SYNTHESIS PAPER ON SUSTAINABLE TRANSPORTATION

Prepared for the Sustainable and Healthy Communities Research Program – Theme 4

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1 SUMMARY

This document synthesizes current effects information, assessment tools and resources, best practices, and research needs related to sustainable transportation development and implementation and describes a wide variety of causal relationships and feedback effects of significance to transportation issues. This document does not reflect an exhaustive literature review, but instead highlights relevant work that will aid the EPA in its efforts to identify sustainable-transportation research. This especially applies to research meant to produce information, tools, and resources that will be of use to decision-makers in individual communities as they address a range of common issues, including those that were identified in the public-outreach portion of the Sustainable and Healthy Communities Research Program (SHCRP). Almost anyone with a stake in their community's future (including government agencies, developers, residents, businesses, and nonprofit organizations) may derive some use from the tools, resources, and other knowledge presented in this document. A critical use of this kind of scientifically-validated information is to overcome the assumptions and inertia that can perpetuate old patterns and problems. The relationships identified in this synthesis paper also support the development of the Total Resources, Impacts, and Outcomes (TRIO) framework, a sustainability assessment toolkit being developed by the EPA to help communities make more sustainable decisions through illuminating the comprehensive implications of decision options. The aspects of sustainable transportation discussed here reflect those research areas that are pertinent to the mission of EPA (widely held in common with other federal, state, and local agencies) and/or reflect the latest research, based on the knowledge of the authors, spanning the environmental, economic, and social dimensions of sustainability.

Briefly, this paper provides background on the history of surface transportation in the United States, as well as current trends in transportation. This discussion of transportation trends is provided to convey the issues created by those patterns. Over the course of the twentieth century, the desire for greater speed and independence of travel led first to the popularization of motorized public transit systems and then to a transition to driving private automobiles on paved roadways. This latter transition was aided greatly by federal programs to fund the construction of an efficient highway system. Initially, the roads funded under these programs were primarily designed with the goal of minimizing traffic congestion. Over time, however, policies have been implemented to make transportation projects be part of comprehensive planning processes, allow more funding to go to alternative modes of transportation, require greater stakeholder involvement in transportation planning, and necessitate the consideration of environmental and other sustainability issues in the project approval process. Regardless, automobile travel and highway building have been major contributors to the growth and decentralization of urban areas. The current state of automobile dependence and decentralized cities has produced a number of sustainability issues, including the heavy use of fossil fuels, a shortage of alternative transportation options, and a reduction in the efficiency with which municipal services can be provided. In response, various ideas have been gaining ground in recent years of ways to use transportation and land use policies to either slow or reverse these trends.

Next, the paper goes over various strategies and categories of tools that may be used to assess community sustainability, including in the realm of transportation. This includes a discussion of how to

create hierarchies of broad goals, specific objectives, and quantifiable performance measures and indicators against which to judge future plans and current conditions, as well as explanations of different types of modeling and visioning methodologies and their pros and cons. Of particular interest are those methods and tools that employ systems thinking, wherein phenomena are not viewed in isolation from one another. It is worth noting that tools and methods for assessing the broad subject of sustainability carry significant limitations, including the inherent subjectivity involved in deciding which measures of sustainability to consider and how to weight them relative to one another, as well as the frequent infeasibility of acquiring important pieces of data. After covering these limitations, the paper provides a list of specific models, tools, and other sustainability-related resources, both particular and not particular to transportation issues and created both by the U.S. EPA and by other organizations. Throughout the remaining sections of the paper, additional tools and resources are listed that have narrower focuses related to the particular aspects of transportation sustainability that those sections are about.

The next section synthesizes what is currently known about the factors that influence travelers' choices regarding transportation modes, trip frequencies, trip lengths, and trip purposes, which are among the most important questions in ascertaining the sustainability-related implications of a transportation policy or investment. First, a discussion is provided of the interdependent ways in which various aspects of the built environment (including density, diversity of land uses, design, distance to public transit, and destination accessibility) affect travel behavior, followed by a list of correlations between these things that past studies have quantified. Other factors that influence travel behavior include the supply and price of parking and the distinction between neighborhood-scale travel and regional travel. In most metropolitan areas, private automobiles (and sometimes public transit vehicles) are the favored travel mode for long trips, whereas the best opportunities to encourage nonmotorized travel, by a variety of tactics and for a variety of trip purposes, will generally be in the realm of short trips. Another important driver of transportation behavior is the capacity of the transportation system, changes to which may carry various unintended consequences, including the phenomenon of "induced demand," wherein reduced traffic congestion motivates people to increase the amount they drive until congestion levels return to what they once were. Various strategies exist for reducing traffic congestion without increasing roadway capacity, some of which include incentivizing people to travel during off-peak periods of the day, establishing High Occupancy Toll (HOT) lanes, and "trip aggregation," wherein various ridesharing and demand-responsive transit services are used to increase the number of passengers per vehicle. Meanwhile, just as traffic congestion is often an issue on roadways, crowding is sometimes a problem on public transit vehicles and might affect travel behavior. When contemplating policy levers that affect travel behavior, it is necessary to also consider the numerous economic, social, and psychological motivations that are involved. In this regard, the phenomenon of residential self-selection is particularly noteworthy, wherein people choose to move to neighborhoods that are conducive to what was already their favored mode of transportation, as opposed to just using whichever modes are viable in their original neighborhood. At the same time, people's travel behavior is greatly affected by their socioeconomic status, what type of job they have, whether or not they possess an automobile, and various other personal characteristics. As part of this discussion, the paper calls out the issues of what determines how students travel to school and what travel behavior is engaged in by elderly people. Finally, the section on travel behavior describes the pros and cons of several different strategies for modeling travel, addresses the issue of data limitations in modeling, and lists some specific modeling tools and resources for predicting and assessing travel behavior outcomes.

The following section addresses the subject of how transportation affects air quality. Transportation sources significantly contribute to global, regional, and local air quality impacts. This includes a demonstrated link between adverse human health effects and exposures to air pollutants from traffic emissions near large roadways and other transportation sources. One of the implications of this link is that even though compact urban forms may reduce motorized transportation and hence reduce overall air pollutant emissions, they may also bring people into closer contact with those emissions. Although pollutant concentrations are usually greatest near the source, many factors determine how they are dispersed, making it difficult to recommend “safe” distances from a major transportation facility at which to establish particular land uses and creating an area of significant research needs. Over time, technology and regulation have had varying levels of success at reducing emissions of various components of transportation-related air pollution. The section concludes with a list of models, tools, resources, and guidance documents created by the EPA to help decision-makers measure and control air pollution from transportation sources.

The section on air pollution from transportation is followed by a section on the related topics of transportation energy use and climate change impacts, with transportation being a major contributor to society-wide energy use and greenhouse gas (GHG) emissions. The primary ways in which transportation energy use and climate change impacts may be reduced include reducing transportation demand, shifting the balance between transportation modes, improving the efficiency of the overall transportation system (such as by lower traffic congestion levels), and adopting new vehicle and fuel technologies. One of the critical indicators of transportation demand and energy consumption is vehicle-miles traveled (VMT) per capita, which may be affected through a variety of mechanisms discussed in the earlier section of the paper on drivers of transportation behavior. Although shifting from the use of single-passenger vehicles to public transit generally reduces transportation energy use and GHG emissions, the size of those reductions is largely dependent upon the number of riders per transit vehicle in service and the fuel efficiency of the transit vehicles themselves. A critical tool in reducing energy use and GHG emissions is the federal Corporate Average Fuel Economy (CAFE) standards, wherein fuel efficiency rates are set that the light-duty vehicle fleet must achieve by particular model years. However, there is a significant knowledge gap in the area of how state and local governments may motivate the adoption of new vehicle and fuel technologies. Beyond technological changes, vehicle fuel efficiency may also be improved by encouraging more consistent driving speeds and less vehicle idling, both by influencing how drivers choose to operate their vehicles and by adjusting the traffic management measures employed on the roadway system. Depending on the fuel in question, alternative vehicle fuels may prove to be less emitting and more renewable than conventional vehicle fuels. However, the existence of these benefits is dependent upon many factors, including the lifecycle energy use and emissions stemming from the various stages of fuel and vehicle production, use, and disposal. If a local community decides that a particular fuel is preferable to those which currently predominate, they may take measures to increase provision of the infrastructure to distribute that fuel (fueling stations, etc.) or simply decide that the government vehicle fleet will transition to that fuel. However, perhaps a more critical emerging trend is the growth in vehicle electrification, which couples the transportation sector to the local electric grid. Vehicle electrification suggests a number of emerging questions related to interactions between the built environment, private vehicle fleets, and the energy system, including the question of what the relative impacts are of direct vehicle emissions and power-plant emissions that result from generating electricity for plug-in vehicles. Regardless of the particular energy-use and GHG reduction strategies, if any, that a community employs, they may benefit from the use of such tools as greenhouse gas footprint analysis and emissions calculators, which estimate the GHG footprint of an entire system (or community), transportation service, or facility.

The next topic discussed in this paper is that of water issues related to transportation. The first aspect of this topic to be addressed is stormwater runoff from transportation facilities, which constitute the majority of overall impervious surface area. Such runoff has a significant, negative effect on watershed health and transports various waterborne pollutants, including those from transportation sources. Design-based strategies for mitigating stormwater runoff may include establishing a basin at a low point in a catchment area to hold rainwater until it infiltrates into the ground, evaporates, or is harnessed by humans, as well as creating or preserving pervious areas along the path that water follows from upland areas to lowland areas, whether in the form of vegetated areas or pervious pavement. Both commercial and government modeling tools are available for assessing stormwater runoff impacts, using more complex inputs than a mere calculation of the percent of an area that is impervious. Meanwhile, another current topic of modeling is the behavior of fuel that leaks from storage facilities and vehicles into the groundwater and soil gas.

Another major aspect of the topic of transportation-related water issues addressed in this paper is that of the relationship between transportation infrastructure and drinking-water and wastewater infrastructure. A brief overview is provided of the planning processes that are generally used for water infrastructure systems, whose forms, once established, are difficult to change, and whose pipes generally run in parallel to transportation corridors. Currently, many U.S. urban areas are transitioning from monocentric forms to polycentric forms as their areas expand, aided in large part by changes to the transportation system that were discussed in earlier sections, a phenomenon to which water systems have been slow to adjust. As a result, the efficiency and effectiveness of those water systems are reduced. The planning of water systems may be improved through the use of various scenario-planning tools, methods of projecting future populations and land use patterns, and other planning and engineering tools and models. Benefits could also be derived from more closely integrating water-system planning with other planning practices, including efforts to achieve multiple urban planning goals by promoting compact and infill development through an adaptive process. In addition to the issues that are faced by the primary water systems of metropolitan areas, rapid urban expansion and "leap-frog" development along transportation corridors also often place a strain on the small-scale water systems that serve exurban communities. Meanwhile, densely-developed urban centers are often reliant upon very old water systems (sometimes including combined sanitary and stormwater sewers) that have become less effective with age but would be very difficult to upgrade in such an environment.

The last aspect of the water-issues topic to be addressed in this paper is that of water usage and wastewater generation in the production of transportation fuels. In this regard, particular attention is given to the matter of biomass-based fuels.

After the section on water issues comes a section on human well-being issues related to transportation, most especially physical health outcomes. The health-effects discussion begins by covering direct health impacts from the transportation sector, including those from air pollution, noise pollution, and traffic injuries. Regarding transportation air pollution, discussions are provided both of the relative impacts on different populations and of the significance of transportation-related sources of air pollution other than vehicle tailpipe emissions. Meanwhile, vehicle-traffic-related noise has been found to be a distinct source of adverse health outcomes, even when controlling for air pollution. As for injuries and deaths from traffic accidents, which are among the leading causes of morbidity and mortality in the United States, a discussion is provided of the relative amounts of risk associated with motorized and nonmotorized personal transportation. After covering direct health impacts from the transportation sector, the paper turns its attention to indirect impacts. The first indirect impact to be discussed is the potential to realize the health benefits of increased physical activity by encouraging nonmotorized transportation. Next, the paper describes how people's physical health may be indirectly affected when the nature of the transportation system reduces their access to housing, jobs, opportunities for social interaction, and important services (including healthcare), both by making it physically difficult to reach the locations of those things and by transportation expenses reducing the amount of money available for other uses in household budgets. The last indirect causal relationship between the transportation sector and health impacts to be discussed is that of transportation activities contributing to global climate change, and hence to the health impacts that climate change produces. Finally, several analysis and assessment tools are described that may be useful for determining physical health impacts from transportation, including tools produced by the EPA.

In addition to physical health outcomes, the section on human well-being also discusses impacts of the transportation system on social interaction and equity issues. Transportation corridors (and the traffic, noise, and air pollution associated with them) often represent a physical and/or psychological barrier to perpendicular movement, potentially reducing people's use of public spaces. At the same time, reliance on single-occupant motor vehicles removes opportunities that people would otherwise have to interact with one another while traveling by other modes, affecting psychological outcomes. On the subject of equity, meanwhile, in addition to there being various equity issues associated with the externalities of transportation policies and decisions (as discussed in other sections), it is also necessary to consider whether or not there is equity in the distribution of destination accessibility among the members of a population and in how much money they must pay for transportation. Several broad ways of thinking about this type of equity are discussed here.

