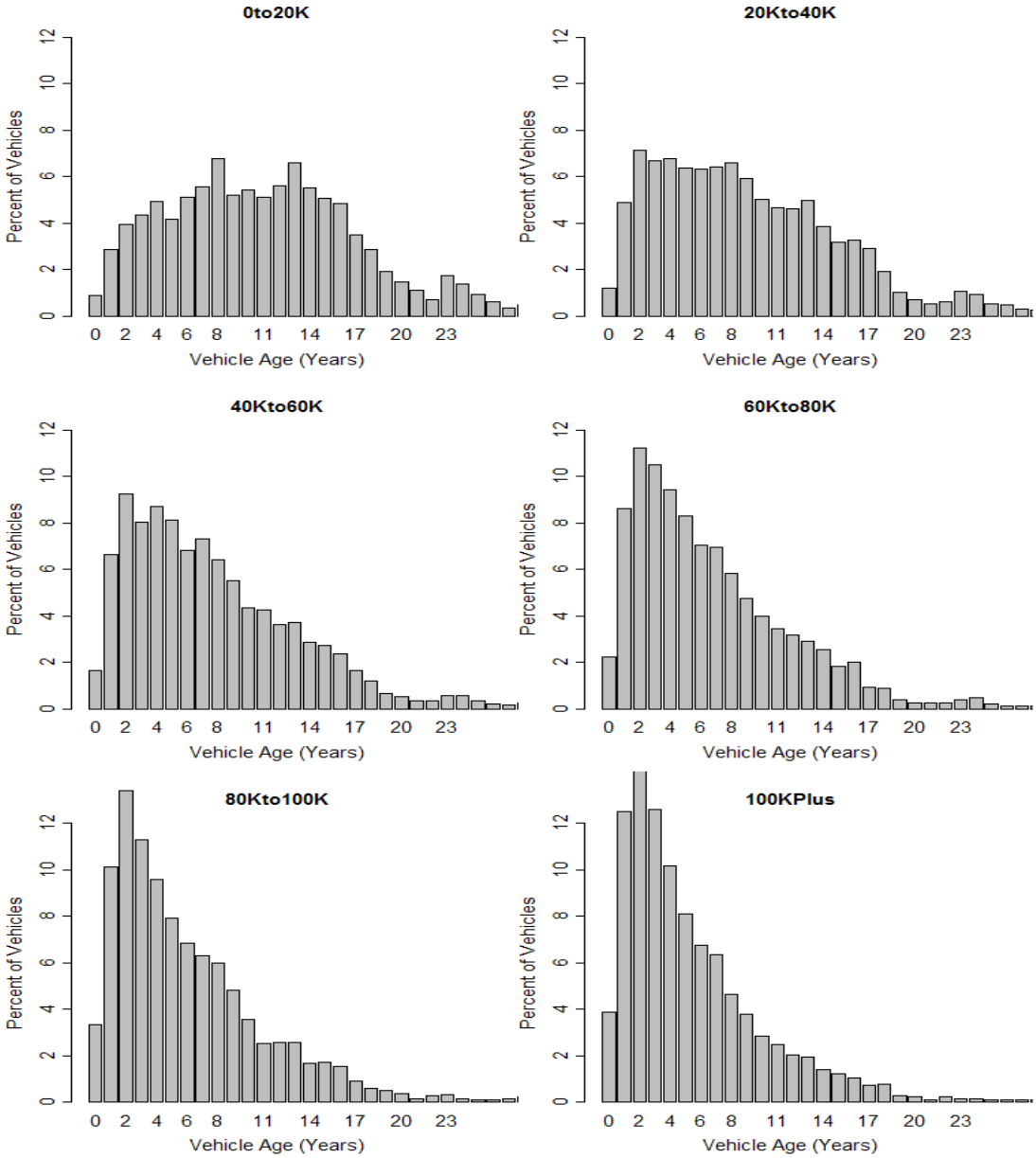


Figure B-4: Vehicle Age Distribution by Household Income Group in Western Census Region Households

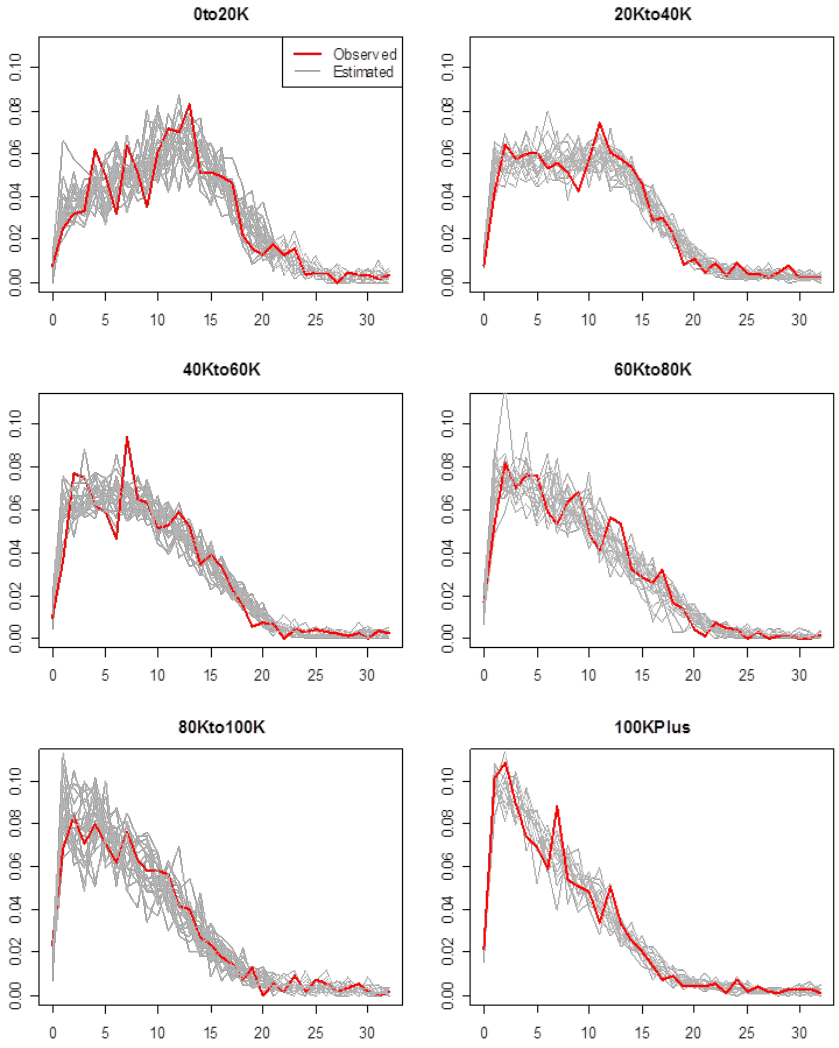


Figure B-5: Observed and Estimated Auto Age Proportions By Income Group (20 model runs)

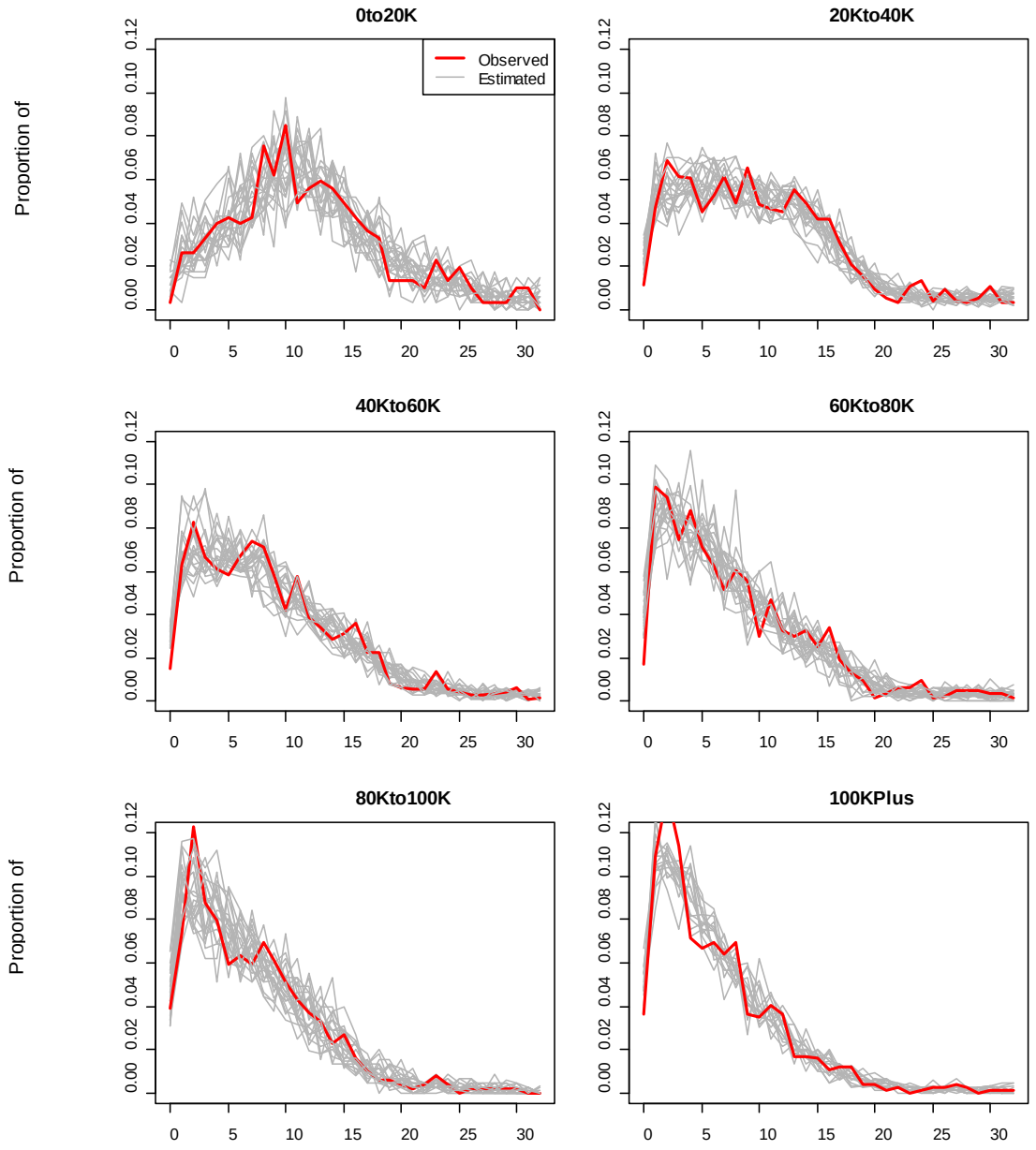


Figure B-6: Observed and Estimated Light Truck Age Proportions By Income Group (20 model runs)

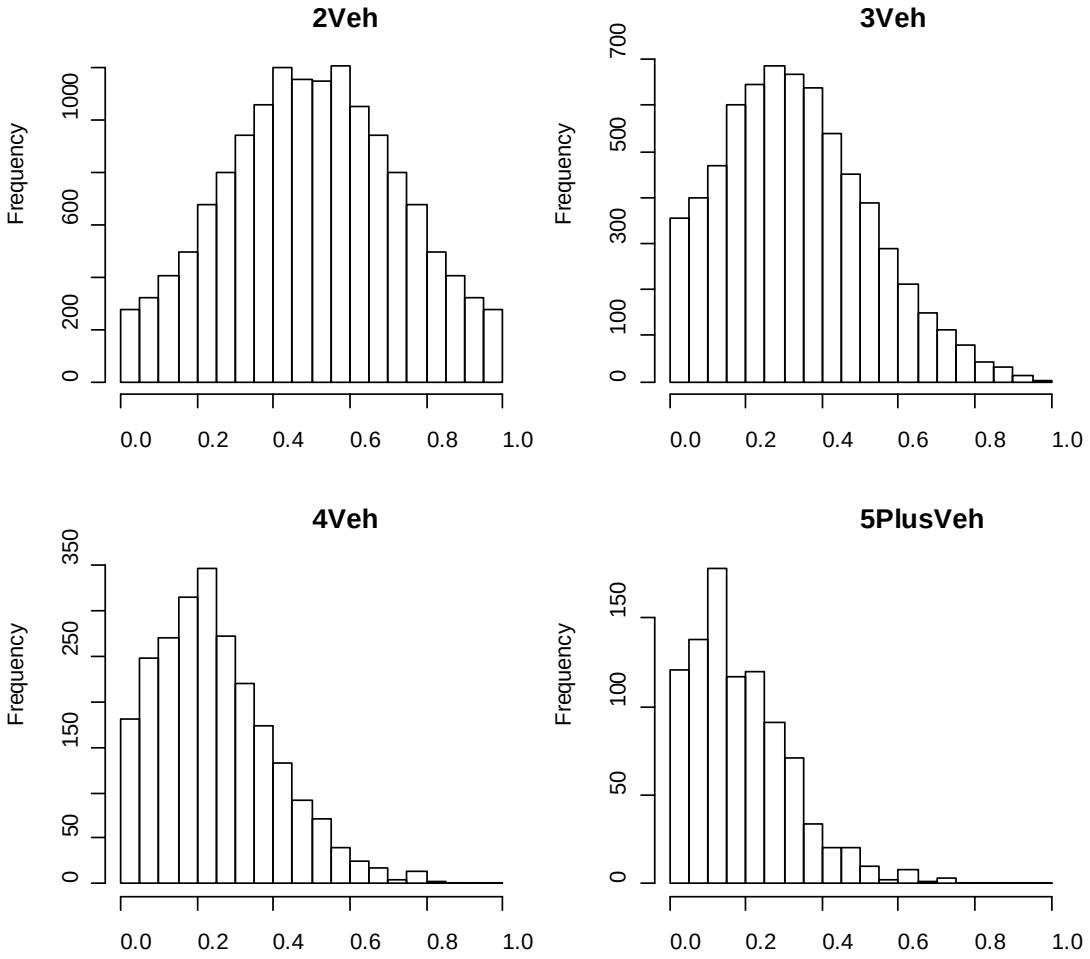


Figure B-7: Distribution of Vehicle Mileage Proportions By Number of Household Vehicles

Non-motorized Vehicle Model

The non-motorized vehicle model predicts the ownership and use of non-motorized vehicles (where non-motorized vehicles are bicycles, and also electric bicycles, Segways and similar vehicles that are small, light-weight and can travel at bicycle speeds or slightly higher than bicycle speeds). "Modeling the potential future effect of non-motorized vehicles is a challenge because of limited information about how people will use two-wheeled electric vehicles in U.S. cities and how the use of non-motorized vehicles in general is affected by the availability of facilities. Given the challenge, the approach taken is to model the potential for diverting household DVMT to non-motorized vehicles rather than modeling the use of non-motorized vehicles. The core concept of the model is that non-motorized vehicle usage will primarily be a substitute for short-distance single-occupant vehicle (SOV) travel. Therefore, the core component of the model is a model of the proportion of the household vehicle travel that occurs in short-distance SOV tours. This model determines the maximum potential for household VMT to be diverted to non-motorized vehicles given a specified tour length threshold." (Gregor, 2011, p. 107)

The factors that determine the total household VMT that is diverted to non-motorized travel are:

The proportion of households that have and use non-motorized vehicles - A model is developed to predict the number of non-motorized vehicles owned by each household. This model is based on NHTS bicycle ownership data. The model is implemented with a function that allows the user to input an overall non-motorized vehicle ownership rate for the population.

The proportion of SOV tours that non-motorized vehicles may be substituted for - A factor is used to include the effect of weather and trip purpose on limiting trips by non-motorized vehicles. This factor is multiplied by the potential VMT that might be diverted by the household for households having non-motorized vehicles to calculate the VMT that is diverted.

Estimating a Stochastic Model of SOV Travel Proportions

The proportion of household VMT in short-distance SOV tours is tabulated from the NHTS day trip data at tour distance thresholds of 5 miles, 10 miles, 15 miles and 20 miles. The data reveals a relationship between the SOV proportions and household income, household size, household VMT, population density, and urban mixed-use character. Figure B-8 shows that the data can be grouped into three categories: (1) households doing no SOV travel, (2) households doing all SOV travel, and (3) households doing some SOV travel, with most households clustered in the first or third groups. As the NHTS data represent a single survey day and not averages for the household, stochastic models were estimated to predict the proportion of SOV travel that might occur on any given day. These were applied 100 times for each household to derive household averages. Linear models were then estimated using the household averages; Table B-18 through Table B-21 show the coefficients and estimation statistics (Gregor, 2011, p. 107).

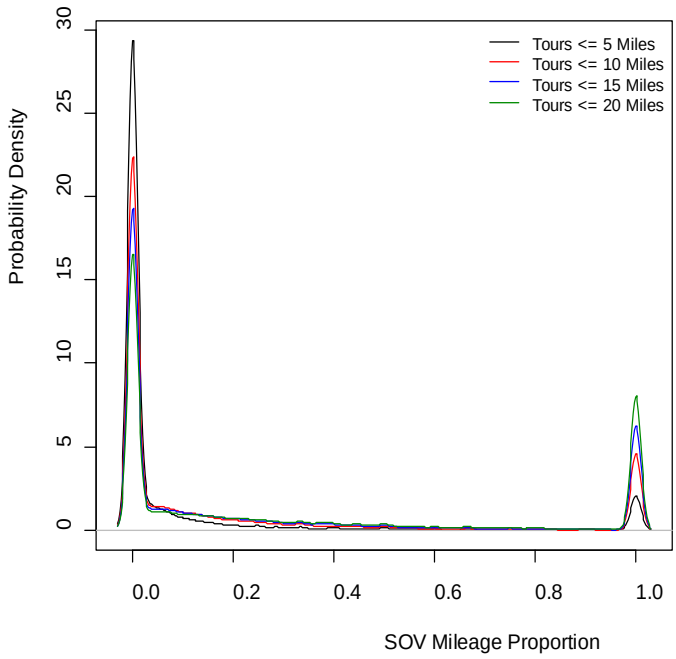


Figure B-8. Distribution of the Proportion of Household DVMT in SOV Tours

Table B-18: Estimation Results for Linear Model of the Proportion of Household VMT in SOV Tours <= 5 Miles

Description	Variable	Estimate
Alternative Specific Constant	**(Intercept)**	**0.532**
Total annual household income in dollars	**Hhincttl**	**-0.00000125**
Log of census tract population density in persons per square mi	**LogDen**	**0.0192**
Log of persons per household	**LogSize**	**-0.265**
Household is in an urban mixed-use area	**Urban**	**0.0888**
Log of daily vehicle miles traveled	**LogDvmt**	**-0.122**
Household income interacted with daily VMT	**Hhincttl:LogDvmt**	**0.000000392**
Log of population density interacted with log of daily VMT	**LogDen:LogDvmt**	**-0.0074**
Log of household size interacted with log of daily VMT	**LogSize:LogDvmt**	**0.0649**
Household income interacted with log of population density	**Hhincttl:LogDen**	**4.26E-08**
Household income interacted with log of household size	**Hhincttl:LogSize**	**-0.000000388**
Household income interacted with urban mixed use area	**Hhincttl:Urban**	**0.000000295**
Log of population density interacted with log of household size	**LogDen:LogSize**	**0.00732**
Log of population density interacted with urban mixed use area	**LogDen:Urban**	**-0.0133**