The last category of transportation-sector impacts to be discussed in this paper is economic outcomes. This discussion starts by describing several basic questions and concepts that ought to be considered when assessing the economic impacts of a transportation project or policy, as well as a series of best practices for modeling direct and indirect costs and benefits. One of the most fundamental ways in which transportation projects and policies affect economic outcomes is through changes in accessibility, which may be manifested in a variety of different ways, both within a single mode of transportation and across modes and in terms of both travel times and monetary travel costs. Among other impacts, changes in accessibility tend to affect local real estate prices, often starting in the period after a transportation project has been announced but before it has actually opened. However, the economic benefits associated with a transportation project are not always limited to improved accessibility. Often, such projects will be implemented in tandem with other local improvements, investments, and policy changes, as well as draw the attention of private-sector actors to the area. As businesses become agglomerated around a transportation project or some other focal point, complementary businesses may locate near one another to save on transportation costs and similar businesses may come to be in greater competition with one another, potentially lowering prices but also potentially causing products to be more differentiated. After describing these phenomena, the paper describes the idea of a regional adjustment model, which attempts to perform the task (highly relevant to economic analyses, including those related to transportation) of simultaneously accounting both for the possibility of jobs attracting people to an area and for the possibility of people attracting jobs to an area. Then, the paper summarizes a few different models that describe, in simplified terms, the relationship between traffic volumes, real estate values, and the amount of land dedicated to transportation infrastructure in an urban area. After that, an overview is provided of market imperfections, wherein the price of something is unequal to either the cost of supplying it or the value of using it, typically as a result of either government actions or private-sector monopolies and oligopolies. Transportation projects may, by different mechanisms, either create or mitigate market imperfections. Another important concept is that of import substitution, wherein a specific geographic area experiences economic benefits from purchasing goods and services (including those related to transportation) from local sources. Regardless of what benefits (economic or otherwise) a transportation project or policy is meant to achieve or how those benefits are achieved, part of the assessment must always be how cost-effectively the project or policy meets its objectives. This includes considering tradeoffs between different types of costs, taking advantage of economies of scale, and comparing a variety of different traffic engineering options. In addition, the funding mechanisms for transportation systems prompt a variety of equity considerations. Such mechanisms as fuel taxes, vehicle registration taxes, vehicle sales taxes, general sales taxes, and tolls and fares may be compared both in terms of how proportional a person's monetary contribution is to their use of the transportation system and in terms of how regressive the relationship is between that monetary contribution and the income of the one who must pay it. The economics section of the paper concludes by briefly listing some tools for analyzing economic impacts from transportation project alternatives.

Following the main body of this document is a section that assesses the sustainability of transportation policies and practices related to "Complete Streets" design principles (wherein transportation corridors are designed to accommodate multiple modes of transportation) and compares them with more typical urban designs, oriented around personal vehicle use. This comparison highlights many of the sustainability principles presented in this paper, as well as the assessment tools described. This comparison also demonstrates the consideration of transportation and other land-use decisions through a systems approach to account for the multiple benefits, and potential costs, of transportation-related decisions, including the indication of tradeoffs, co-benefits, and mitigating factors.

The final section of this document is a compilation of important information gaps described by cited researchers and highlighted throughout the paper. It is organized to highlight issues raised in the previous discussions rather than to consolidate and integrate the research needs.

2 INTRODUCTION

2.1 Purpose of this Document

This document synthesizes current (as of June 2013) effects information, assessment tools and resources, best practices, and research needs related to sustainable transportation development and implementation and describes a wide variety of causal relationships and feedback effects of significance to transportation issues. This document does not reflect an exhaustive literature review, but instead highlights relevant work that will aid the EPA in its efforts to identify sustainable-transportation research. The vision statement developed by the Environmental Protection Agency (EPA) Office of Research and Development (ORD) for the Sustainable and Healthy Communities Research Program (SHCRP) reads:

"The Sustainable and Healthy Communities Research Program (SHC) will inform and empower decision-makers in communities, as well as in federal, state, and tribal programs, to effectively and equitably weigh and integrate human health, socioeconomic, environmental, and ecological factors into their decisions in a way that fosters community sustainability."

When state and federal government agencies set policies meant to promote sustainable development and sustainable transportation systems, local communities and their individual members often implement and adhere to these policies, both in law and in spirit. However, if these communities and community members are not cognizant of the externalities of their decisions in one sector (such as transportation), they may incur unintended negative consequences in other sectors or fail to take advantage of potential cobenefits. The SHCRP prepared this document to provide a summary of existing tools, resources, and indicators that may be used to create and implement sustainability plans, with special attention given to those tools, resources, and indicators that relate to sustainable transportation and are rooted in a systems perspective of interrelated variables. Ideally, communities will be able to use these tools, resources, and indicators to assess their current local conditions, forecast the likely future consequences of various different policy alternatives, and monitor whether existing transportation and/or sustainability policies are meeting their objectives. Many of the tools and resources presented here will allow communities to better identify practical, effective, and equitable ways to meet both present and future needs of the natural environment, the economy, and human society, both within their own local context and within the context of the country and world at large.

This document also identifies new tools being developed and research needed to further advance sustainable transportation development. Eventually, local communities will also be able to take advantage of a new toolkit being developed under the SHCRP and to which this paper contributes, called the Total Resources, Impacts, and Outcomes (TRIO) framework. This dynamic framework for analyzing sustainability impacts will be based upon many different causal relationships and feedback loops that are established as existing between various measures of a community's past, present, and future situations. This document attempts to highlight many of these causal relationships and feedback loops related to transportation. Also identified in this document are correlations that may be indicative of causal relationships, as well as theoretical relationships that appear indicative, but have not yet been researched enough to be either proven or disproven. The primary goal of this document is to help researchers and practitioners identify existing resources to implement sustainable transportation planning. The document also identifies knowledge gaps, and the research needed to fill those gaps, in order to enhance and improve the planning process and advance the ultimate goal of holistically informed transportation network designs.

2.2 Community Priorities

The EPA recognizes that communities want to become more sustainable and are moving in this direction. Given the SHCRP goal of supporting decision-making at all levels of government that affects community sustainability, it is important to know where those decision-making-support efforts should be focused. As such, the SHCRP conducted a variety of outreach activities in 2011 to gain insight into how information can better support effective decision-making for sustainable outcomes. Despite differences in format and audience, common themes emerged. The most useful information for decision-making is that which regards the holistic implications of decisions – positive and negative, short- and long-term, and for all three dimensions of sustainability (environmental, social, and economic) – especially those common decisions made at a community scale that have significant potential impacts, including those that concern transportation, land use, buildings and infrastructure, and waste and materials management. Also deemed to be of high priority were issues regarding metrics, indicators, and indices, especially issues about how to characterize "sustainability" and understand decision-making itself.

Identifying these issues and priorities helped inform the design of the SHCRP. As a result, this document is one of four decision-sector knowledge-synthesis documents informing subsequent SHCRP efforts, on the topics of transportation, land use, buildings and infrastructure, and waste and materials management.

2.3 Decision Agents that May Use this Document

Substantial stakeholder involvement is an important element of nearly any community planning. Almost anyone with a stake in their community's future may derive some use from the tools, resources, and other knowledge presented in this document. A critical use of this kind of scientifically-validated information is to overcome the assumptions and inertia that can perpetuate old patterns and problems. In addition to local, tribal, state, and federal government agencies, decision agents and stakeholders in transportation planning include private land developers, the end-users of the transportation system, and various external stakeholders, such as nonprofit organizations or other residents and businesses located near the transportation system. Transportation sustainability issues that tend to be important for local government agencies include assuring a high quality of life for their constituents, achieving social justice, and ensuring that their plans for the future are financially feasible. Meanwhile, private developers are understandably concerned foremost with the economic implications of transportation projects and sustainability policies. As for the end-users of the transportation system, personal interests and conveniences tend to take priority, such as the affordability of housing and commercial real estate, high-quality and timely access to destinations and services, and ensuring that the transportation system helps produce natural and built environments that are comfortable and healthy to live in. Many stakeholders, who may nonetheless be very directly affected in other ways by a given proposal under consideration, tend to be the most motivated when they perceive the possibility of exposure to some significant risk or danger. At times, various interests may come into conflict with one another, creating the necessity to agree on what specific issues are at stake and how they should be prioritized (Wallbaum, Krank, and Teloh 2011). It is in this identification and refinement of issues and prioritization of objectives that the tools, resources, and other information in this document may be especially useful.

2.4 Structure of the Document

This document presents key issues for consideration in sustainable transportation planning and development, especially at the level of community-scale decision-making.

First, background is provided on the history of surface transportation in the United States, as well as current trends in transportation. This discussion of transportation trends is provided to convey the issues created by those patterns.

The main body of the document discusses various tools, resources, and known causal relationships and correlations that may help communities evaluate the sustainability of their current transportation systems and predict what they can do in order to optimize the system's sustainability in the future. The relationships identified in this synthesis paper support the development of the Total Resources, Impacts, and Outcomes (TRIO) framework, a sustainability assessment toolkit being developed by the EPA to help communities make more sustainable decisions through illuminating the comprehensive implications of decision options. In addition to identifying known tools, resources, indicators, and relationships, this paper also identifies issues related to sustainable transportation that represent important knowledge gaps and ought to be studied more in the future. The following are the major topics addressed in the main body of the paper:

- A compilation of existing tools, resources, and methods for integrating the various aspects of sustainable transportation into a single analysis, as opposed to addressing each sustainability goal separately. This includes a discussion of inherent obstacles to such integrated sustainability analyses.
- A discussion of factors that determine how people will use the transportation system and of ways in which those factors might be analyzed. Whatever decisions a community makes about the future of its transportation system, a large proportion of the sustainability outcomes of those decisions will depend upon the ways in which they do or do not motivate individual travelers to change their travel behavior.

- Transportation impacts on air quality.
- Transportation impacts on energy use and climate change.
- Transportation impacts on water quality and quantity, including water that serves human needs and water that serves other ecological functions.
- Transportation impacts on human health and well-being. This includes both physical well-being and psychological and social well-being.
- Transportation impacts on economic prosperity, equity, and sustainability, including impacts on government budgets.

Near the end of this synthesis, various sustainability components discussed throughout the paper are considered in the context of the specific issue of "Complete Streets" design practices, with frequent reference to the specific assessment tools identified throughout the paper. "Complete Streets" was chosen as the focus of this illustrative discussion because it is a transportation topic with a strong connection to a wide variety of community-sustainability issues and a growing number of cities are adopting "Complete Streets" policies.

2.5 Research Methods

After a general outline was created of the topics deemed most pertinent to this synthesis paper, the paper was created by compiling sections written by various subject-matter experts within the EPA. Each author was provided with the same set of general guidelines regarding what types of information to look for on their particular research topic, so that all sections would address the same basic themes.

The authors of this synthesis paper gave particular attention to two tasks. The first task was identifying known cause-and-effect relationships between communities' transportation-related decisions and sustainability outcomes, as well as possible cause-and-effect relationships that warrant additional research. The second task was to identify sustainability tools and resources that might be used by communities or other relevant decision-makers to assess positive and negative outcomes from various transportation-related decisions they are considering.

2.6 Limitations

Due to limitations of time and personnel, this is not an exhaustive review of the available literature related to sustainable transportation. However, this document provides a good overview of current knowledge on the topic, as well as resources and best practices for implementing TRIO and research needed to further the SHCRP.

Because this research synthesis does not represent an exhaustive review of the literature or resources publicly available, not all aspects of the relationship between transportation and sustainability are addressed. However, the synthesis focuses, where possible, on relevant variables that are within the capacity of community decision-makers to affect. In addition, this synthesis includes only a handful of the many tools and resources that could be useful for measuring and/or advancing sustainable transportation. The aspects of sustainable transportation that are included in this synthesis paper reflect those research areas that are pertinent to the mission of EPA (widely held in common with other federal, state, and local agencies) and/or reflect the latest research, based on the knowledge of the authors.

3 U.S. TRANSPORTATION BACKGROUND: HISTORY AND TRENDS

In order to understand how United States communities' transportation systems can be made more sustainable, it is important to have a clear idea of how those systems have developed and changed over the years. The factors that caused them to change, and how those changes in the transportation sector have affected other characteristics of this country's communities is also important. In addition, understanding what present-day trends are molding the future of American transportation, American society, and their measures of sustainability helps determine whether individual communities want to encourage or discourage these trends.

3.1 The Building of the Motorized Transportation System in the United States

Motorized passenger transportation in the United States began in the late 1800s and early 1900s, as a series of transitions were made from horse-drawn railcars to steam-engine transit to cable cars to electric streetcars to heavy-rail subway lines to bus transit to travel by personal automobile on paved, all-weather roads, with each of these transitions being motivated by the desire for greater speed and independence (Sinha 2003). Of all the public transit modes that predated the popularization of private automobiles, electric streetcars were one of the most influential. In the year 1920, there were 40,000 miles of electric rail lines in the United States and the mean number of transit trips per person per year was 250, which is approximately eight times contemporary transit usage (Sinha 2003). Even before the affordability of personal automobiles vastly accelerated the process, electric rail transit was helping to bring about the rapid expansion and decentralization of urban areas in the United States (Levinson 2004, Sinha 2003).

The rise of private automobiles as the dominant mode of U.S. transportation was facilitated not just by the production of motor vehicles that the majority of working adults could afford, but also by the creation of a highly sophisticated system of highways. The first thirty years of the 20th century saw a series of uncoordinated intercity roads give way to a national system of paved and numbered roadways that were equipped with uniform signage. Some major milestones in this process were the Federal-Aid Road Act of 1916, which established 50-50 federal-state cost sharing for highway construction, and the Federal-Aid Road Act of 1921, which defined primary roadways, secondary roadways, and urban road systems that were eligible for government aid. During the 1930s, limited-access highways started being built within individual metropolitan areas, leading to the 1940 opening of the Pennsylvania Turnpike, the first intercity limited-access highway in the country. In 1944, the federal government defined the National System of Interstate and Defense Highways, the financing of which was established as a 90-10 federal-state split by the Federal-Aid Act of 1956. These federal actions resulted in the modern interstate highway system, which in turn served as inspiration for the construction of many more highways in the post-World War II era (Levinson 2004).

During the postwar highway-building era, transportation engineers concerned themselves primarily with reducing traffic congestion and maintaining design standards, as opposed to mitigating impacts for the various dimensions of what is now called sustainability (Levinson 2004, Mercier 2009). However, in 1962, the federal government began requiring that urban areas have ongoing comprehensive and cooperative transportation planning processes in order to prevent conflicts between past, present, and future transportation projects and between transportation projects and other features of the urban environment. Then, in 1969, the National Environmental Policy Act (NEPA) started requiring that assessments be made of the impacts of proposed infrastructure projects on the environment and how those impacts could be mitigated. In 1970, the Clean Air Act was passed, which set transportation emissions targets and ambient air quality standards. As of 1973, federal highway money can be spent on public transit improvements. More significant changes to the thinking behind transportation policy would come in the 1990s, when additional federal funding would be provided for improving air quality, mitigating traffic congestion, and improving transportation options for pedestrians and cyclists (Levinson 2004). Also, the importance that federal law places on involving the general public in transportation planning decisions was enhanced by both NEPA (1969) and the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) (Lemp et al. 2008). One caveat to all of these laws and policy changes from the last half century, though, is that as state and federal requirements regarding how transportation projects are planned, designed, and constructed have gotten more complex, the time and money needed to complete any given project have noticeably increased (Levinson 2004).