Table B-19: Estimation Results for Linear Model of the Proportion of Household VMT in SOV Tours <= 10 Miles

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	0.779
Total annual household income in dollars	Hhincttl	-0.000000154
Log of census tract population density in persons per square mi	LogDen	0.033
Log of persons per household	LogSize	-0.359
Household is in an urban mixed-use area	Urban	0.332
Log of daily vehicle miles traveled	LogDvmt	-0.179
Household income interacted with log of daily VMT	Hhincttl:LogDvmt	0.000000159
Log of population density interacted with log of daily VMT	LogDen:LogDvmt	-0.00819
Log of household size interacted with log of daily VMT	LogSize:LogDvmt	0.0862
Urban mixed use area interacted with log of daily VMT	Urban:LogDvmt	0.00419
Household income interacted with log of population density	Hhincttl:LogDen	1.48E-08
Household income interacted with log of household size	Hhincttl:LogSize	-0.000000241
Household income interacted with urban mixed use area	Hhincttl:Urban	0.000000366
Log of population density interacted with log of household size	LogDen:LogSize	0.00435
Log of population density interacted with urban mixed use area	LogDen:Urban	-0.0448
Log of household size interacted with urban mixed use area	LogSize:Urban	0.00509

Table B-20: Estimation Results for Linear Model of the Proportion of Household VMT in SOV Tours <= 15 Miles

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	0.936
Total annual household income in dollars	Hhincttl	0.000000701
Log of census tract population density in persons per square mi	LogDen	0.0274
Log of persons per household	LogSize	-0.366
Household is in an urban mixed-use area	Urban	0.339
Log of daily vehicle miles traveled	LogDvmt	-0.209
Household income interacted with log of daily VMT	Hhincttl:LogDvmt	-6.51E-08
Log of population density interacted with log of daily VMT	LogDen:LogDvmt	-0.0051
Log of household size interacted with log of daily VMT	LogSize:LogDvmt	0.0857
Urban mixed use area interacted with log of daily VMT	Urban:LogDvmt	0.0152
Household income interacted with urban mixed use area	Hhincttl:Urban	0.000000233
Log of population density interacted with urban mixed use area	LogDen:Urban	-0.0503
Log of household size interacted with urban mixed use area	LogSize:Urban	0.0166

Table B-21: Estimation Results for Linear Model of the Proportion of Household VMT in SOV Tours <= 20 Miles

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	1.04
Total annual household income in dollars	Hhincttl	0.00000223
Log of census tract population density in persons per square mi	LogDen	0.0185
Log of persons per household	LogSize	-0.375
Household is in an urban mixed-use area	Urban	0.346
Log of daily vehicle miles traveled	LogDvmt	-0.224
Household income interacted with log of daily VMT	Hhincttl:LogDvmt	-0.000000385
Log of population density interacted with log of daily VMT	LogDen:LogDvmt	-0.000963
Log of household size interacted with log of daily VMT	LogSize:LogDvmt	0.0833
Urban mixed use area interacted with log of daily VMT	Urban:LogDvmt	0.0164
Household income interacted with log of population density	Hhincttl:LogDen	-5.61E-08
Household income interacted with log of household size	Hhincttl:LogSize	0.000000215
Household income interacted with urban mixed use area	Hhincttl:Urban	0.000000143
Log of population density interacted with log of household size	LogDen:LogSize	-0.00277
Log of population density interacted with urban mixed use area	LogDen:Urban	-0.0504
Log of household size interacted with urban mixed use area	LogSize:Urban	0.0108

To constrain the results from linear models to be between 0 and 1, a logistic transform was applied to the results, which also improves the model fit. Parameters were estimated for each mileage threshold that maximized the correlation and minimized the difference in the mean values. The form of the logistic function is as follows (Gregor, 2011, p. 118-119):

$$\text{PropTransform} = \frac{1}{1+\exp(-\alpha \bullet (\text{PropModel} - \beta))} - (0.5 - \beta)$$

The model application interpolates between the results of the seperate distance models, depending on the input tour length threshold. "Figure B-9 shows the distributions in household SOV mileage proportions that result from applying the models with interpolation to a range of thresholds. It also compares the mean values estimated for the 5-, 10-, 15-, and 20-mile thresholds with the mean values from the survey." (Gregor, 2011, p. 121)

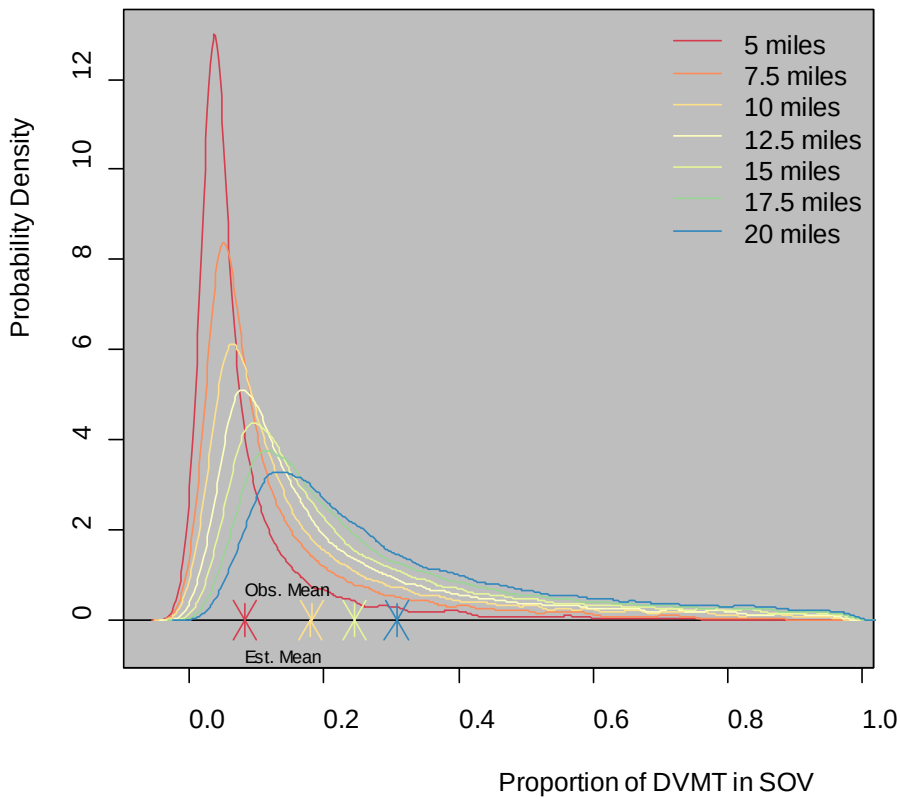


Figure B-9: Comparison of Modeled Distributions of SOV Travel Proportions by Tour Mileage Threshold

Estimating a Non-motorized Vehicle Ownership Model

NHTS survey data on the number of full-sized bicycles in the household was used to estimate the non-motorized vehicle ownership model. Figure B-10 shows how the mean number of full-sized bicycles owned varies with household characteristics and the characteristics of the neighborhood in which the households lives. The linear model predicts the number of bicycles owned by a household based dependent variables including on the ages of household member (AgeXtoY), household income (Hhincttl), household size (Hhsize), the number of vehicles per driving age household member (VehPerDrvAgePop), and the natural log of population density (LogDen). The model's coefficients are shown in Table B-22. In application, the model calibrates to an input target bicycle ownshership level by adjusting the model's intercept (Gregor, 2011, p. 122-123).

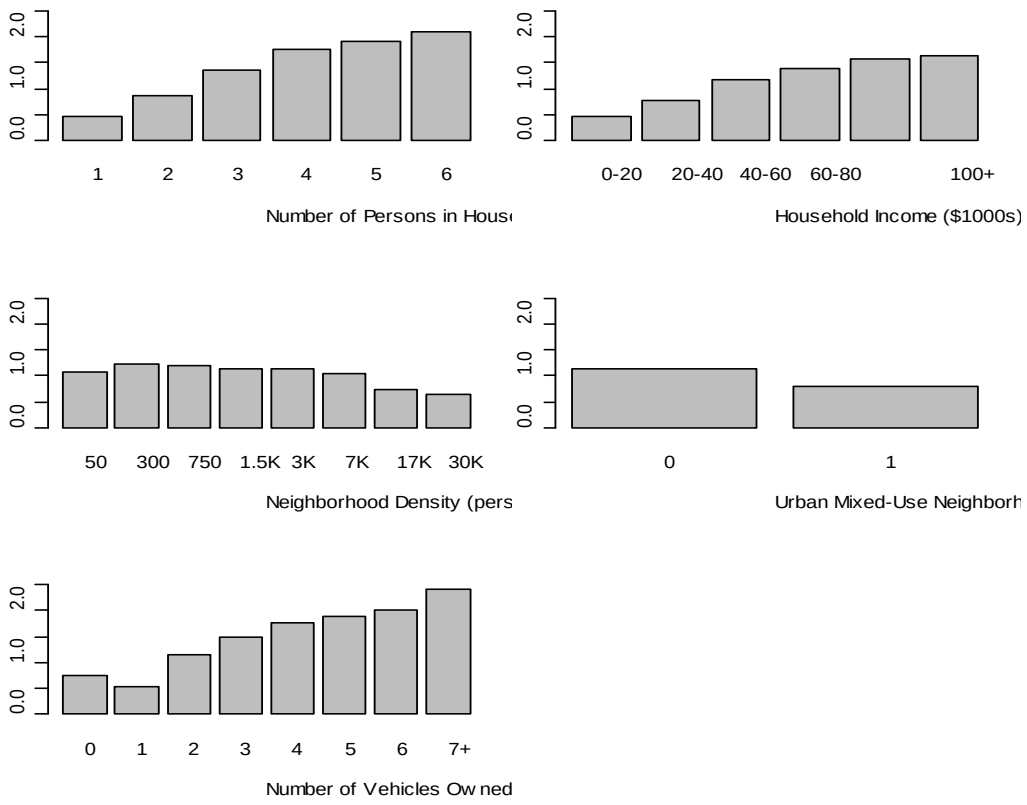


Figure B-10: Mean Number of Full-Sized Bicycles Owned per Household by Household Type and Environmental Characteristics

Table B-22: Household Non-motorized Vehicle Ownership Model

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	0.24
Dummy variable if household is in the Midwest region	Census_rMidwest	0.186
Dummy variable if household is in the Southern region	Census_rSouth	-0.147
Dummy variable if household is in the Western region	Census_rWest	-0.0152
Number of persons per household	Hhsize	0.166
Household income interacted with persons ages 15-19	Hhincttl:Age15to19	0.00000357
Household income interacted with persons ages 30-54	Hhincttl:Age30to54	0.00000249
Household income interacted with persons ages 55-64	Hhincttl:Age55to64	0.00000172
Persons age 15-19 interacted with vehicles per driver	Age15to19:VehPerDrvAgePop	0.217
Persons age 20-29 interacted with vehicles per driver	VehPerDrvAgePop:Age20to29	0.164
Persons age 30-54 interacted with vehicles per driver	Age30to54:VehPerDrvAgePop	0.199
Persons age 55-64 interacted with vehicles per driver	Age55to64:VehPerDrvAgePop	0.212
Persons age 65+ interacted with vehicles per driver	VehPerDrvAgePop:Age65Plus	0.148
Persons age 20-29 interacted with log of population density	Age20to29:LogDen	-0.014
Persons age 30-54 interacted with log of population density	Age30to54:LogDen	-0.0157
Persons age 55-64 interacted with log of population density	Age55to64:LogDen	-0.0264
Persons age 65+ interacted with log of population density	Age65Plus:LogDen	-0.0247

Calculating Non-motorized Weight Vehicle VMT

"Non-motorized vehicle VMT is calculated as follows:

$$LtVehDvmt = SovProp * PropSuitable * LtVehOwnRatio / SharingRatio$$

where:

- SovProp = proportion of DVMT traveled by SOV within specified mileage threshold (calculated by the SOV proportions model)
- PropSuitable = proportion of SOV travel suitable for non-motorized vehicle travel (an input assumption)
- LtVehicleOwnRatio = ratio of non-motorized vehicles to number of driving age persons (non-motorized vehicle ownership calculated by model)
- SharingRatio = ratio of non-motorized vehicles to driving age persons necessary for every person to have a non-motorized vehicle available to meet their needs (e.g. a sharing ratio of 0.5 means that one non-motorized vehicle could be shared by a 2-person household)." (Gregor, 2011, p. 126)

Sources

The vehicles models were adapted from the Greenhouse Gas Statewide Transportation Emissions Planning (GreenSTEP) Model Documentation (November, 2010) prepared by Brian Gregor of the Oregon Department of Transportation, Transportation Planning Analysis Unit and the subsequent Energy and Emissions Reduction Policy Analysis Tool Model Documentation (draft August 2011) prepared by Resource Systems Group for the Federal Highway Administration.

Travel Demand Models

Household Vehicle Miles Traveled Models

The household vehicle miles travel models estimate average household VMT by first predicting, with a binomial logit model, whether each household travels at all by vehicle on a given day and then calculating, with a linear model, the amount of vehicle travel a household is likely to for the day. The models include a stochastic error term to reflect day-to-day variability in household travel.

"As with income, household vehicle travel follows a power distribution. This is shown in the histogram on the left side of Figure B-11. Because the distribution is not normal, transformation is in order to improve the model fit and produce more uniform distribution of residuals. A power transformation with an exponent of 0.18 minimizes the skewness of the distribution. This is shown in the right-hand plot. The right-hand plot illustrates why it is necessary to use two models to predict household VMT. The power transform of household VMT places the zero VMT households in a grouping that is discontinuous with the households

that have some vehicle travel. Including the zero with the other VMT households would distort the model." (Gregor, 2011, p. 41)

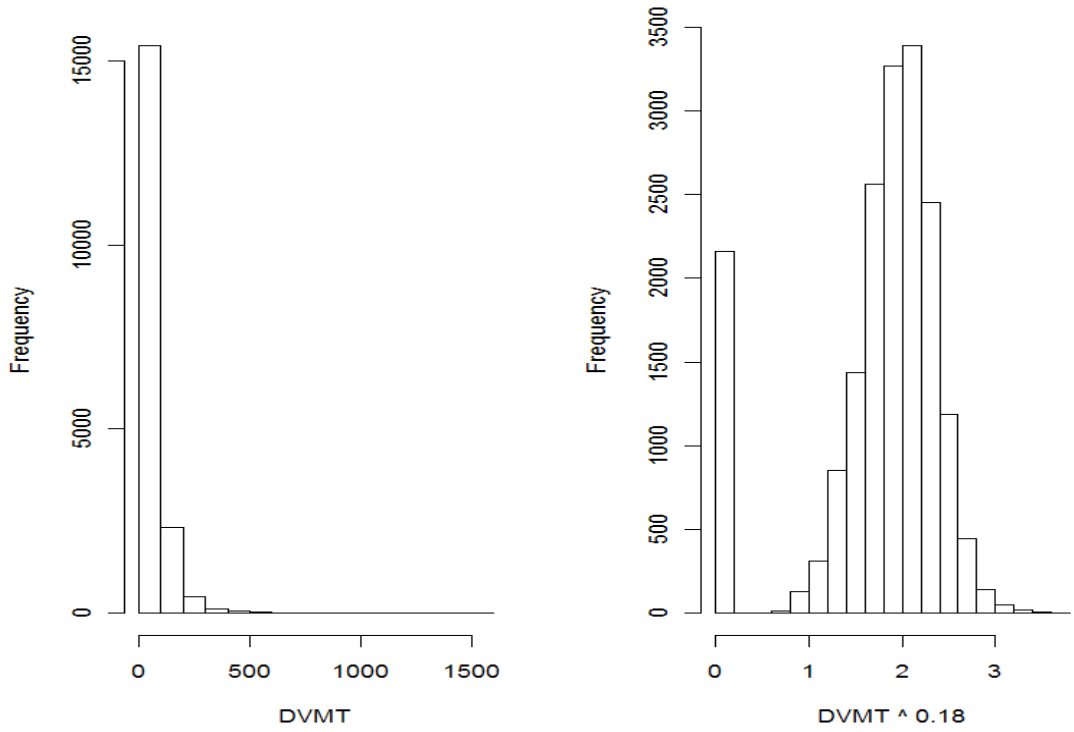


Figure B-11: Household VMT and Power-Transformed VMT

Table B-23 shows the coefficients of the zero VMT household model. "The probability of zero VMT increases with higher population density, zero vehicle ownership, higher levels of transit service, presence of urban mixed-use characteristics, and presence of persons aged 65 or older. The probability of zero VMT decreases with more driving age persons, higher income, more household vehicles, and more persons in the 30 to 54 age group." (Gregor, 2011, p. 43)

Table B-23: Zero VMT Household Model

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	3.7
Number of driving age persons	DrvAgePop	-0.522
Natural log of annual household income	LogIncome	-0.486
Census tract population density in persons per square mile	Htppopdn	0.0000298
Number of persons 65 years old or older in the household	Age65Plus	0.32
Annual transit revenue miles per capita	Tranmilescap	0.00837
Number of household vehicles	Hhvehcnt	-0.361
Households with no vehicles	ZeroVeh	3.43
Transit revenue miles per capita interacting with households in an urban mixed-use area	Tranmilescap:Urban	0.0109

Table B-24 shows the coefficients of the household VMT model. “Higher incomes, more vehicles, more driving age persons, and greater freeway supplies are associated with more vehicle travel. Persons age 65 or older, higher population densities, urban mixed-use characteristics, and higher levels of public transit service are associated with less vehicle travel.” (Gregor, 2011, p. 44)

Table B-24: Household VMT Model

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	0.781
Number of persons 65 years old or older in the household	Age65Plus	-0.0718
Natural log of annual household income	LogIncome	0.0869
Census tract population density in persons per square mile	Htppopdn	-0.00000369
Regional ratio of freeway lane-miles per 1000 persons	Fwylnmicap	0.0338
Household is in an urban mixed-use area	Urban	-0.0518
Number of household vehicles	Hhvehcnt	0.0609
Number of driving age persons	DrvAgePop	0.0723
Transit revenue miles per capita interacting with households in an urban mixed-use area	Htppopdn:Tranmilescap	-5.98E-08

A similar approach to that used with the household income model is followed to replicate the observed variability in the VMT distribution. A normally distributed random error is added to the model to reproduce the distribution. “The size of this “error term” (standard deviation) was estimated by taking the square root of the difference in the observed and estimated variances of the power-transformed VMT. The final value was calibrated by adjusting the estimated value so that the observed and estimated VMT means match.” (Gregor, 2011, p. 45). Figure B-12 and Figure B-13 show that the addition on the error term brings the modeled distribution of VMT much closer to the observed distribution.