3.2 The Movement of U.S. Urban Populations in the Era of Motorized Transportation

In the early 1900s, many urban theorists saw decentralization as an effective means of addressing a variety of social and health problems that urban areas of that time were experiencing. The decentralization that these theorists advocated has now come into being, thanks in no small part to the modern transportation system, and is now faulted by many for helping to create numerous present-day sustainability issues, such as urban sprawl and reliance on personal motor vehicles (Tomalty 2009). Both the populations and the spatial extents of metropolitan areas have grown especially rapidly since the end of World War II, correlating with the expansion of the freeway transportation system in the United States, as well as increases in average wealth and government programs expanding the population able to afford a single-family home (Chi and Stone 2005, Sinha 2003, Kim 2007). At the same time, sprawl development that takes place beyond the urban fringe is also partially the result of people seeking out attractive natural scenery and cheaper land prices (Carruthers and Vias 2005). Still, highway interchanges have emerged as significant attractors of economic development (Levinson 2004), contributing to declines in the percentage of a metropolitan area's population that still has ties to the central city (Sinha 2003). Manufacturing jobs have largely moved out of cities' central business districts, which are now mostly dominated by service-sector industries (Chang 2007).

One way of measuring the simultaneous growth and decentralization of urban populations is the density gradient, comparing population density with distance from the central business district (Figure 1). Over the last 120 years, the slope of the density gradient of U.S. metropolitan areas has consistently become less and less pronounced, indicating less and less difference between the population density of the city center and each successive ring of suburbs (Kim 2007). Meanwhile, there exists evidence that average urban population densities actually increased slightly during the first half of the 1900s, before falling rapidly during the second half of the century. In 1940, the average population density of U.S. metropolitan areas was 347 people per square mile, which grew to 589 people per square mile by 1960 and then dropped to 288 people per square mile by 1990. Prior to 1960, metropolitan populations were both growing and moving out from the central cities, but increases in metropolitan land area did not always keep up with these changes. After 1960, the addition of new land to metropolitan areas greatly outpaced population increases (Kim 2007). In 1970, the U.S. census confirmed that for the first time in history, a majority of the population of U.S. metropolitan areas was actually living outside of those metropolitan areas' central cities, a far cry from the pre-World War II model of dense concentric rings of development around an urban core (Sinha 2003). Throughout all of these changes in population patterns that have accompanied the era of motorized transportation in the United States, not only have existing cities become less concentrated, but many new major cities have come into being that, because of the time in history when their basic structures were established, adopted far less dense development patterns than what most of the older cities have come to possess (Kim 2007). Finally, the trends that have been described here for the United States as a whole generally also hold true for each of the various regions within the country (Kim 2007). More information on trends in U.S. land use may be found in the concurrent SHCRP Theme 4 synthesis paper on land use.

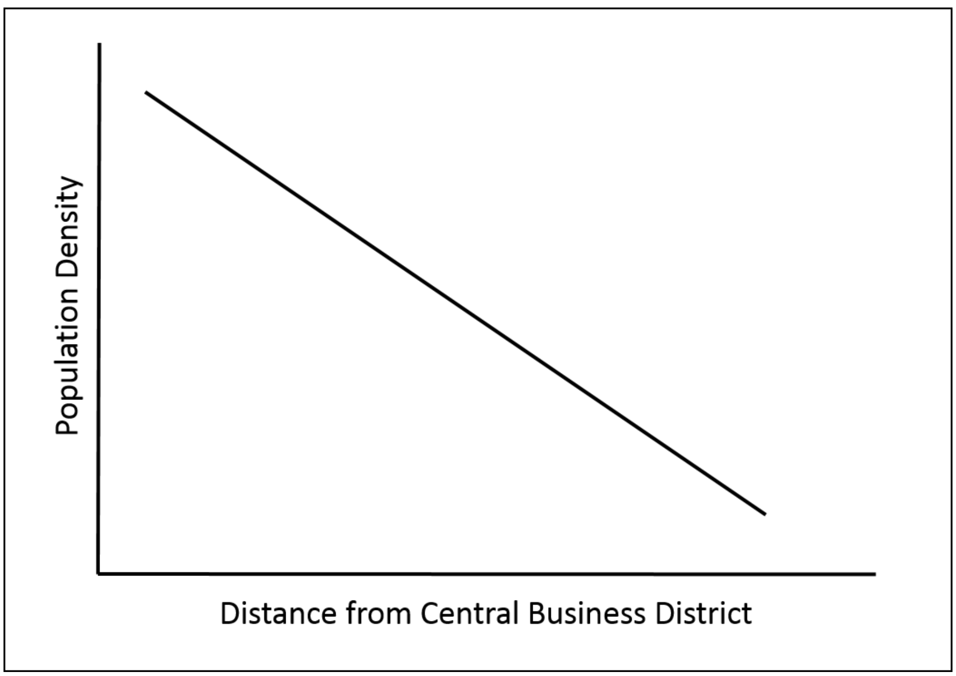

Figure 1: Urban density gradient.

3.3 Present Conditions and Predicted Directions of U.S. Transportation and Land Use

As of 2004, there were approximately one million miles of roadways in the United States (Levinson 2004), on which personal vehicles traveled a combined total of 2.245 trillion miles in 2009 (Santos et al. 2011). About a fourth of U.S. motor vehicle travel takes place on the interstate highway system, even though that system only represents about 2% of U.S. roads overall, and highways in general (as opposed to just interstate highways) account for 80% of passenger miles traveled between U.S. cities and 90% of passenger miles traveled within cities. Meanwhile, trucks (as opposed to trains, planes, ships, etc.) carry a third of all interstate freight and highway transportation represents 16% of the Gross National Product (Levinson 2004).

As this highway-heavy transportation system was coming into being over a period of decades, the problem of traffic congestion first showed up in central cities, but then began moving out into the suburbs along with the many people and businesses that moved in the same direction (Levinson 2004). For a long time, the response of transportation engineers to this traffic congestion was to build more lane-miles of roads to accommodate the apparent increase in demand. However, this approach has changed in recent years (Mercier 2009). Transportation planners in the United States have now largely made the transition from building new highways to primarily managing the ones that exist (Levinson 2004). However, travel by personal automobile is still a convenient enough mode of transportation in most U.S. cities that public transit is largely regarded as something that is only used by people for whom driving a car is not a viable option (Sinha 2003). At the same time, the historically low average densities of U.S. urban areas have both made it more expensive than it used to be to provide basic infrastructure to a given number of users and increased the number of miles that transit vehicles must travel in order to accommodate the same number of customers - to the point where no transit system in the country can operate without large government subsidies (Sinha 2003). Further deepening the disparity between private and public transportation, the consequences of peak-hour automobile travel on U.S. highways are generally not reflected in the price of taking part in it (price of fuel, tolls, etc.) (Levinson 2004).

Based on these and other trends, a number of projections can be made regarding surface transportation and land use in the United States. First of all, social and economic problems are likely to arise from the combination of great travel distances caused by a low-density development pattern and high fuel prices caused by dwindling fossil fuel reserves (Mercier 2009). Second, if present trends continue, the demand for roads will continue to grow faster than the population. However, as the percentage of Americans who own automobiles reaches saturation level and stops increasing, the rate of growth in the demand for roads is likely to be mitigated (Levinson 2004). Projections suggest that most U.S. population growth will continue to be located in urban areas, which will continue to become more dispersed and develop multiple centers of activity, even though their original central cities will continue to play an important role (Levinson 2004). Most policies and plans intended to affect urban land use and transportation systems in the United States will continue to face the challenge of metropolitan areas being divided into a very large number of largely uncoordinated municipal governments (Levinson 2004, Sinha 2003).

3.4 Current Ideas that Break with the Past

One particular idea that has gained traction in recent years is that of promoting sustainability through the creation of an urban environment where all modes of transportation can compete on even terms, as opposed to automobile travel being underpriced while other means of travel are not feasible across wide areas (Sinha 2003).

Another contemporary idea is that of changing the land use patterns in a given area for the express purpose of changing how people choose to use the transportation system. Many of the strategies spawned by this idea, including policies that promote denser development and less separation of land uses, are included under the umbrella term of “smart growth,” especially when implemented at a city-wide or regional scale; more on the topic of smart growth may be found in the concurrent SHCRP synthesis paper on sustainable land use practices. Meanwhile, some people advance the ideas of neotraditional development, wherein urban forms are created that resemble those which existed prior to when automobiles became the dominant transportation mode, while others advance the idea of Transit-Oriented Development (TOD), wherein compact, easily-walkable, mixed-land-use neighborhoods are built around transit stops, bringing customers to the transit lines rather than the other way around (Sinha 2003).

~~Finally, w~~When road projects are brought under consideration, the concept of context-sensitive design, agreeing to the increase in project costs that comes from considering factors other than the safety and capacity of a given part of the road system, has also become increasingly popular. Ideally, the design process would be collaborative, involve substantial stakeholder input, and produce solutions that consider the ecological, social, economic, and aesthetic characteristics of the area around a transportation facility at the same time as satisfying the more basic objectives of safety, system efficiency, and cost-effectiveness. Examples of context-sensitive design practices may include building highways along routes where their negative impacts are likely to be the least, building below grade or underground, incorporating other land uses into a facility’s right-of-way, or even choosing in a particular case to satisfy transportation demand through an expansion of the public transit system and walking and cycling facilities instead of an expansion of the highway system or other road network (Levinson 2004, U.S. Department of Transportation).

Finally, those with responsibility over the U.S. transportation system will increasingly have to assess ~~its~~ projects, policies and priorities in the context of climate change adaptation and mitigation. In terms of *adaptation*, transportation systems – including highway systems, roads and bridges, and transit systems, as well as rail, port, and airport~~s~~ operations – are already being affected by extreme weather events. These extreme events can include heat waves, drought, tropical storms and hurricanes, sea level rise and higher storm surges, and heavy precipitation events. Their impacts and frequency will differ across regions and communities. Nonetheless, as these events become more frequent or severe as the climate changes, all communities will need to consider their resiliency to climate-related impacts. In terms of *mitigation*, in order to achieve the greenhouse gas (GHG) reduction levels that are needed to reach a stabilization target, the challenges to the transportation sector are “daunting” (Mashayekh et al. 2012)~~(Mashayehk et al. 2011)~~. Strategies to reduce CO_2 will require an “all of the above” approach incorporating all aspects of travel demand, vehicle technology, and low~~-~~-carbon fuels. ~~-~~In later

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sections~~this paper~~, this paper~~we~~ will focus on ~~the~~ mitigation strategies that are within the purview of community-level decision-~~-~~makers~~ing~~, ~~in~~ particularly those related to~~,~~ travel demand.

4 SUSTAINABILITY ASSESSMENT

4.1 Integrated Tools, Resources, and Indicators

For some time now, there has been a consensus that the three major (interrelated) elements of sustainability are environment, economy, and society (or human well-being). However, these elements can be refined and expanded to include a variety of more particular factors of relevance, including natural and human ecology, political concerns, technological limitations, regulatory frameworks, resource conservation, human health, and demographic, socioeconomic, geographic, and intergenerational equity (Koo, Ariaratnam, and Kavazanjian 2009, Mercier 2009, Ramani et al. 2011). In order to effectively assess how well a given community's transportation decisions are supporting the various elements of sustainability and create plans in response to that assessment, establishing a hierarchy of goals, objectives, subobjectives, and performance measures can be helpful. The overarching goal of sustainability is divided into a series of goals that are specific to the various elements of sustainability, which are then further divided into a series of increasingly more specific objectives, based upon social theories of which human actions have a meaningful effect on the objectives and goals above them. Ultimately, these objectives reach a level of specificity where attainment is believed to be met when certain quantifiable performance measures reach specific target values. Then, armed with a means of assessing sustainability in concrete terms, corresponding policy instruments can be created to help achieve the various performance measures (Black, Paez, and Suthanaya 2002, Ramani et al. 2011). Before performance measures are used to make any actual policy decisions, they may also be used to facilitate communication between the various actors and stakeholders in the transportation planning process (Ramani et al. 2011). Even though the best time to utilize sustainability performance measures is at the beginning of the transportation planning process (e.g., to set goals), they can also be used to track the achievement of sustainability-related objectives at most other project stages, including the selection of building materials, design, construction, operations, maintenance, and after the decommissioning of infrastructure (Koo, Ariaratnam, and Kavazanjian 2009). Major categories of decisions that performance measures can be utilized to support include future system capacity, predicting future levels of demand, selecting construction materials and methods, amounts of land to use, and what future upgrades and rehabilitations require investment (Koo, Ariaratnam, and Kavazanjian 2009). Sustainability assessment tools are strongly recommended to be incorporated into existing planning processes, rather than operating as stand-alone, often disconnected, inputs to the decision-making process (Wallbaum, Krank, and Teloh 2011). Sustainability goals that a community adopts should also be mutually reinforcing since at least some trade-offs must eventually be made (Tomalty 2009). Typically, only one or two performance measures/indicators are recommended for each lower-level objective and these measures and indicators should be understandable to a very broad audience (Ramani et al. 2011).

The various indicators and performance measures that a community adopts may be distinguished from one another by a variety of different means, serving the purpose of helping to ascertain how they can best be used. For example, a given indicator may measure either small-scale or large-scale effects and either temporary conditions or permanent conditions (Koo, Ariaratnam, and Kavazanjian 2009). Performance measures may also be categorized according to whether they are ordinary quantifiable measures of the achievement of a subobjective, a composite measure of all of the different aspects of a given objective, or a qualitative assessment of progress towards a given goal (Black, Paez, and Suthanaya 2002). Finally, certain performance measures may be subjectively deemed to be of greater significance than others (Koo, Ariaratnam, and Kavazanjian 2009). For example, certain elements of an unsustainable society (such as climate change, the loss of soil, and the loss of biodiversity) are arguably of greater impact than others (such as noise and traffic accidents), based upon the duration and extent of their impacts (Black, Paez, and Suthanaya 2002).