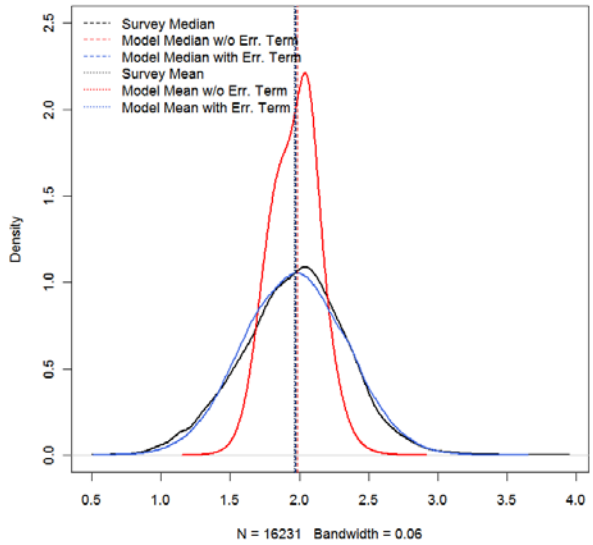


Figure B-12.Observed and Estimated Distributions of Power-Transformed VMT for Metropolitan Households

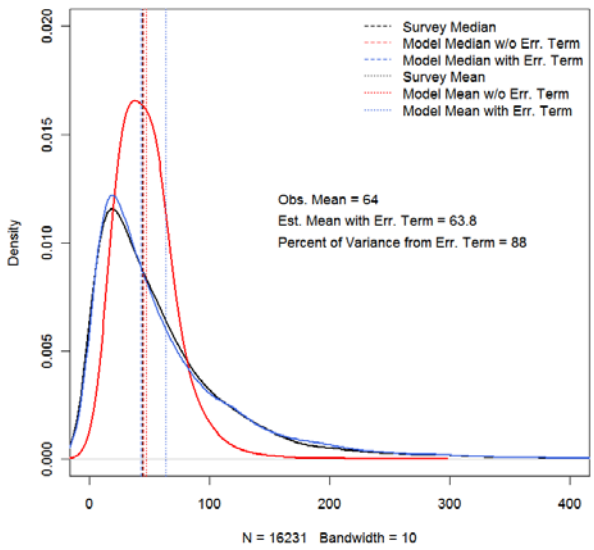


Figure B-13.Observed and Estimated Distributions of VMT for Metropolitan Households

The use of error terms also provides a way to calculate annual average VMT, which is important in order to calculate annual household fuel consumption, costs, and emissions. The NHTS, like most household travel surveys, only collects data for one survey day so it does not report household annual averages. "Kuhnimhof and Gringmuth, using data from the multiday German Mobility Panel, found that the day-to-day variation in personal travel for an individual was much greater than the variation between persons. (pp. 178-185) They estimated that 70 per cent of all variance in mileage per person per day was intrapersonal (i.e. day-to-day variation in a person's travel). If this percentage holds true for variation in household VMT, then day-to-day variation in household vehicle travel would account for 80 percent (0.7 / 0.88) of the unexplained variation in regional household travel that is captured by the calibrated random error term." (Gregor, 2011, p. 48) Therefore, as day-to-day travel variation is likely to be responsible for most of the unexplained variation in household travel, the travel models were run many times to develop distributions of vehicle travel for each household. The zero VMT and daily household VMT models were run 100 times for each household in the survey dataset. This was repeated 30 times and the results averaged for each household.

A linear model for predicting the simulated average VMT was then estimated, as the linear model is much faster in application. Table B-25 shows the coefficients of the model, which are the same as those used in the daily VMT model shown above. "Higher incomes, more vehicles, more drivers, and a greater freeway supply increase the average household VMT. Owning no vehicles, living at higher population density, more public transit service, and living in an urban mixed-use area decrease the average household VMT." (Gregor, 2011, p. 49)

Table B-25: Regional Household Average VMT Model

Description	Variable	Estimate
Alternative Specific Constant	(Intercept)	0.647
Households in the Census Midwest region	Census_rMidwest	0.0000717
Households in the Census South region	Census_rSouth	-0.000735
Households in the Census West region	Census_rWest	0.00155
Natural log of annual household income	LogIncome	0.107
Census tract population density in persons per square mile	Htppopdn	-0.00000316
Number of household vehicles	Hhvehcnt	0.058
Households with zero vehicles	ZeroVeh	-0.59
Annual transit revenue miles per capita	Tranmilescap	-0.000176
Regional ratio of freeway lane-miles per 1000 persons	Fwylnmicap	0.0337
Number of driving age persons	DrvAgePop	0.0857
Number of persons 65 years old or older in the household	Age65Plus	-0.0768
Household is in an urban mixed-use area	Urban	-0.0613
Transit revenue miles per capita interacting with households in an urban mixed-use area	Htppopdn:Tranmilescap	-0.000000115

Vehicle Cost Models

No costs are included in any of the household vehicle travel models. The effects of all variable vehicle costs (costs that vary with the amount of vehicle travel rather than with the number of vehicles owned) on travel are handled by a household travel budget model described in this section. It is important that we be able to reasonably account for the effects of fuel prices and similar variable costs such as fuel or carbon taxes on the amount of vehicle travel. There is a significant interest in using pricing mechanisms to affect the demand for vehicle travel, so we need a model to estimate what the effect of pricing might be. We also need to be able to account for the effect of future fuel price increases on vehicle travel.

The budget approach to modeling is based on the perspective that households make their travel decisions within money and time budget constraints. This was fundamental to the work of Yacov Zahavi in the 1970s and early 1980s. (Zahavi, 1979) More recently, Michael Wegener has referred back to the work of Zahavi and proposed that models need to be based more on budget constraints and less on observed preferences (Wegener, 2008).

The basic model concept is as follows:

- Household spending on gasoline and other variable costs is done within a household transportation budget that is relatively stable. Households shift expenses between transportation budget categories as needed.
- As long as it is possible for the household to shift expenditures among components of the transportation budget, the household response to changes in fuel prices can be inelastic. However, when fuel prices or other variable costs increase to the point where it is no longer possible to shift money from other parts of the transportation budget, the household will necessarily reduce their travel in direct proportion to the cost increase (ceteris paribus).

- The transition between inelastic and elastic behavior will not be abrupt unless there is little time for the household to recognize the impact of the cost increases on the budget or respond to the cost increases. If the changes are more gradual, the transition will be less abrupt.

Total household expenditures on transportation have remained fairly constant over the 25-year period from 1984 to 2008. Changes in gasoline prices appear to have had little or no effect on the quantity of gasoline consumed. Changes in price also appear to have had little or no effect on household VMT. The shifting of household expenditures among the different transportation expenditure categories has been responsible for the inelasticity in household gasoline consumption and household VMT with respect to gasoline price.

Although gasoline consumption and VMT have changed little with respect to price over the last 25 years, it would not be wise to assume that this relationship will continue into the future if gasoline prices increase beyond 2008 levels. If the preceding analysis is correct and households do balance out costs within a fixed transportation budget, there will necessarily be adjustments to gasoline consumption if fuel costs rise to high enough levels. At some point, it would no longer be possible to reduce vehicle purchases or other vehicle expenditures in order to avoid reducing gasoline consumption. Vehicles still need to be insured, licensed, maintained, and repaired. Vehicle purchases can be put off, but not indefinitely. When a household reaches the point when it is no longer possible to shift expenditures to other categories they will have to reduce gasoline consumption. If they cannot increase the fuel economy of the vehicles they drive, they will have to reduce the amount that they drive.

To model the transportation budget it is necessary to estimate the size of the transportation budget. Then it is necessary to estimate the maximum proportion of that budget that can be used for fuel and other variable costs.

The budget model is very simple. First, a base level of travel is estimated using the average household VMT model described in the previous section. This model estimates household travel as a function of the household income, number and ages of persons in the household, population density and mixed-use character where the household resides, freeway supply, and public transit supply. Since 2001 is at the end of a long period of low fuel prices, the model reflects an equilibrium condition between low fuel prices and other factors affecting vehicle travel. It therefore is a good representation of a base level of vehicle travel without budget constraints.

Second, a maximum household budget expenditure is calculated based on the assumption about the maximum proportion of household income that may be spent (a default of 10% of household income is assumed, but the model is not hard-coded with this default value. It is possible to input other values. The most recent consumer expenditure survey (2010) has a 12% transportation expenditure (http://www.bls.gov/opub/focus/volume2_number12/cex_2_12.htm)). From this budget and the base forecast of vehicle travel, a threshold level for average household cost per mile of travel is calculated. If the cost per mile is less than the threshold level, then the household can continue to travel at the base level. If the cost per mile is greater than the threshold, then the household has to reduce the amount of travel in proportion to the increase in cost above the threshold. Figure B-14 shows the shape of the curve for hypothetical households having different incomes. The flat portions of the curves show the potentially inelastic portions

to the left of the threshold. The perfectly elastic portions of the curves are to the right of the cost thresholds.

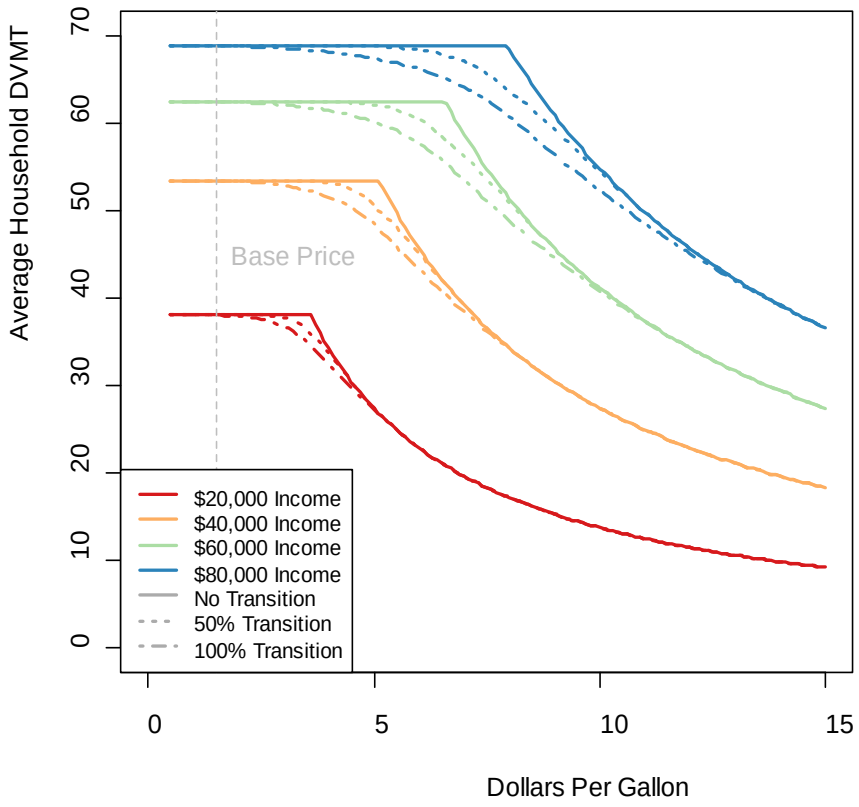


Figure B-14: Illustration of Budget Functions and Transition Curves

The figure also shows transition curves that may be specified between the inelastic and elastic portions of the curves. The transition curves are calculated using a hyperbolic cosine function that is symmetrical about the average cost threshold. These transition curves are specified by the location of the start of the transition between the base cost per mile and the threshold cost per mile.

Several tests were run on this budget model. The purpose of the first set of tests was to calculate the elasticity of travel demand with respect to fuel price. The VMT models were applied to the respective household datasets over a range of fuel prices from $1 to $10 dollars per gallon. Fuel price elasticities were then calculated at each dollar increment in the range. Table B-26 shows the results of modeling assuming a full transition. Elasticities increase as prices increase. They decrease as incomes increase. This appears to be reasonable behavior consistent with the budget principle. The low elasticities at low price increases are consistent with other studies that have found recent price elasticities to be low.

Table B-26: Fuel Price Elasticity Calculated from Application of Regional VMT Model and Budget Model

Income	Fuel Price Range (Dollars per Gallon)								
	$1-$2	$2-$3	$3-$4	$4-$5	$5-$6	$6-$7	$7-$8	$8-$9	$9-$10
$0-$30K	-0.062	-0.288	-0.495	-0.658	-0.776	-0.854	-0.905	-0.939	-0.960
$30K-$40K	-0.021	-0.150	-0.321	-0.482	-0.619	-0.726	-0.804	-0.860	-0.899
$40K-$50K	-0.016	-0.117	-0.268	-0.428	-0.561	-0.669	-0.754	-0.816	-0.862
$50K-$70K	-0.006	-0.068	-0.198	-0.355	-0.498	-0.619	-0.711	-0.781	-0.834
$70K+	-0.002	-0.032	-0.102	-0.201	-0.315	-0.430	-0.538	-0.629	-0.704

The household budget approach solves the problems exhibited by previous models. It matches recent travel trends that have exhibited low fuel price elasticity. It also is sensitive to large increases in prices. Moreover, it does this with a simple and strong conceptual model.

Bus and Passenger Rail Vehicle Miles Traveled

Annual transit revenue miles are calculated to provide inputs to the household vehicle ownership and travel models. It is a straightforward process to compute total bus and passenger rail vehicle miles traveled by multiplying the revenue miles by a factor that accounts for non-revenue service travel. An average of 1.12 is used.

Fleet average bus fuel economy and rail energy efficiency are calculated similarly to the way in it is calculated for light vehicles. Bus and rail fuel economy by model year is an input to the model. Different assumptions on future improvements to fuel economy can be modeled by varying these inputs. Buses and rail cars are assigned to age bins based on a reference age distribution and input assumption for adjusting the 95th percentile vehicle age. The age proportions by model year are used with the fuel economy inputs by model year to compute an overall fleet average fuel economy.

Heavy Truck VMT Model

The forecast of heavy truck VMT is straightforward. Future total regional income is calculated from the forecasts of population and average per capita income. Then the percentage change in total regional income from the base year is calculated. The base year heavy truck VMT is multiplied by this change and any relative change factor the user may have supplied. The Federal Highway Cost Allocation Study is used to calculate the average proportion of truck VMT by urban area functional class (Table B-27).

Table B-27: Heavy Truck VMT Proportions by Urban Functional Class

Functional Class	Heavy Truck Proportion
Principal Arterial – Interstate	8.3%
Principal Arterial – Other Freeway or Expressway	5.6%
Principal Arterial – Other	5.4%
Minor Arterial	4.2%
Collector	3.8%
Local	3.6%

Average fleet fuel economy for heavy trucks is calculated similarly to the way in it is calculated for light vehicles. Heavy truck fuel economy by model year is an input to the model. Different assumptions on future improvements to fuel economy can be modeled by varying these inputs. Heavy trucks are assigned to age bins based on a reference truck age distribution and input assumption for adjusting the 95th percentile truck age. The age proportions by model year are used with the fuel economy inputs by model year to compute an overall fleet average fuel economy.

Sources

The vehicles models were adapted from the Greenhouse Gas Statewide Transportation Emissions Planning (GreenSTEP) Model Documentation (November, 2010) prepared by Brian Gregor of the Oregon Department of Transportation, Transportation Planning Analysis Unit and the subsequent Energy and Emissions Reduction Policy Analysis Tool Model Documentation (draft August 2011) prepared by Resource Systems Group for the Federal Highway Administration.

Congestion by Functional Class

The congestion model estimates speed and hence delay and the impact on fuel economy of congestion for freeways and arterials and for light vehicle, trucks and buses. The first step of the model allocates VMT to a simplified functional class breakdown of freeways, arterials, and other roads. For trucks and buses, VMT is allocated using fixed proportions (as described above). The auto and light truck proportion on freeways and arterials vs. other roads is first calculated using a fixed proportion from the Federal Highway Cost Allocation Study. Then auto and light truck VMT is allocated between freeways and arterials using this regression model, estimated using data from the 2009 Texas Transportation Institute Urban Mobility Report (based on 2007 data) augmented with VMT proportions calculated from Highway Statistics Table HM-71:

*Freeway VMT Proportion=0.07686+2.59032*Freeway Lane Mile Ratio*

Freeway lane mile ratio is the lane miles of freeways divided by the sum of the lane miles of freeways and arterials. When applied to the VMT reported in the 2009 version of the Urban Mobility Report by the Texas Transportation Institute (TTI), the relationship is linear (Figure B-15).

The next stage of the congestion model predicts the proportions of VMT experiencing different levels of congestion using models estimated from Urban Mobility Report categories and data. The level of congestion is described using five categories: uncongested, moderately congested, heavily congested, severely congested, and extremely congested. Figure B-16 shows the relationship between the traffic volume per lane and the amount of VMT allocated to each congestion category for freeways; similar relationships are used for arterials. The portion of allocated VMT is calculated the four categories shown, with the proportion for the moderately congested category calculated as the remainder (Gregor, 2011, p. 131).