Even though the ideal is to develop indicators and performance measures that relate directly to desired sustainability outcomes, there are certain indicators that do not automatically represent sustainability or unsustainability, but may be at the root of what causes other indicator values to be either “good” or “bad”. In systems approaches to transportation planning, the first impacts of the transportation system to be modeled are generally those on population and land use patterns, which are then used as the basis for calculating other impacts (Sastry 1973). Population density and job density have been shown in studies to explain more of the variation in numerous sustainability indicators than any other factor (Sinha 2003). Population and employment growth rates have cumulative effects, a quality which enhances their influence over other indicators (Duthie et al. 2010). Other major determinants of model outputs include trip-generation rates and how people carry out their transportation mode choices (Duthie et al. 2010). Travel patterns have an effect on other sustainability performance measures and can easily be used as a proxy for transportation energy use and emissions (Black, Paez, and Suthanaya 2002). Drivers of individual travelers’ transportation behavior will be discussed shortly.

When performance indicators are applied to the act of transportation and land use planning, they may be employed not just in conventional modeling activities but also in visioning exercises. The primary function of most traditional land use and transportation models is to extrapolate existing trends into the future, with the process usually controlled by technical analysts. Visioning involves projecting several different future scenarios, usually including both a so-called “ideal” scenario and a do-nothing scenario, with the process requiring extensive stakeholder involvement. When planning professionals assemble traditional mathematical models of transportation and land use, they input data on land use inventories, zoning policies, existing highway networks, employment, and household distribution, typically aggregated into zones. Some of these models are also able to account for future changes in government policy and in the transportation system, but may still be invalidated by various unexpected events, such as changes in migration patterns, and by faulty assumptions about the preferred behaviors of various actors. Meanwhile, visioning processes entail a lengthy public-participation process that first produces a set of very general guiding principles and then uses those principles to evaluate different development scenarios, which are often projected as GIS maps for purposes of comparison. A series of specific strategies can be drafted for the purpose of implementing whichever scenario is deemed to be the most preferable. Many of the computer programs used for these scenario-building and visioning processes also incorporate a conventional travel demand model, but usually not a rigorous land-use model.

Ultimately, modeling and visioning serve two different purposes, the former the purpose of projecting the likely outcomes of historical trends and the latter the purpose of creating an integrated vision of what direction would be most beneficial for a community (Lemp et al. 2008).

A number of different models are capable of projecting land use and transportation effects in an integrated fashion (Black, Paez, and Suthanaya 2002). One common type is called a gravity model, wherein the locations of job centers and households are determined by where the transportation system will offer the greatest accessibility to other destinations. Another common type of model is a cellular automata model, in which a community is divided into a series of cells, each affected by their nearest neighbors. Also of note are input-output models, which are geared towards economic impacts, large-scale analysis, and travel costs, and discrete response simulations, which are based on predicting the choices that individuals make. These models require very large quantities of data to work properly, especially discrete response simulations (Lemp et al. 2008).

Table 1: Types of integrated land use/transportation models (Lemp et al. 2008)

Gravity models	Predicted locations of job centers and households are determined by where the transportation system will offer the greatest accessibility to other destinations.
Cellular automata models	A community is divided into a series of cells, each affected by their nearest neighbors, in order to predict how private-sector actors will change each cell's land use.
Input-output models	Geared towards large-scale analysis and estimating economic impacts and travel costs in a given scenario.
Discrete response simulations	Based on predicting the choices that individuals make that affect the relationship between transportation and land use. Require especially large quantities of data (though all of these model types have substantial data requirements).

In addition to transportation and land use models, other types of decision-making tools exist that are not specific to any particular context, providing flexibility to incorporate the multitude of variables and causal relationships that are part of sustainability. These can be used, for example, to discover indirect effects and perform benefit-cost analyses. Two tools that fall into this category are system dynamics models and Multi-Criteria Decision-Making (MCDM) models. System dynamics models, which are characterized by causal loop diagrams, got their start in the early 1960s. Originally, this was a tool to anticipate the outcomes of decisions in an industrial setting, although it has since been adapted to many other applications. In the context of community planning, subsystems are created within the larger model, typically including macroeconomic factors, regional economic factors, environmental conditions, and the state of the transportation system. One noteworthy limitation of system dynamics models is not accounting for how particular indicators vary by geographic coordinates across the area being studied (Black, Paez, and Suthanaya 2002). Once causal links within a system are characterized, the mechanisms by which a single policy action has the potential to advance several different goals at the same time can be more evident (Mercier 2009). An example of a system-dynamics diagram, created using the freeware version of the computer program *Vensim*, may be seen in Figure 2, showing inputs to the amount of automobile travel by a neighborhood's residents. As evidenced in that figure, system dynamics models have a tendency to become very complicated very quickly.

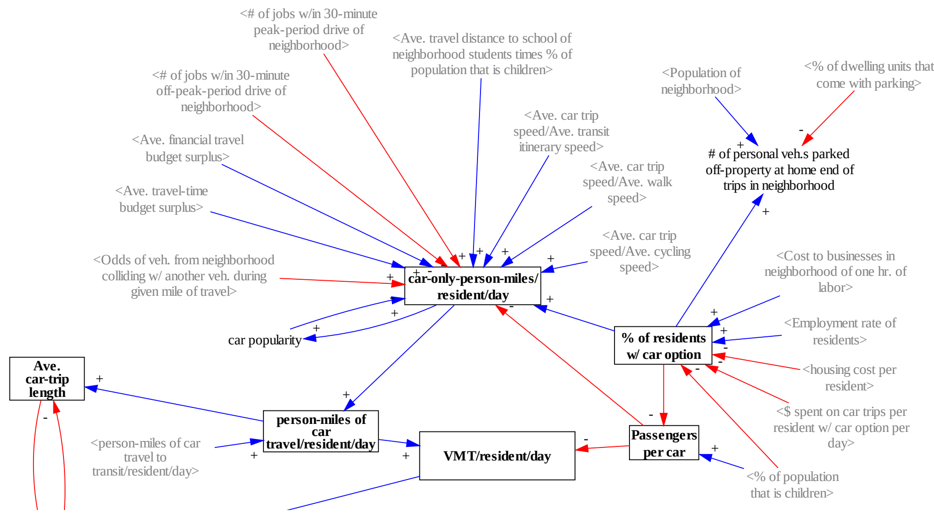

Figure 2: Segment of a system-dynamics diagram showing inputs to neighborhood residents' Vehicle Miles Traveled (VMT). Red arrows represent negative causal relationships and blue arrows represent positive causal relationships. A negative causal relationship means that an increase in value or quantity of one component leads to a decrease in value or quantity of the other component (and a decrease in value or quantity of the first component leads to an increase in value or quantity of the second component). A positive causal relationship means that an increase in value or quantity of one component leads to an increase in value or quantity of the other component (and a decrease in value or quantity of the first component leads to a decrease in value or quantity of the second component).

Meanwhile, MCDM models operate by assigning weights to a number of different variables and then adding them together to form a single composite measure (Koo, Ariaratnam, and Kavazanjian 2009). Some common forms of MCDMs include the Multi-Attribute Utility Theory (MAUT), the analytical hierarchy process, and the outranking method. Under MAUT, the process starts with identifying a list of quantifiable measures, ranking them by importance, assigning them values between zero and one that are in keeping with their respective ranks, and identifying the best and worst possible values for each measure. The actual values of each measure under a given scenario are transformed into a proportion of the difference between the theoretical worst and best possible values. These proportions are multiplied by the respective values between zero and one assigned to each measure as its weight earlier in the process. When the results of these calculations are added together, they produce a weighted composite measure of all of the variables under consideration, on a scale of zero to one, which may be used to compare the desirability of various scenarios that decision-makers are able to bring about through different sets of choices (Ramani et al. 2011).

There are correlations identified among transportation-related variables that are simultaneously important for transportation, land use, and various other decision sectors (Sinha 2003):

- Population density and job density, known together as activity density, are *positively* correlated with transit boardings per person per year.
- Meanwhile, transit demand per capita is *negatively* correlated with:
  - the provision of roads,
  - the rates of ownership and use of private vehicles,
  - and the number of parking spaces per employee in central business districts.
- Transportation energy consumed per person is:
  - *negatively* correlated with activity density and
  - *positively* correlated with both the demand for personal motor vehicles and the provision of roadways.
- The percentage of work trips that people make by public transit is *negatively* correlated with:
  - carbon-dioxide emissions from transportation,
  - transportation-accident fatalities per capita,
  - the amount of investment that is made in roadways,
  - and the price of gasoline.

Of all the variables described above, population and job density are the ones with the greatest impact on the others, and changes in these densities produce especially large effects in the other indicators when the starting densities are particularly low (Sinha 2003). Subsequent sections of this paper will discuss these and other correlations, as well as the causal relationships that are theorized to explain them, grouped according to which dimension of sustainability they most closely relate to.

4.1.1 Limitations

No matter what system for creating and using sustainable transportation performance measures is implemented, certain limitations will be inherent. For example, sustainability has many elements with many ways of assessing each of those elements, so judgments must be made regarding which elements to include and regarding the best assessment methods for the elements. In addition, many of the decisions involved in creating a system of sustainability performance measurements may be subjective in nature, such as deciding how to quantify an indicator when extremely high values may be sustainable in some contexts while extremely low values may be sustainable in other contexts (El-Diraby, Abdulhai, and Pramod 2005). A further challenge can be when the costs of a transportation project, especially the financial and economic costs, are much easier to calculate than the benefits (Sastry 1973). Beyond that, many performance measures are either difficult to obtain data for or simply too politically sensitive to be put to effective use (Ramani et al. 2011). When analyzing performance measures together, capturing multiple dimensions of the situation in a single variable can be difficult. However, the analysis of multiple variables can become confused by correlations among them (Cervero and Duncan 2003). Some limitations to the creation of effective sustainable transportation performance measurements can be remedied through expanded research efforts. Some examples include:

- insufficient research on the measurement of sustainability in the regular functions of a transportation agency (Ramani et al. 2011),
- uncertainty in the inputs of transportation and land use models (Duthie et al. 2010), and

- insufficient research on how the built environment affects pedestrian and bicycle travel, as opposed to motorized transportation (Cervero and Duncan 2003, Wong, Faulkner, and Buliung 2011).

Meanwhile, when performance measurements are used in visioning processes, the issue of feasibility is often neglected in the creation of preferred scenarios, and the attendant stakeholder-involvement process may last so long that new events in the community render the scenarios under development obsolete. Conversely, transportation and land use models frequently have the problem of requiring very large and detailed datasets and considerable expertise to work properly (Lemp et al. 2008). In addition, many of the software packages that are used to analyze sustainable transportation performance measures lack the ability to exchange data with one another (El-Diraby, Abdulhai, and Pramod 2005).

4.1.2 Specific Models, Tools, and Other Resources from the U.S. Environmental Protection Agency (EPA)

The EPA tools and resources listed below include those that both are and are not products of the Sustainable and Healthy Communities Research Program. A sample list of tools and resources produced specifically through the SHCRP may be found at http://www2.epa.gov/sites/production/files/2013-12/documents/shc-fact-sheet.pdf. For a summary of all of the EPA tools mentioned in any section of this document, including the dimensions of sustainability to which each tool is most relevant, see Table 2, below.

- *Smart Location Database (SLD)*: A product of the EPA's Office of Sustainable Communities, the Smart Location Database is a resource of particular relevance to issues of transportation sustainability, as it aids in the measurement of how conducive a community's built environment is to efficient, affordable, safe, healthy, flexible, equitable, and low-resource-consuming (and hence low-emissions) transportation options. Drawing from numerous other sources and making additional calculations where necessary, this database reports information at the census-block-group level for the entire United States, with the exception that public-transit-related data is not available for all metropolitan areas. In addition to reporting various demographic and employment data, the Smart Location Database contains numerous measures of the so-called "Five Ds" of how the built environment affects transportation behavior (discussed later in this paper): Density (of population, employment, dwelling units, etc.), Diversity (of land uses), Design (of the transportation network), Distance to Transit, and Destination Accessibility. After a particular geographic extent of the United States is selected, the database's contents may be viewed or downloaded as tabular data, viewed in an interactive online map, or downloaded as GIS shapefiles that can be viewed and manipulated using computer mapping software. Version 2.0 of the Smart Location Database was released in July 2013 and both the database and its documentation may be accessed through http://www.epa.gov/smartgrowth/smartlocationdatabase.htm (U.S. Environmental Protection Agency 2014).
- *Green Communities Program*: The Green Communities Program helps communities to better understand sustainable development by introducing them to a basic planning process and then

assisting them to implement that process by providing access to a vast array of tools and information. Encouraged to look holistically at their current situations, planners are asked to envision their community as it is (Step 1: Community Assessment), as it will be in the future if no action is taken (Step 2: Trends Analysis), and as the community wants to be (Step 3: Visioning Process). Communities are then asked to develop an action plan (Step 4) that will help them realize their sustainable development goals. Implementation of the action plan is the final step (Step 5). A Green Community uses and encourages modes of travel other than the automobile; street and circulation patterns encourage pedestrian movement, and efficient transportation systems maximize accessibility and the movement of people and goods, providing economic benefits. Increased opportunities for the use of pedestrian and bicycling facilities help to create a sense of community, reduce car-miles driven, and contribute to general well-being and a good quality of life. The Green Communities planning process and web-based toolkit encourage communities to consider various transportation issues, including the provision of public transit, as a part of their sustainable development planning processes. The Green Communities website, http://www.epa.gov/greenkit/index.htm, includes sample transportation action plans and information on action plan indicators (U.S. Environmental Protection Agency).