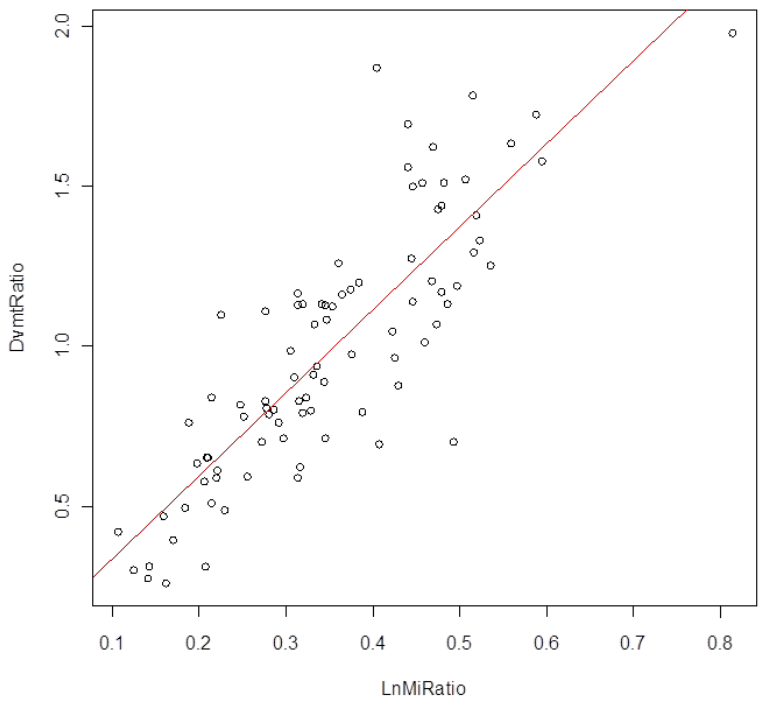


Figure B-15: Relationship of Freeway to Arterial VMT

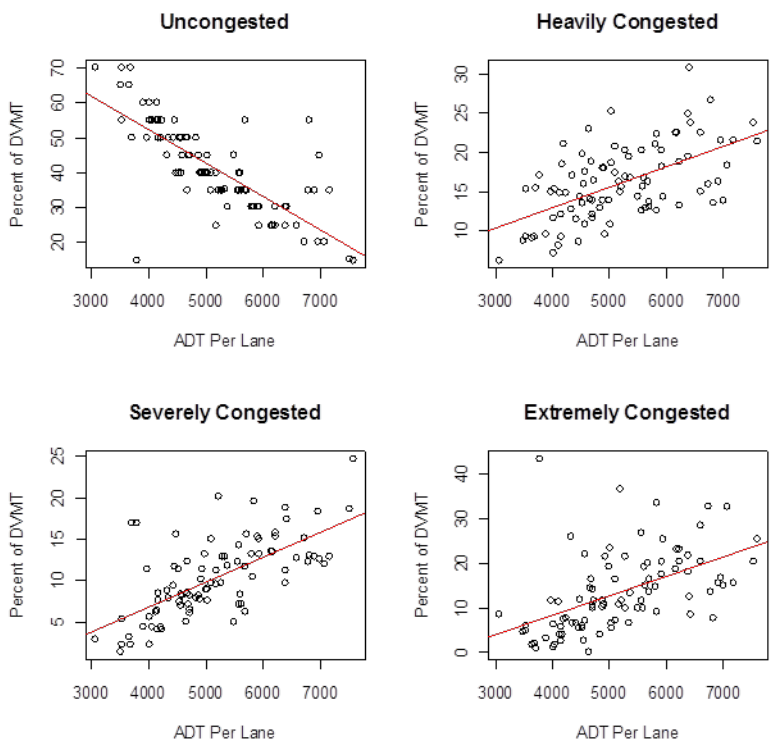


Figure B-16: Freeway VMT Percentages by Congestion Level vs. Average Daily Traffic Per Lane

Speeds by Congestion Levels

The relationship between the congestion category and speeds is based on the Urban Mobility Report, which provides an average trip speed for each congestion level and allows VMT to be allocated to speed bins. Then fuel economy is calculated using speed and fuel economy curves, shown in Figure B-17. Two sources are used for these curves: those compiled by the FHWA using the EPA's MOVES model (Jeff Houk, Federal Highway Administration, personal communication with Brian Gregor, ODOT. The curves were derived from the MOVES model) and from the Transportation Energy Data Book (Davis, Diegel, & Boundy, Transportation Energy Databook, 29th Edition, U.S. Department of Energy, Oak Ridge National Laboratory, July 2010, Table 4.29.). The fuel economy values are indexed to fuel economy values at 60 MPH. The default values used in the model are the curves prepared by Jeff Houk for buses and trucks and those based on the Energy Data Book for light vehicles (Gregor, 2011, p. 136).

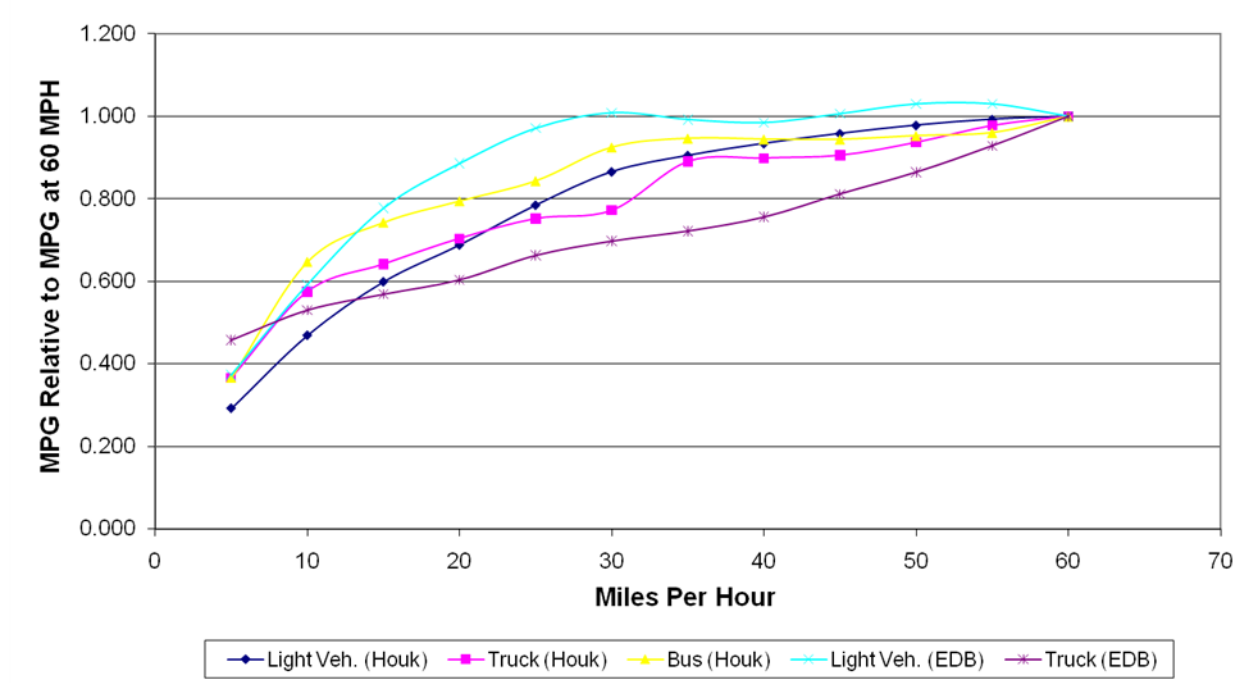


Figure B-17: Comparison of Fuel Economy—Speed Curves from Houk and Energy Data Book

The speed and fuel economy curves are normalized for used in the model. "Normalization was simply the division of the fuel economy at each speed level by the fuel economy at the assumed freeflow speed for each functional classification (freeway = 60 MPH, arterial = 30 MPH, other = 20 MPH). This normalization is necessary because average fleet fuel economy values already account for the split of travel between "highway" and "city" driving. If fuel economy were adjusted relative to freeway speeds there would be a double counting of the effects of "city" driving on fuel economy. Bus fuel economy normalization on arterials and other roadways is based on the respective average estimated service speeds, 20 MPH and 15 MPH, respectively. Figure B-18 shows the normalized curves for freeways. Figure B-19 shows the

normalized curves for arterials. In Figure B-19Figure B-19: Arterial Speed and Fuel Economy Relationships by Vehicle Type the bus value is 1 at 20 MPH rather than 30 MPH. That is because the assumed route speed for buses on arterials is 20 MPH. The model caps bus speeds at 20 MPH on arterials. Since it is assumed that "other roadways" are unaffected by congestion, fuel economy for VMT occurring on these roadways is not adjusted in response to speed."(Gregor, 2011, p. 137)

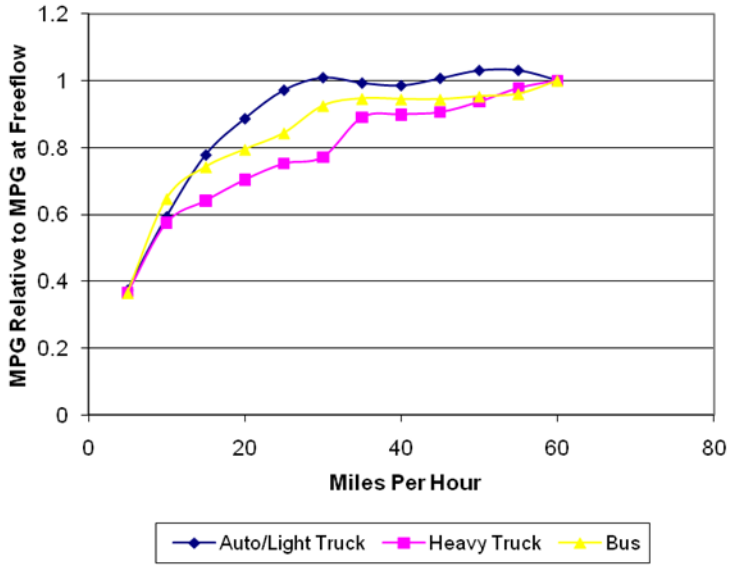


Figure B-18: Freeway Speed and Fuel Economy Relationships by Vehicle Type

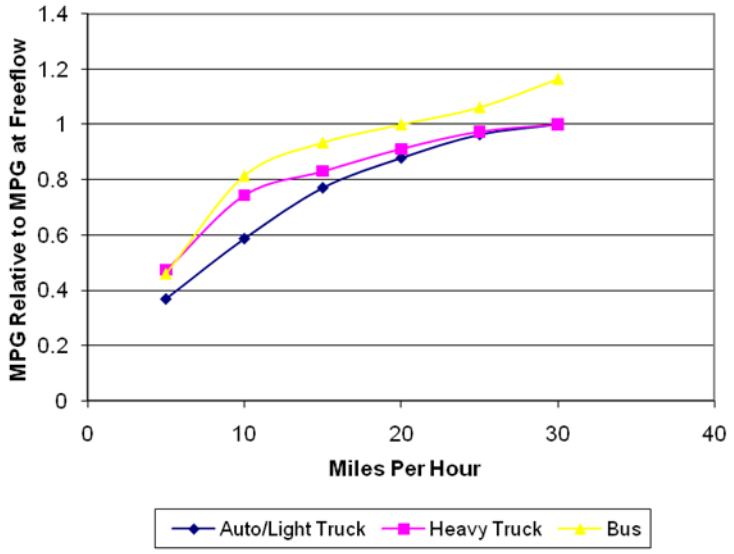


Figure B-19: Arterial Speed and Fuel Economy Relationships by Vehicle Type

Sources

The congestion models were adapted from the Greenhouse Gas Statewide Transportation Emissions Planning (GreenSTEP) Model Documentation (November, 2010) prepared by Brian Gregor of the Oregon Department of Transportation, Transportation Planning Analysis Unit and the subsequent Energy and Emissions Reduction Policy Analysis Tool Model Documentation (draft August 2011) prepared by Resource Systems Group for the Federal Highway Administration. As part of the model development and validation process, GreenSTEP evaluated data from the 2009 Urban Mobility Report prepared by the Texas Transportation Institute to determine the relationship between freeway and arterial lane miles. GreenSTEP model development process also evaluated this same TTI report to identify the relationship between VMT by freeways and arterials with the resulting level of congestion.

Policies

Parking Pricing Policies

Parking pricing is a trip-based cost, commonly paid for at one or both ends of a trip, and sometimes paid for on a monthly basis. The standard practice for handling parking pricing in urban travel demand models is to include it in the trip costs for auto travel. That is what is done here, but in a more general way. Two types of parking costs are addressed in the model - parking costs at places of employment and parking costs at other places. Daily parking costs are calculated for each household and added in with other variable costs.

For employer-based parking, the proportion of employees that pay for parking is a policy input. Employer-based parking includes parking provided at the employment site as well as parking in other parking facilities near the employment site. A related policy variable is the availability of free parking in the vicinity of employment sites. This is specified as the ratio of employment parking to available parking in the vicinity of employment sites. It is assumed that the proportion of employees who pay for parking is a function of the proportion of employers who charge for parking and the employment parking proportion of total parking available in the vicinity of employment sites. After the proportion of workers paying for parking has been calculated, the proportion of working age adults paying for parking is calculated using the labor force participation rate (0.65).

Another policy input is the proportion of employment parking that is converted from being free to payment under a “cash-out buy-back” type of program. Under these programs all employees are charged for employer-provided parking but they are also provided with a stipend equal to the parking cost regardless of whether they use the parking or not. This provides an incentive for employees to carpool or use other modes of transportation to get to work.

The rate per working age adult and the proportion of “cash-out buy-back” parking are used in a Monte Carlo process to determine the number of adults in the household who have to pay for parking at their place of work and the number who pay through a “cash-out buy-back” program. Households are charged the daily parking rate for the number of working age persons identified as paying for parking. Their income is increased for the number of working age

persons identified as participating in “cash-out buy-back” programs with the amount equal to the daily parking rate times the number of working days in a year (260).

Parking charges associated with non-work travel are specified in terms of the proportion of non-work vehicle trips that incur parking costs. The daily household parking cost for non-work travel is calculated as the proportion of non-work trips that incur a parking cost times the average proportion of VMT that is for non-work travel (0.78) times the average daily parking.

The parking pricing model is adapted from the Greenhouse Gas Statewide Transportation Emissions Planning (GreenSTEP) Model Documentation (November, 2010) prepared by Brian Gregor of the Oregon Department of Transportation, Transportation Planning Analysis Unit and the subsequent Energy and Emissions Reduction Policy Analysis Tool Model Documentation (draft August 2011) prepared by Resource Systems Group for the Federal Highway Administration.

ITS Policies

The ITS policy measures the effects of incident management supported by ITS. The congestion model contains two sets of relationships between congestion and speed, derived from Urban Mobility Report – one with and one without incidents. “The model uses the mean speeds with and without incidents to compute an overall average speed by road type and congestion level, as shown in Figure B-20 for freeways and Figure B-21 for arterials. The approach provides a simple level of sensitivity testing of the potential effects of incident management programs on emissions. An average speed is calculated for each congestion level by interpolating between the incident and non-incident speeds based on an assumed reduction in incidents. For example, an assumed reduction of 0.5 would result in a calculated value that is midway between the incident and non-incident speed levels. Speeds are treated differently for autos, light trucks, and heavy trucks than for buses. For the former, speeds are derived from the congestion models just described for freeways and arterials. Speeds on other roadways are assumed to be 20 MPH and unaffected by congestion. For bus VMT on freeways, speeds are those calculated for freeways as described, but for arterials and other local streets, speeds are based on bus service characteristics derived from transit agency data. The assumed speed for arterial service is one standard deviation above the mean of all bus routes (21 MPH). The assumed speed for other roadway service is one standard deviation below the mean (13 MPH). These values are rounded to 20 MPH and 15 MPH, respectively.” (Gregor, 2011, p. 135-136)

The approach to estimating the effects of ITS programs is adapted from the Greenhouse Gas Statewide Transportation Emissions Planning (GreenSTEP) Model Documentation (November, 2010) prepared by Brian Gregor of the Oregon Department of Transportation, Transportation Planning Analysis Unit and the subsequent Energy and Emissions Reduction Policy Analysis Tool Model Documentation (draft August 2011) prepared by Resource Systems Group for the Federal Highway Administration.

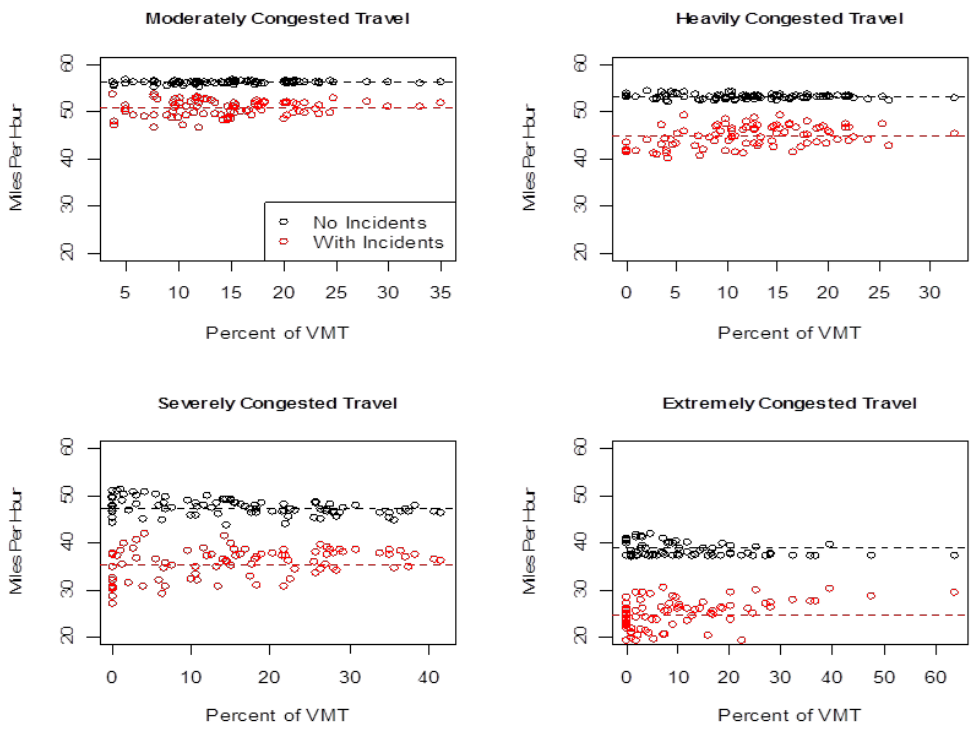


Figure B-20: Estimated Freeway Speeds by Congestion Level

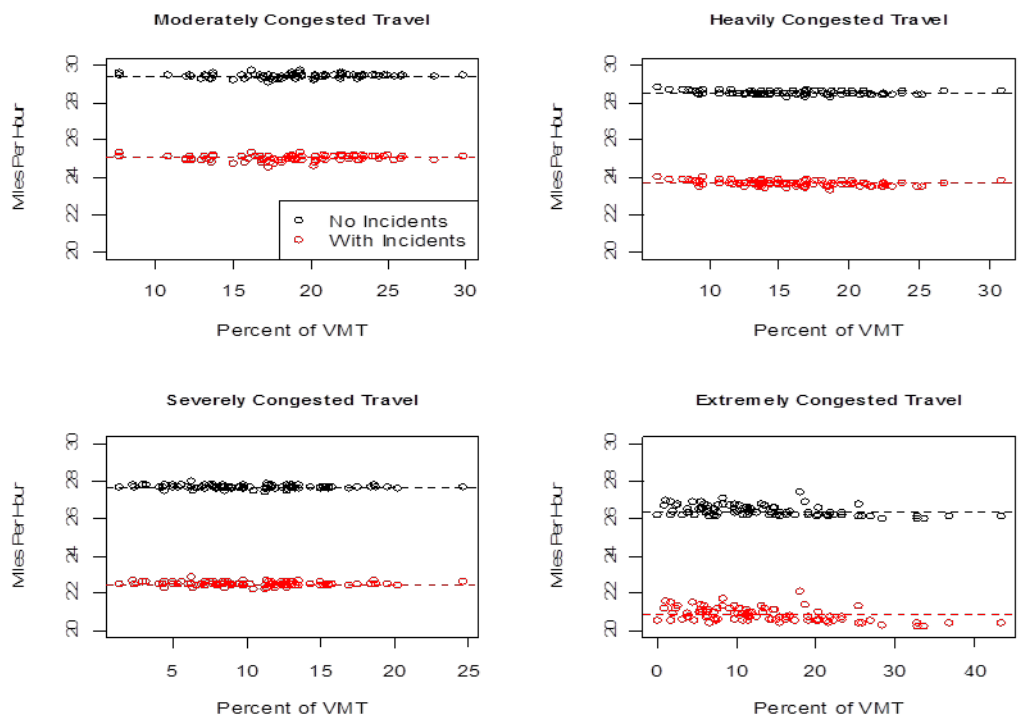


Figure B-21: Estimated Arterial Speeds by Congestion Level