- *EnviroAtlas*: EnviroAtlas is an interactive, web-based decision-support mapping tool designed to provide information about ecosystems and their benefits to society. EnviroAtlas also addresses point- and nonpoint-source pollution, landcover conversion and fragmentation, resource restoration, and shifts in demographics and natural hazards, all of which can drive changes in the production of and demand for these benefits. Decisions about resource use and environmental policy are often made with an incomplete understanding of the interactions between human activities and beneficial ecosystem processes and functions. EnviroAtlas provides users with maps, analytical tools, and other information for interpreting the distribution of ecosystem services across the conterminous United States, and for understanding how they can be conserved and enhanced in the future. In the context of transportation projects, EnviroAtlas can help guide where best to preserve, restore, or construct ecosystems for maximum public benefit. Data in EnviroAtlas may be used to inform methods to value and pay for ecosystem services, which may also influence restoration decisions and project locations. EnviroAtlas presents data at national and community scales. The national component summarizes data by 12-digit hydrologic unit codes (HUCs, of which there are approximately 90,000 in the conterminous U.S.). The community component summarizes data by census block group for selected cities and towns, with some data (like vegetative cover) at a finer scale. Both components also include pixel-based and other spatially detailed maps; all of these data are available via web services and direct download. EnviroAtlas is designed for staff from all levels of government, environmental and public health professionals, researchers, educators, nongovernmental organizations, and anyone else with an interest in ecosystem services and their role in supporting sustainable and healthy communities. It does not require special software, technical expertise, or a scientific background. In beta release through December, 2013, EnviroAtlas is accessible via http://www.epa.gov/research/enviroatlas/index.htm. Part of EnviroAtlas is the Eco-Health

Relationship Browser, which makes information on health and well-being implications of built and natural environments easily accessible. The Browser is available online at [http://www.epa.gov/research/healthscience/browser/introduction.html and from the EnviroAtlas homepage](http://www.epa.gov/research/healthscience/browser/introduction.html).

- *Database of Sustainability Indicators and Indices (DOSII)*: EPA researchers developed a Database of Sustainability Indicators and Indices, as well as a corresponding framework document on the selection and use of sustainability indicators (U.S. Environmental Protection Agency 2012c). DOSII is a searchable inventory of peer-reviewed sustainability indicators classified into a single taxonomy system, supporting decision making by providing candidate indicators (and indices) relevant to specific sustainability-related interests (e.g., air, water, energy, communities, transportation, etc.). In addition, an interactive web-based tool (e-DOSII) is being developed to extend DOSII's search capabilities to communities and to provide information through a user-friendly web interface. While the target audience of this work is EPA personnel, external organizations interested in measuring some aspect of sustainability have found it useful, too. The current version of DOSII and the related framework document are presently available online, and DOSII is scheduled for delivery in October 2014.
- *Decision Analysis for a Sustainable Environment, Economy, and Society (DASEES)*: Not yet publicly available, the Decision Analysis for a Sustainable Environment, Economy, and Society is a web-based decision-support framework intended to help community stakeholders arrive at sustainable courses of action. DASEES is organized around the five steps of 1) establishing the context for a decision, 2) determining what objectives are meant to be achieved, 3) listing various options for accomplishing those objectives in the given context, 4) evaluating the relative desirability of the listed options, and 5) implementing the best available option. For each of these steps, DASEES provides various analytical tools, allowing stakeholders in a given community to customize their modeling efforts to fit the unique circumstances surrounding a particular decision. The tools in DASEES are able to combine disparate outcome metrics into one composite measure, whose inputs are weighted both according to a given community's priorities and according to the inverse of how much uncertainty is attached to each measurement or calculation. Outputs may take the form of tables, charts, or GIS maps. Along with the actual tools, DASEES provides case studies and other guidance on the use of the framework (Stockton et al. 2011).
- *Community-Focused Exposure and Risk Screening Tool (C-FERST)*: The Community-Focused Exposure and Risk Screening Tool is designed for assessing exposure in a given community to a variety of stressors of public health, based on location-specific data, so that problems and solutions can be prioritized. C-FERST was created because it can be very difficult for a community to draw the necessary linkages between the presence of a given stressor and the degree of human exposure to that stressor. Because C-FERST's outputs include GIS maps of these stressors, the model is useful for addressing issues of environmental justice. In the current version of C-FERST, which is still being pilot-tested, only chemical stressors are considered. However, future versions are expected to incorporate a wide variety of both chemical and nonchemical stressors, consequently making C-FERST relevant to far more than

just human health outcomes. Future versions of C-FERST are also expected to predict what the outcomes would be of various hypothetical actions that a community might take, integrate with other decision-support tools, and possess various other enhancements. In general, C-FERST is intended for use by community leaders and is not well-suited for assessments by ordinary residents (U.S. Environmental Protection Agency 2013a).

- *Tribal-Focused Environmental Risk and Sustainability Tool (Tribal-FERST)*: The Tribal-Focused Environmental Risk and Sustainability Tool, still being pilot-tested and enhanced, is an Internet-based decision-support tool specifically designed for use by tribal communities to address the unique sustainability issues that they face, especially those in the areas of human health and ecology. Tribal-FERST will be set up to provide step-by-step guidance for determining a priority order in which to address various problems and risks and for assessing the results of different actions. At each of the steps in this guidance, users will be provided with scientific information relevant to their specific situation, links to other tools that might be of help to them, and the ability to create overlay maps of many different datasets (U.S. Environmental Protection Agency 2013e).
- *Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI)*: The Tool for the Reduction and Assessment of Chemical and other environmental Impacts allows the characterization of the following impact categories: ozone depletion, global climate change, acidification, eutrophication, smog formation, human health, ecotoxicity, and fossil fuel depletion (Bare 2012, Bare 2011, Bare et al. 2002). Midpoint-level characterizations (e.g., ozone depletion potentials (ODPs) and global warming potentials (GWPs)) allow minimal incorporation of value choices and assumptions while also allowing the most comprehensive inclusion of endpoint impacts (Bare et al. 2000). When combined with local data or life-cycle inventory data (e.g., air, water, and soil emissions), TRACI can be used to compare the relative impacts of two or more options, as a way of supporting sustainability decisions. For example, scenarios could be developed for two alternative transportation-related decisions to determine which of the options would be expected to have a less negative environmental impact in one or all of the above impact categories.
- *Final Ecosystem Goods and Services Classification System (FEGS-CS)*: The Final Ecosystem Goods and Services Classification System is a database currently under development by the EPA, meant to be used by both public- and private-sector actors, that consists of quantifiable metrics that describe the ultimate, tangible ways in which the natural environment might affect the lives of humans. While one might deem a given ecological feature to be generally beneficial, the exact character and magnitude of its impacts are context-dependent. By including these contextual considerations, the metrics in FEGS-CS may serve as inputs to an overall accounting of the positive and negative outcomes of a given action. As a result, it may also be possible to determine what ecologically beneficial actions would be sufficient to compensate for the effects of a given action that is ecologically detrimental. Classifying ecosystem services in terms of their final effects on humans also has the advantage of linking the natural and social sciences and the advantage of avoiding the double-counting of benefits (U.S. Environmental Protection Agency 2012b, Landers and Nahlik 2013).

- *National Ecosystem Services Classification System (NESCS)*: The National Ecosystem Services Classification System is being developed concurrently with the FEGS-CS. NESCS will link the theoretical constructs of ecology and economics in order to create an exhaustive accounting of all of the known pathways by which humans derive value from ecosystems. To date, most economic analyses have been blind to those things to which a concrete price cannot be attached and most ecological analyses have been blind to the ways in which humans value ecosystem goods and services. NESCS will use FEGS-CS to define and code all of the conceivable inputs to the accounting, ensuring that direct and indirect effects are not confused with one another and that drivers whose influences are distinct from one another are not counted together. By mapping mutually exclusive pathways, NESCS will ensure that all effects are counted and that none of them are double-counted. The resulting algorithms may be used to calculate the value to humans of any given natural area, contributing to decisions on preservation, mitigation, and restoration priorities.
- *EcoService Models Library (ESML)*: Also currently under development at the EPA is the EcoService Models Library, which will be a searchable database describing mathematical functions that various research efforts have shown to link the inputs and outputs of a given ecological process. The ESML is meant as a resource for the developers of decision-support tools, guiding them to equations that they may decide to use to represent individual causal relationships within their models (U.S. Environmental Protection Agency 2012a). This resource is expected to be finished in 2014 and is expected to be available over the Internet in 2015.

Table 2: EPA tools of relevance to transportation sustainability

Tool	**Dimension(s) of Sustainability**	**Description**
Community Cumulative Assessment Tool (CCAT)	Social (Human Health)	A computerized, step-by-step assessment method that leads users through a guided, yet flexible, process to relate stressors to impacts, compare a wide range of issues simultaneously, and develop a “to-do” list of actions to address health and environmental impacts in their community, constituting a component of the larger Community-Focused Exposure and Risk Screening Tool (C-FERST)
Community-Focused Exposure and Risk Screening Tool (C-FERST)	Social (Human Health)	A spatially-explicit tool for assessing degrees of human exposure to various public health stressors in a community
Community Multiscale Air Quality (CMAQ) model	Environmental (Air)	A multiscale, multipollutant, “one atmosphere” model that includes a meteorological component to describe atmospheric conditions, emission models for anthropogenic

		and natural emissions that are released into the troposphere, and a chemical-transport model (CTM) to simulate chemical transformations, atmospheric transport, and fate
Database of Sustainability Indicators and Indices (DOSII)	Environmental, Economic, and Social	A searchable taxonomy of peer-reviewed indicators and indices of relevance to a wide variety of sustainability-related issues
Decision Analysis for a Sustainable Environment, Economy, and Society (DASEES)	Environmental, Economic, and Social	A community-scale decision-support framework that allows users to choose among a variety of analysis tools in order to create models tailored to their specific situation and the particular question under consideration
Eco-Health Relationship Browser	Environmental and Social (Public Health)	An interactive, web-based tool that reflects a detailed review of the recent scientific literature and displays published linkages between ecosystem services and many aspects of public health and well-being, accessible through EnviroAtlas
EcoService Models Library (ESML)	Environmental	A searchable database describing mathematical functions that various research efforts have shown to link the inputs and outputs of a given ecological process, meant as a resource for the developers of decision-support tools
EnviroAtlas	Environmental	An online, interactive mapping tool that reports and helps analyze the distribution of ecosystem services across the conterminous United States
EPANet	Environmental (Water)	A planning and engineering tool that models drinking water supply systems
Final Ecosystem Goods and Services Classification System (FEGS-CS)	Environmental	A database of quantifiable metrics of the ultimate, tangible ways in which the natural environment might affect the lives of humans, with consideration of the context-dependent nature of such effects

Green Communities Program	Environmental, Economic, and Social	Provides an online toolkit with links to many different sustainability-related tools, models, indicator systems, and case studies, organized around a five-step planning process
Integrated Climate and Land-Use Scenario (ICLUS)	Environmental, Economic, and Social	A large development scenario covering the entire U.S. that projects housing density and land use categories to the year 2100
MOtor Vehicle Emission Simulator (MOVES) model	Environmental (Air)	A model for estimating air pollution emissions from all on-road motor vehicles, including cars, trucks, motorcycles and buses, that allows emissions to be analyzed at various geographic scales
National Ecosystem Services Classification System (NESCS)	Environmental and Economic	Links the theoretical constructs of ecology and economics to create an exhaustive accounting of the known pathways by which humans derive value from ecosystems, using FEGS-CS to define and code the inputs
PVIScreen	Environmental (Water and Air)	A model that accounts for the transport and fate of fuel components in soil gas and groundwater, including the case of them causing indoor air contamination (called vapor intrusion)
Smart Growth Index (SGI)	Environmental, Economic, and Social	A GIS-based planning tool used for modeling base and alternative land-use and transportation scenarios for a single point in time and comparing them on the basis of pre-programmed indicators
Smart Location Database (SLD)	Environmental, Economic, and Social (Transportation Behavior)	Database of measures of built-environment, demographic, employment, and other characteristics that affect travel behavior, reported at the Census-Block-Group level for the entire United States
Storm-Water Management Model (SWMM)	Environmental (Water)	A tool for assessing stormwater runoff impacts, able to model runoff volumes from impervious and pervious surfaces in a network

		of catchments and subcatchments under many different circumstances, primarily geared towards use in urban areas, but also having nonurban applications
Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI)	Environmental	Characterizes several different categories of environmental impacts (ozone depletion, global climate change, acidification, eutrophication, smog formation, human health, ecotoxicity, and fossil fuel depletion) for scenarios that the user wishes to compare
Tribal-Focused Environmental Risk and Sustainability Tool (Tribal-FERST)	Environmental and Social (Human Health)	Provides step-by-step guidance for tribal communities to determine a priority order in which to address various problems and risks and to assess the results of different actions, with relevant scientific information and links to other tools supplied at each step

4.1.3 Non-EPA Models, Tools, and Other Resources

- An important tool supported by the Federal Highway Administration (FHWA) is the Infrastructure Voluntary Evaluation Sustainability Tool (INVEST). Version 1.0 of this tool was released in October 2012. INVEST is free and available for use by the general public. The program is designed as a scorecard that includes criteria for evaluating environmental, economic, and social impacts of transportation projects at a variety of scales and at various stages throughout the planning and implementation processes, including system planning, project development, and operations and maintenance. INVEST primarily focuses on highway projects (U.S. Department of Transportation).
- The Leadership in Energy and Environmental Design (LEED) rating system, a product of the United States Green Building Council (USGBC), is a comprehensive, flexible, and very widely used tool for rating the environmental sustainability of the design, construction, and operation of individual buildings and neighborhoods, although not geared specifically to transportation planning (U.S. Green Building Council). Foreign counterparts to LEED include Canada's SBTool07, which includes economic and societal indicators, and the United Kingdom's Building Research Establishment Environmental Assessment Method (BREEAM), which, much like LEED in the United States, primarily focuses on the natural environment and energy consumption (Wallbaum, Krank, and Teloh 2011). The portion of LEED most relevant to sustainable transportation is the LEED for Neighborhood Development (LEED-ND) rating system, which is applied to geographic areas within cities, rather than individual structures. Among other things, this rating system gives points for neighborhood design features that are likely to reduce vehicle miles traveled (VMT) and increase nonmotorized transportation. The following are some

transportation-related features that LEED-ND awards points for (U.S. Green Building Council, Congress for the New Urbanism, and Natural Resources Defense Council 2012):

- Development activities that take place near public transit stops at which transit vehicles stop sufficiently frequently.
- Developments that are near existing developed areas, such that traveling to those areas will entail shorter trips than would otherwise be the case.
- Highly-connected, grid-like transportation corridors that form small city blocks.
- Adequate transportation facilities for both motorized and nonmotorized modes of travel.
- Close proximities between housing units and employment locations.
- Neighborhood centers with many different kinds of destinations in close proximity.
- Short distances between building entrances and transportation corridors.
- Dense and/or compact development patterns that place more destinations within a shorter trip distance.
- Pedestrian and bicycle facilities that are safe, appealing, and comfortable to use.
- Small quantities of land dedicated to motor vehicle parking.
- Transportation Demand Management (TDM) programs that offer financial incentives for people to drive less.
- Public schools that are small, numerous, and located in close proximity to the homes of a large percentage of the students who attend them.

- The GreenLITES programs (from the New York State Department of Transportation) and the Greenroads rating system have their primary focus on issues of civil engineering, construction, and maintenance. These rating systems are based on the LEED rating system (Ramani et al. 2011).
- A key issue in transportation planning is the impact that transportation and land use have on one another and how they collectively impact the environment. The Transportation Research Board has developed a decision support tool called Transportation for Communities: Advancing Projects through Partnerships (TCAPP), available at www.transportationforcommunities.com. TCAPP has a broad focus, but it in part zooms in on the linkage between transportation and land use. It provides examples of integrating transportation and land-use decisions from Maryland, Oregon, New York State, the Thurston region in Washington State, and the Sacramento area. Maryland and New York are given as examples of states that promote smart growth in their transportation decisions. Oregon uses GreenSTEP, a modeling tool that calculates measures of such things as household travel and vehicle emissions and can be used to evaluate environmental effects of land use patterns and transportation services at a fine level of detail (http://www.oregon.gov/ODOT/TD/OSTI/docs/media/model.pdf). The Thurston Regional Planning Council, in addition to its various policies promoting smart growth, uses Community Viz to develop and compare scenarios. Community Viz and other geospatial visioning tools are powerful and flexible planning models that can calculate environmental impacts and a variety of other outcomes resulting from given land use and transportation scenarios. Tools such as Community Viz can be linked to external models, including travel demand models. An array of other tools and methods that are more broadly applicable to transportation and ecological

decision-making are listed and briefly described in TCAPP, in its section on the Integrated Ecological Framework, a process for accounting for ecological values early in the transportation planning process.

- The System for Planning and Research in Towns and Cities for Urban Sustainability (SPARTACUS) indicator system is a four-step forecasting model that involves identifying land use, transportation, and pricing policy elements and then testing scenarios for different combinations of packaged policies to determine their long-term sustainability. Included within this modeling system is MEPLAN, a land use/transportation interaction model. Also included are the ability to analyze data at a very fine geographic scale using GIS and a decision-support tool that allows the user to create weighted composite indicators of sustainability (Black, Paez, and Suthanaya 2002).
- The Integrated Transportation Gravity-based Land Use Model (ITGLUM) is a very simple land use/transportation gravity-based model (Duthie et al. 2010).
- Slope, Land-use, Exclusion, Urban extent, Transportation, and Hill shade (SLEUTH) is an example of an integrated transportation and land use model that uses the cellular automata approach of defining cells within a community and then determining how each of those cells is affected by its immediate neighbors (Lemp et al. 2008).
- TRANUS and the Random-Utility-Based Multiregional Input-Output (RUBMRIO) model are land use/transportation models that use an input-output model to produce results primarily focused on forecasting economic and trade effects. (Lemp et al. 2008).
- UrbanSim is an open source modeling program that users can expand to meet their needs. This model is dynamic, highly disaggregated in its scale of analysis, and accounts for the behavior of households, private companies, real estate developers, and public officials (Lemp et al. 2008).
- The Transportation, Economic, and Land Use Model (TELUM) is a free program from the FHWA that makes use of a gravity-based model, wherein data is geographically aggregated into zones (Lemp et al. 2008).
- The California Urban Futures models (CUFI and CUFII) are discrete response simulations that are meant to carry out GIS analyses of large metropolitan areas, with CUFI placing particular importance on real estate profitability as a determinant of development patterns (Lemp et al. 2008).
- The Comprehensive Econometric Micro-Simulator for Daily Activity-Travel Patterns and the Mid-Ohio Regional Planning Commission's activity-based travel-demand model are two more programs relevant to transportation and land use applications (Lemp et al. 2008).
- Some examples of available GIS scenario-building/visioning tools include Community Viz (already mentioned), California's PLACE3S, and the Charlottesville, Virginia region's CorPlan (Lemp et al. 2008).
- Some land-use models have the potential to serve as scenario-planning tools. The program What if? provides functions for its users to assign areas of land weights according to their relative importance, along with ratings of their suitability for development and how easy to convert their land use is. The program UPlan allows its users to specify attractiveness criteria for land areas that represent the land's value and accessibility. In both of these programs, the

object of the user-inputted ratings and criteria is to allocate demand across a geographic area (Lemp et al. 2008).

4.2 Drivers of Transportation Behavior

Although there are some sustainability outcomes that a piece of transportation infrastructure will affect regardless of whether and how people use it, one of the most important questions in ascertaining the sustainability-related implications of a transportation policy or investment is what impact it will have on people's transportation-related behavior. This includes choices regarding transportation modes, trip frequencies, trip lengths, and trip purposes. The purpose of this section is to synthesize what is currently known about the factors that influence travelers' choices in these matters. Factors to be considered here include characteristics of the transportation system, governmental policies related to transportation, and drivers of behavior that a community's transportation decision-makers can only influence indirectly, such as travelers' attitudes.

The most heavily researched topic in all of urban planning is the effect of the built environment (i.e., land use patterns and physical infrastructure) on transportation demand and transportation behavior (Ewing and Cervero 2010). However, in spite of all of this research, causal linkages between the built environment and transportation behavior have been difficult to establish and quantify, leaving knowledge gaps (Frank et al. 2008, Scheiner and Holz-Rau 2013). One reason for this difficulty is the highly interdependent nature of the relationship between transportation systems and land use patterns. First, changes to the size and nature of the transportation system alter the amount of accessibility that people have to various destinations. Then, this change in accessibility prompts the development community to alter land use patterns in such a way as to make the most profitable use of the transportation system, which also alters the amount of accessibility that people have to various types of destinations. All of these changes in accessibility affect the frequency, length, duration, mode, timing, destination, and purpose of the trips that people choose to make. Finally, these changes in travel behavior affect the balance between transportation demand and transportation supply and the distribution of travel demand across the transportation network, which prompts transportation planners to make additional changes to the system (Kitamura 2009, Szeto, Jaber, and O'Mahony 2010). More on the relationship between land use and travel behavior may be found in the concurrent SHCRP Theme 4 synthesis paper on land use.

Ewing and Cervero (2010) sort the various aspects of the built environment that are relevant to transportation behavior into a series of broad, overlapping categories that they refer to as the "Five Ds" (and which are also the thematic basis of the measures in the Smart Location Database, discussed above): Density (of population, employment, dwelling units, commercial floor space, etc.), Diversity (of land uses), Design (of the transportation network), Destination Accessibility, and Distance to Transit. Ewing and Cervero regard these built-environment variables as affecting travel behavior alongside the other relevant factors of Demand Management (which includes, but is not limited to, the supply and cost of parking) and Demographics. In the same paper, they synthesize 62 separate studies of the relationship between the built environment and travel behavior. This synthesis includes tables of average elasticity values from the pooled samples of the various studies analyzed (each elasticity value describing the strength of the relationships between various aspects of the built environment and people's travel behavior, where a 1% change in variable A is predicted to produce an X% change in variable B), as well as an appendix containing elasticity estimates from the original studies. If a transportation planner finds a study in the appendix that had good methodology and which is from a geographic location sufficiently close to the one they serve, the planner could potentially borrow an elasticity value directly from that study for use in their own calculations. The average elasticities from the pooled samples, meanwhile, could potentially be used in various sketch-planning situations to estimate amounts of driving, walking, and transit use that may result from a given act of government or development project, relative to a base scenario. An important caveat to the use of this resource, however, is that the average elasticities contained in it have not been tested for statistical significance (Ewing and Cervero 2010, Gim 2012).

The most-studied of all of the characteristics of the built environment that affect travel behavior is density. The reasons for this particular research focus are that density is a relatively easy variable to measure, a relatively easy driver to influence through policy decisions, and highly correlated with many other built-environment characteristics that tend to change travel behavior in similar ways (Gim 2012). However, when other built-environment characteristics are controlled for, the influences of population density and employment density on travel behavior are actually quite modest. Among the significant built-environment characteristics that are correlated with high population and employment density in a neighborhood are highly-mixed land uses, small city blocks, and a location near the center of a metropolitan area, all of which are associated with fewer Vehicle Miles Traveled (VMT) and greater mode shares for walking, biking, and public transit (Ewing and Cervero 2010). Even though the association between density and travel behavior is based to a large degree on correlations, it may still serve as a useful tool for perceiving important relationships. For instance, one analysis found that the smaller an area's population density, the greater the change in travel behavior would be from a given change in density (Sinha 2003). However, another analysis found that in European cities, which are generally denser than U.S. cities, the effect of density and urban form on travel behavior is significantly stronger than in U.S. cities, based upon a review of the conclusions of travel-behavior studies from each of those two regions (Gim 2012).

Another much-studied aspect of the built environment in transportation-behavior research is land-use diversity, which consists of both the number of different land uses within a given area and the relative amounts of each of those uses that are present. When this aspect of the built environment is studied, the most commonly used measures are entropy metrics, wherein a scale is established where a low number represents a single land use within an area and a high number represents a great variety of uses within that area. However, the less-used measure of the ratio between jobs and housing in an area (or jobs and population) has a stronger relationship with nonmotorized transportation than entropy measures do (when the number of jobs in an area and the number of working-age residents of that area are similar to one another, it increases the opportunities for easy commuting without a motor vehicle) (Ewing and Cervero 2010). Research to date has given little attention to the travel-behavior effects of the land uses that surround a person's place of work, as opposed to those that surround their place of residence (Frank et al. 2008).

The effect of the design of the transportation network on travel behavior is especially difficult to measure, because it represents the collective impact of many different types of design features. For example, aspects of transportation network design include the size of city blocks, the number of intersections per square mile, the proportion of intersections that are four-way intersections, the proportion of the street network that has sidewalks, the width of the streets, the distances that buildings are set back from the curb, the number and quality of marked pedestrian-crossing locations, the distinction between a grid-based network and a curvilinear network, and many other features. Consequently, various composite measures are sometimes created that combine design features that are known to affect travel behavior in similar ways (Ewing and Cervero 2010).

One common way of measuring access to public transit within a given area is to calculate the shortest distance that someone would have to travel along the transportation network to reach a transit stop from each residence or job location within the area and take the average of those figures. Other measures include transit-route density, transit-stop density, and the average distance between transit stops. Not surprisingly, there exists a strong relationship between how close someone lives to a public transit stop and how likely they are to use public transit, a fact which reinforces the common practice of transit agencies of trying to run buses within a quarter mile of most of the households in their service areas (Ewing and Cervero 2010).

It is to get the best possible use out of an area's transit accessibility that there exists the practice of Transit-Oriented Development (TOD). In this practice, a tight cluster of mixed-use development is created around a public transit station, such that people who either live there or work there may be within easy walking distance of both the transit station and most of the businesses and amenities within the development. Usually, these developments that are built to be conducive to transit use are centered around a rail station, but they may sometimes be centered around a bus stop. Most of the existing literature on Transit-Oriented Development is focused on the policy tools used by government agencies in their creation, as opposed to addressing design concerns such as ascertaining the appropriate amount of travel by each non-transit mode of transportation to accommodate (Jacobson and Forsyth 2008).

Of all of the categories of built-environment characteristics identified by Ewing and Cervero (2010), Destination Accessibility has the strongest influence on travel behavior. One may consider accessibility at either a local scale (for example, the distance from a person's home to the nearest store) or a regional scale (for example, the distance to the nearest central business district or the number of jobs or attractions located within a given travel time of a given location). Most of all, having greater access to a greater number of destinations is highly associated with lower VMT per capita. At the core of an urban area, there are more destinations that can be easily reached without the use of a personal motor vehicle, and even when a personal motor vehicle is used, the necessary trip lengths are shorter. Most developed areas near the center of a city produce less VMT per capita than a pedestrian-oriented, compact, mixed-use development in a remote location. VMT is also reduced (to a lesser degree) by high intersection density and street connectivity, while a very small dampening influence is exerted on VMT by population density and job density, with the influence of population density being stronger than the influence of job density. Meanwhile, the built-environment characteristics that have the strongest (positive) relationship with travel by foot are high intersection densities, a balanced ratio between jobs and dwelling units, and short distances between homes and stores. There is evidence of a stronger relationship between intersection density and walking than between street connectivity and walking; one possible explanation is that a given study area might have highly connected streets, but also very long city blocks that inhibit walkability for people who must travel around them. The transportation network design elements of intersection density and street connectivity also constitute the second tier of major built-environment drivers of transit use (after Distance to Transit), enabling less circuitous travel to and from transit stops and allowing transit providers to consider a greater number of potential transit vehicle routes. The third tier of built-environment drivers of transit use consists of measures of land-use mixture, possibly due to sufficiently mixed land uses enabling the running of errands on the way to or from a transit stop.

4.2.1 Correlations and Elasticities Regarding the Built Environment and Travel Behavior

The following are some numerically-expressed relationships between the built environment and travel behavior that various studies have quantified:

- In a study of National Ambient Air Quality Standard (NAAQS) Nonattainment Metropolitan Statistical Areas (NMSAs), researchers estimated that if all households in NAAQS NMSAs were located within 0.1 miles of a transit stop, it would reduce the number of private motor vehicles by 9% and reduce VMT by 11%. The authors estimated that this is similar to the effect that would be produced by a 50% increase in gasoline prices (Kim and Kim 2004).
- In a synthesis of the results of many different studies of built-environment effects on travel behavior, Ewing and Cervero (2010) arrived at an elasticity between VMT and employment accessibility by automobile of -0.20. A 10% increase in employment accessibility by automobile would be associated with a 2% reduction in VMT. This was almost as strong as the combined elasticities with VMT found to exist for density, land use diversity, and transportation network design. In a different synthesis of built-environment-and-travel-behavior studies from 2001, the same authors stated that doubling a neighborhood's density would cause both VMT per capita and vehicle trips per capita to go down by 5%.
- A 10% increase in roadway capacity, measured in lane-miles, is associated with an increase in VMT of between 5% and 10% (Sinha 2003).
- The amount of road length per capita in different areas explains 70% of the variability in private motor vehicle ownership rates and 76% of the variability in private motor vehicle use rates (Sinha 2003).
- High population densities are associated with a relatively high ratio between a transit agency's revenue from fare collection and that same agency's operating expenses. Population density explains 62% of the variation in these fare recovery ratios (Sinha 2003).
- A change in the ratio of the cost of private-mode transportation per mile traveled to the cost of public transit use per mile traveled is associated with an opposite-direction change in the

percentage of work trips that are made by transit, a relationship which explains 32% of the variation in the latter variable (Sinha 2003).

- Activity density (calculated as the sum of population density and employment density) explains 88% of the variation between different areas in how much they require new road capacity (Sinha 2003).
- Transit demand per person is negatively correlated with the amount of parking per employee in a metropolitan area's Central Business District (CBD), automobile ownership, automobile use, and road provision. The percentage of work trips made by public transit is negatively correlated with the amount of road investment in an area and with fuel prices (Sinha 2003).
- Job density and population density are both significantly correlated with public transit boardings per person per year (Sinha 2003).
- The Land Use, Transportation, Air Quality, and Health (LUTAQH) Study in King County, WA found the following relationships (Frank et al. 2008):
    - The biggest determining factor in people's travel choices is the amount of time that they spend traveling, indicating the significance of both traffic congestion and time spent waiting to transfer between transit vehicles.
    - A 5% increase in residential density, the connectivity of the street network, land use mixture, and the ratio of retail floor area to land area used for retail, all at the same time, would be associated with a 32% increase in walking.
    - Each additional motor vehicle that a household owns decreases the odds of people in that household using public transit by 42%.
    - A quarter-mile increase in the average distance from a person's home to the nearest transit stop would be associated with a 16% decrease in transit use.
    - A quarter-mile increase in the average distance from a person's workplace to the nearest transit stop would be associated with a 32% decrease in transit use.
    - Each additional institution or recreational facility within a one-kilometer walk of a person's home increases their odds of walking by 20%.

4.2.2 Parking

There exists a shortage of available data on the effect of the parking supply on people's transportation mode choices. However, there is enough evidence to determine that the dampening effect of scarce or expensive parking on automobile use is significant. Travelers perceive one additional minute spent walking to or from a parking space as a greater burden than one additional minute spent driving (Frank et al. 2008).

4.2.3 Neighborhood-Scale Travel versus Regional Travel

Individual neighborhoods and other geographic subdivisions of a large study area are bound to have unique characteristics that influence travel behavior within them. Therefore, consideration should be given to both local drivers of short-trip behavior and regional drivers of long-trip behavior, bearing in mind that the regional transportation environment is influenced by the various neighborhood-scale transportation environments that are contained within it (Black, Paez, and Suthanaya 2002). When a person habitually uses a particular mode of transportation for long trips, the odds of them also using that same mode of transportation for short trips increases (or vice versa). For example, people who possess bus passes (indicating that they are probably frequent transit users) are more likely than other people both to use public transit for long trips and to use public transit for short trips (Kim and Ulfarsson 2008). However, substantial differences between people's favored transportation modes for trips within their home neighborhoods and trips within a larger region (urban or otherwise) also commonly exist. In a study from the borough of the Bronx in New York City, an increase in trips that last less than 30 minutes was associated with more automobile travel and an increase in trips that last between 30 minutes and 90 minutes was associated with more travel by public transit. The authors of the study explained these associations by observing that, in New York City, long distance car trips are discouraged by a combination of traffic congestion, scarce parking, and expensive tolls, while the financial cost of using transit is unaffected by distance and the average speed of a short transit itinerary will tend to be lower than the average speed of a long transit itinerary on account of a large percentage of a short itinerary's duration being spent on travel to and from transit stops (by other modes) and waiting for transit vehicles to arrive. Consequently, the authors concluded that an increase in the number of jobs in the Bronx would increase automobile usage by the borough's residents and increase the number of people commuting into the Bronx by way of that particular region's most-favored transportation mode for long-distance commutes (i.e., public transit) (Berechman and Paaswell 1997).

The case of such transit-heavy locations as New York City notwithstanding, most people's favored mode of transportation for long trips across a region is the private automobile. Because of low-density development patterns and the speed and flexibility of private motor vehicles, altering the built environment in such a way as to substantially reduce private automobile use on long trips would be a very difficult undertaking (but one generally regarded as being helpful in the advancement of various sustainability goals). However, the conversion of short trips from motorized modes to nonmotorized modes could likely be achieved with greater ease. Among other things, the promotion of short, nonmotorized trips could reduce traffic congestion, since a large proportion of the automobile trips that short, nonmotorized trips would be capable of replacing are non-work trips carried out during rush hour, such as to run errands, drop off children, or engage in recreational activities. Nonetheless, drivers of travel behavior on short, non-work trips are currently little-studied, especially in the United States (Kim and Ulfarsson 2008).

The largest driver of people's mode choices for short trips is the purpose for which the trip is being undertaken. When people choose to use an automobile for a short trip in spite of the presence of the necessary infrastructure to make that trip efficiently by a different mode, one of the most common reasons for that choice is the need to transport heavy cargo that would be difficult to carry under their own power. Other common reasons include the transportation of passengers, the need to save time, the knowledge that one will require an automobile for some later trip that will start from the endpoint of the current trip, physical infirmity, and simply using a car for the reason that it is available. According to studies from the United States and Europe, among non-automobile modes of transportation used for short trips (defined variously as those trips with a maximum distance of between one and two miles), walking is more common than either public transit or cycling, which are rarely used for such trips.

People are reluctant to use transit for short trips because it would require coordinating their actions with a transit schedule that might not provide much service during off-peak times of day and because time spent traveling to and from transit stops (by other modes) and waiting for transit vehicles to arrive at stops reduce the average speed of a short transit trip more than they would the average speed of a long transit trip. Meanwhile, even though cycling is faster than walking, it produces less time savings on short trips than on long trips, leaving people with less reason to ignore any perceived safety concerns with cycling, or the risk of their bicycle being stolen, or the difficulty of riding a bicycle in inclement weather. People are more likely to ride a bicycle on a short trip if that trip is across level terrain (Kim and Ulfarsson 2008).

As with long trips, congestion charging and a limited parking supply discourage the use of automobiles for short trips. The use of public transit for short trips is greater in more urban areas, where there is less distance between transit stops, where transit fares are lower, and where the overall level of service of the transit system is greater. Nonmotorized modes of transportation are more likely to be used when safe, comfortable paths are provided for them which are separated from the flow of automobile traffic, there is an adequate supply of bike racks, and short door-to-door travel distances exist between a given origin point and various destinations. The short trips on which people are most likely to walk are ones that are for social or recreational activities (including eating out at restaurants). People are less likely to walk on shopping trips, possibly out of a reluctance to have to carry their purchases home unassisted. Families with children (that need an efficient mode of transportation for running errands and that take part in more group activities) tend to drive more on short trips. The elderly are less likely than other people to walk on short trips while people who have lived at their current address for less than one year are more likely than other people to walk on short trips. Finally, one of the most important factors in determining a person's mode choices for short trips (and which is reflective of other factors) is their individual threshold distance below which they see walking as preferable and above which they see driving as preferable (assuming that both of those modes are available to them). Not surprisingly, frequent walkers have higher threshold distances and frequent drivers have shorter threshold distances. Short threshold distances are also associated with perceived exertion from walking and with age (Kim and Ulfarsson 2008). In addition to the previously discussed factors of destination accessibility, intersection density, and traffic safety, walking is also encouraged by aesthetics (both natural and architectural), safety from crime, low noise levels, low pollution levels, the absence of "physical disorder," and amenities such as benches and sidewalk retail/restaurants (Neckerman et al. 2009).

4.2.4 Transportation System Capacity as a Driver of Travel Behavior

When new capacity is added to a congested transportation system (e.g., in the form of new roads or lanes), one can assume that people's travel behavior will change in response. When a transportation agency decides to address the issue of traffic congestion by adding capacity to the roadway system, most of the new capacity is added to arterial roads and highways, rather than smaller collector streets. The ability to travel at high speeds on recently decongested arterial roadways motivates people to engage in more driving, especially for long trips. However, most trips that make use of an arterial roadway both begin and end on lower-order roadways. As a result, when a capacity expansion reduces congestion and increases traffic volume on arterial roads, traffic volumes also increase on roads that have not been (and frequently do not have the room to be) expanded. Therefore, expanding an arterial roadway may simply shift the traffic congestion burden from the arterial road to city streets in an urban core, within which automobile travel may consequently be discouraged for short trips, even while it is being encouraged for long trips (Frank et al. 2008). Meanwhile, capacity is sometimes added to the transportation system in the form of a new exclusive right-of-way for transit vehicles (either trains or buses). When this is done, it is likely that most of the transit riders on the new right-of-way will be people who were already using public transit prior to its opening, as no other mode has been rendered any less convenient than before. However, if an automobile traffic lane is replaced with an exclusive public transit right-of-way that is similar to the remaining parallel automobile lanes in terms of both speed and level of service, some people may be motivated to switch from driving a car along that particular corridor to riding transit along it (Kennedy 2002).

4.2.5 Induced Demand

A major point of contention in the study of travel behavior is the existence of "induced demand." In theory, once capacity is added to a congested road system, people will go on more trips and longer trips, make more of those trips by private automobile, and perform more of their trip making during the peak travel periods of the day. By allowing people to act upon a latent demand for travel that had previously been suppressed by traffic congestion, at least a portion of the initial congestion relief from a capacity expansion is expected to be undone by increases in traffic volume (Kitamura 2009, Kristoffersson and Engelson 2009). However, the phenomenon of induced demand is not well understood, would require very complex theories to model, and is not incorporated into standard travel demand forecasts (Kitamura 2009). Assuming that induced demand exists, it is not limited to the mode of personal automobile travel. There is evidence of significant latent demand in communities for more walkable environments; however, people consider walkability to be one of many neighborhood characteristics to be traded off with others when choosing where to live (Frank et al. 2008).

4.2.6 Peak Spreading

Another important concept related to roadway capacity is that of "peak spreading." When traffic congestion gets bad enough during the peak travel periods of the day, some drivers will choose to avoid the worst of the congestion by commencing their trips either a little before or a little after their preferred time, with the result being a daily pattern of less congested traffic over a longer period of time instead of more congested traffic over a shorter period of time. Because, in most locations, non-peak-period traffic volumes are well below congestion levels, peak spreading is something that transportation planners and engineers often encourage. One of the ways in which greater peak spreading is achieved is through congestion charging, wherein travelers are charged tolls for using major thoroughfares, sometimes with the tolls dependent upon the time of day during which one travels. Potential changes to travel behavior in response to a tolling scheme include traveling by a different mode, traveling along a different route, traveling to different destinations, reducing the frequency of one's trips, and altering one's usual departure times. A toll that remains the same at all times of day may induce people to avoid the toll road by traveling by a more circuitous route that requires them to commence their trips at an earlier time than they would be able to if they took the toll road. However, a greater degree of peak spreading would likely occur if off-peak periods of the day were subject to either no tolls or reduced tolls. In that event, people would have a direct and unambiguous financial incentive to depart on trips at times other than their most preferred times. It is also worth noting that if a congestion charging scheme succeeds in promoting peak spreading, it likely also succeeds in reducing overall traffic (Kristoffersson and Engelson 2009, Ng and Small 2012). Peak spreading may also be facilitated by employers who grant their workers flexibility in determining their hours, so that not everyone is necessarily commuting at the same time (U.S. Environmental Protection Agency 1998).

4.2.7 High Occupancy Toll (HOT) Lanes

If people are not willing to institute congestion charging on an entire thoroughfare, the option exists of creating High-Occupancy Toll (HOT) lanes, which are lanes of a freeway that vehicles with multiple occupants may use for free and that vehicles with only one occupant may use for a fee. The idea is that such restrictions will make the HOT lanes less congested than other lanes, give people a motive to carpool, and provide people with an opportunity to make a tradeoff between time spent traveling and money spent on tolls. Even though only ten HOT lanes existed in the United States as of 2009 (not counting High-Occupancy Vehicle lanes, which only vehicles with multiple occupants are allowed to use), some insights can be gained from existing HOT-lane case studies. First of all, if vehicles with multiple occupants are only able to use the HOT lane for free if they first submit some sort of registration, they are less likely to do so. Multiple-occupant vehicles are also less likely to use a HOT lane if they are merely charged a discounted toll instead of no toll at all. When public transit express buses are allowed to use these special lanes, it increases their speed relative to parallel automobile traffic, which increases transit ridership. When unemployment goes up, the number of people paying to use HOT lanes goes down. Finally, gasoline prices are positively correlated with both carpooling and transit use and negatively correlated with the number of people choosing to pay tolls to use HOT lanes (Goel and Burris 2012).

4.2.8 Trip Aggregation

Another concept used to address limited roadway capacity is that of "trip aggregation." Trip aggregation attempts to achieve a combination of the efficiency that comes from reducing the ratio of motor vehicles to people and the flexibility that makes personal automobiles a more attractive mode of travel than public transit in most cases. One form of trip aggregation is carpooling; however, carpooling is not a feasible option for the majority of trips. Another form of trip aggregation is car-sharing clubs. In these clubs, people who already drive less often than the average person (and perhaps wish to supplement their use of other transportation modes) pay to rent vehicles for as little as one hour and then return the vehicles to designated locations, as opposed to paying the fixed costs of owning an automobile; the same business model is used in bike-sharing programs. Trip aggregation can also take the form of government-subsidized demand-responsive transit services, which at the present time typically serve either residents of rural areas or people with physical handicaps. Due to low passenger volumes and long travel distances, though, these services tend to result in very little trip aggregation. However, through the use of GPS, cell phones, and a centralized system for collecting, organizing, and distributing information, more advanced forms of demand-responsive transit could conceivably be created to transport four to eight passengers in one vehicle from locations within one small area to locations within another small area on relatively little notice and with greater speed and flexibility than ordinary public transit (Tuomisto and Tainio 2005). In the U.S., trip aggregation programs (such as vanpools) may be run privately or by public transit agencies.

4.2.9 Crowding on Transit Vehicles

The impact of capacity constraints on transportation behavior is mostly considered in the context of roadway capacity. However, public transit systems also have limited capacities that, if insufficient to meet demand, may also affect people's travel behavior. The effects of crowding on public transit vehicles is not often modeled, in large part because this is only a significant issue on a small number of transit systems and only on certain parts of those systems or at certain times of day, and it is a particularly difficult phenomenon to predict. A person may choose to take a different transit route either because their preferred route is so crowded that when a transit vehicle reaches their stop there will not necessarily be room for them to get onboard or because vehicles on their preferred route tend to be crowded to the point of discomfort. If a passenger experiences crowding-induced discomfort on a transit vehicle, that discomfort is greater if they are required to stand during the journey rather than sitting. Also, the disutility that people derive from transit-vehicle crowding is taken to increase with the length of the trip. However, longer transit trips are also the ones most likely to either start or end in a low-density area, making them the transit trips on which crowding is least likely to be a serious problem. Although the issue of crowding may motivate transit users to choose different routes or different departure times, some early modeling efforts have indicated that the effect of transit-vehicle crowding on mode choice is not significant (Zorn, Sall, and Wu 2012).

4.2.10 Economic, Social, and Psychological Motivations for Travel Behavior

While correlations may be established between particular environmental characteristics or government policies and particular aspects of people's travel behavior, there does not yet exist an embracing theory of how travel-related decisions are made, as such a theory would need to span many different social sciences (Kitamura 2009). From an economic perspective, travel is treated as a derived demand, only valued to the extent that it is necessary to perform other activities, meaning that the amount of use a transportation system receives is dependent upon the destinations that it connects. In the most simplistic of terms, those transportation systems, routes, and modes where there occurs a drop in the price of travel (measured in terms of both time and money and assuming the presence of worthwhile destinations) will see an increase in travel demand (and actual travel) and a decrease in travel supply (unused capacity). An increase in average travel speeds produces likewise changes in transportation demand and traffic volume, which (assuming volumes increase enough to produce some measure of congestion) causes average travel speeds to decrease. The result of this process, in theory, is a balancing loop that produces an equilibrium combination of traffic volume and average travel speed (Kitamura 2009). Policy-makers, planners, and engineers then manipulate the transportation system in such a way as to produce the most sustainable possible equilibrium points for volume and speed. However, such efforts may result in conflicting objectives. For example, government actors may desire both to decrease traffic congestion and to increase the proportion of travel that is carried out by modes other than the personal automobile. Since reducing traffic congestion has the effect of increasing automobile travel speeds relative to other modes of transportation, this action gives people a strong reason to not travel by those other modes unless required. Therefore, reduced automobile traffic congestion and reduced automobile use are goals that likely require tradeoffs (Frank et al. 2008).

Another important social-science consideration in describing the drivers of travel behavior is that of individual travelers' attitudes towards particular modes of transportation. According to Ewing and Cervero (2010), transportation-related attitudes are still a less influential factor than the built environment in determining people's transportation behavior, but a significant one nonetheless. Various studies have found contradictory evidence regarding whether people alter their behavior to match their attitudes or alter their attitudes to match their behavior (Haustein 2012, Popuri et al. 2011). Under the Theory of Cognitive Dissonance, people make choices and then adjust their attitudes to support the choice they have already made. This contrasts with the much-more-used-in-transportation-research Theory of Planned Behavior, which states that people perform actions because they have the intention to perform them. Under this theory, a person's intention to take part in a particular behavior is determined by their positive or negative valuation of that behavior (attitude), by any social pressure they perceive to do or not do it (subjective norm), and by the degree to which they perceive they are able to do it (perceived behavioral control). Also sometimes considered to be a factor in these decisions is a perceived moral obligation to choose behaviors that conform with one's personal values (personal norm) (Haustein 2012). Aside from savings of time and money, other characteristics of a transportation mode that may contribute to someone valuing it as either "good" or "bad" may include: excitement, prestige, privacy, autonomy, comfort, convenience, perceived safety, reliability, and the ability to have a stress-free trip (Haustein 2012, Popuri et al. 2011). Popuri et al. (2011) found that accounting for such attitudinal factors as these in the modeling of public transit demand results in greater predicted reductions in ridership following service reductions and fare increases. At the same time, if a particular mode of transportation provides people with the opportunity to conduct other activities (such as working on a portable computer or conversing with another person) during their travel, people who take advantage of that opportunity may be better disposed towards that mode and more willing to use it for longer trips; to one degree or another, this motivating factor may apply to any travel mode, including both private automobile travel and public transit, depending upon the availability of an undisruptive environment and any necessary supporting technologies (Gripsrud and Hjorthol 2012).

Of the specific factors influencing people's transportation mode decisions, travel-time reliability is becoming a more popular performance measure among transportation planners. However, the behavioral effects of travel-time reliability are not adequately researched and it is still unclear what relative amount of explanatory power reliability has compared to average time savings. Part of the argument for giving more consideration to reliability (and unreliability) is that average travel times mask any extreme travel-delay events that are severe enough to make a lasting impression in people's minds. Nonetheless, most existing metrics of unreliability are primarily functions of general traffic congestion, rather than more random bottleneck events. A study conducted in the Chicago metropolitan area found that if transit trains have a speed advantage over parallel automobile traffic, also having an advantage in terms of travel-time reliability would increase the odds of people choosing travel by train over travel by automobile. The authors of that study found the effect of travel-time reliability to be significant, but also found it to not be the driving factor in people's mode choices. The same study also found evidence that travelers respond more to travel-time unreliability in the zones around their origin and destination points than to unreliability along their entire travel route and that travelers are more responsive to the average amount of unreliability that exists over the course of a day than to the amount of unreliability that exists during any particular time of day (e.g., morning rush hour, midday, evening rush hour, or nighttime) (Sweet and Chen 2011).

4.2.11 Self-Selection

The greatest source of doubt that exists regarding the magnitude of the effect of the built environment on travel behavior is residential self-selection, the idea that a neighborhood built around a particular kind of transportation behavior will simply attract residents who already had a predisposition towards that kind of transportation behavior rather than motivating other people to change their transportation behavior (Ewing and Cervero 2010). One aspect of this self-selection is the tradeoff that households make between housing costs and transportation costs, as cheaper housing (by floor area) tends to be located in areas with greater transportation costs (such as remote suburbs) and expensive housing tends to be located in areas with lower transportation costs (such as highly walkable urban neighborhoods with good public transit service) (Kitamura 2009). Even though some studies report that residential self-selection reduces the impact of the built environment on travel behavior, nearly all studies on the subject report that the relationship between the built environment and travel behavior remains significant after controlling for self-selection (Ewing and Cervero 2010). One possible explanation for this finding is the existence of latent demand for built-environment characteristics that are currently in short supply, most especially those characteristics that are associated with more walking, more cycling, more transit riding, and less driving. A new development (or redevelopment) with a more compact, more mixed-use, and more walkable layout may attract people who have a predisposition towards modes of transportation other than the personal automobile and who previously lived in a neighborhood where the use of those modes was not feasible (Ewing and Cervero 2010, Frank et al. 2008). If this is the case, it may result in a greater lag time in between when a change is made to the built environment and when any resulting travel-behavior changes are observed, since it takes longer for new residents and workers to move into a neighborhood than for current residents and workers to alter their habits (assuming that they alter their habits at all) (Frank et al. 2008).

4.2.12 Traveler Characteristics

A person's socioeconomic status and other personal characteristics have a significant influence on their transportation behavior (through attitudes, travel requirements, and budgetary concerns). One's socioeconomic characteristics have been estimated to have a greater influence than the built environment on the frequency with which people make trips. Trip lengths have been estimated to be determined more by the built environment than by socioeconomics. VMT and Vehicle Hours Traveled (VHT) have been estimated to be functions of both the built environment and socioeconomics. Transportation mode decisions have been estimated to be influenced by both factors, but probably influenced to a greater extent by socioeconomic characteristics (Ewing and Cervero 2010).

If different modes of transportation cost different amounts to use, and this disparity results in different income groups having different favored modes of transportation, an increase in the number of people in a given income range will likely increase usage of that particular income range's favored transportation mode; however, the mode of walking may not be as sensitive to income as automobiles and public transit (Berechman and Paaswell 1997). At the same time, a person's mode choices may be affected by what kind of job they have, regardless of how much money they make at that job. If somebody's job requires them to travel to multiple geographic locations within a single workday, the odds are greater that they will choose to commute by automobile, since that particular mode provides the necessary flexibility to make those extra midday trips (Berechman and Paaswell 1997). Conversely, if someone consistently works at a single location (regardless of whether or not they drive there), they may benefit from working in a "park once" district, wherein any trips unrelated to their job that they might wish to make during the day can be made on foot, on account of a large variety of destinations having been established within walking distance of either their workplace or the place where they parked (likely with more parking being provided in centralized locations and less being provided at individual businesses) (Metropolitan Area Planning Council 2010).

One of the most significant characteristics of an individual traveler influencing their travel behavior is whether or not they own an automobile. Both because they have more opportunities to do so and because they have evidenced an apparent intent to do so, people who own automobiles are more likely than other people to travel by automobile (and less likely to travel by other modes), a relationship that eclipses most other mode-choice factors (Berechman and Paaswell 1997, Kim and Kim 2004, Kitamura 2009). Furthermore, households with multiple motor vehicles tend to drive more than households with only one motor vehicle, and the difference between the amount of driving done by multi-vehicle households and the amount of driving done by single-vehicle households increases with the number of licensed drivers per household. Related to this, the number of licensed drivers in a household is also the greatest predictor of how many vehicles that household has, more so than household income (Kim and Kim 2004).

4.2.13 Travel to School

Little research has been conducted on the manner in which parents decide how their children will travel to school. In addition to deciding by what mode their children will travel to and from school, parents must also decide whether or not their children need to be escorted to school. Assuming that a child that is too young to drive lives within walking distance of their school and does not ride the school bus, their parents' decision of whether or not they require an escort is largely based on perceptions of safety along the route to school, both from traffic accidents and from criminals. Meanwhile, the simultaneous decision of what mode of transportation should be used for traveling to school is mostly based upon the distance to the school and whatever time constraints the family is subject to at the beginning and end of the school day. If a child's parents have decided that it is safe for them to travel to school unescorted, the parents' schedules do not represent a constraint on the child's ability to walk to school rather than being driven. The desire for their children to get more exercise is not usually a major consideration of parents deciding whether or not to have their offspring walk to school (Faulkner et al. 2010).

Pedestrian-friendly neighborhood design features, such as those that are implemented as part of Safe Routes to School programs, have a noticeable effect on the percentage of students who walk to school.

However, the distance from a student's home to their school and the amount of time required to traverse that distance are the greatest barriers to traveling to school without a motor vehicle. One implication of this fact is that if a school is located in a particularly densely populated area, a correspondingly high percentage of its students will walk to school. If all students are taken to live a half mile from school and all else is assumed constant, 34% of them are estimated to walk to school. If all students are taken to live one mile from school and all else is assumed constant, 19% of them are estimated to walk to school. Because distance and neighborhood density are such important factors, the schools likeliest to achieve high rates of students walking to school are elementary schools, as they have smaller student bodies and therefore smaller attendance zones. However, with each additional year of age, a student's likelihood of traveling to school on foot increases by 0.4% and their likelihood of traveling to school by automobile decreases by 1.4%. Also, children with siblings are more likely to walk to school than single children, possibly due to a combination of parents' safety concerns being alleviated by their offspring walking together and the inconvenience of driving to and from multiple schools each day (McDonald 2008).

4.2.14 Travel by the Elderly

As people age, they eventually reach a point where it is no longer safe for them to drive an automobile. When this happens, if they wish to retain their mobility, they must find other ways of getting around. The most favored mode of transportation among people who are too old to drive is riding in an automobile driven by a relative or friend, especially if the traditions of their family or community dictate that an elderly person's family have a responsibility to assume a strong caregiving role towards them. However, since the current trend is towards a greater percentage of elderly people's adult children moving far away from their parents, a large proportion of the elderly must either adopt other alternatives to the private automobile or assume a state of extremely limited mobility (Waldorf 2003). To understand the travel behavior of the elderly, though, distinctions must be made among them. First of all, there are captive automobile users and captive public transit users, who are constrained to a single mode of transportation either by their physical condition or by a built environment that does not accommodate other transportation modes. Second, there are elderly people who still have access to all modes of transportation and are able to decide between them on the basis of personal preferences. Finally, there are elderly people who are affluent and healthy enough that mobility is not a problem for them, but they still live in an automobile-dominated environment (Haustein 2012). Elderly people tend to place more value on perceived safety from crime than do younger people; although this would seem to suggest a greater reluctance among the elderly to use non-automobile modes of transportation, perceived danger is actually weakly correlated with mode choice, possibly explained by perceived-to-be-dangerous trips being shifted to perceived-to-be-safer times of day or being made with company. Other factors influencing the use of cars by the elderly include weather considerations, the availability of cars, and the perceived quality of public transit in their area. The mode share of public transit among the elderly is affected by their attitudes towards transit, how close they live to the center of a metropolitan area, and whether automobile transportation is available to them. Meanwhile, bicycle use among the elderly is affected by their attitudes towards it and weather considerations (Haustein 2012). Even assuming that high-quality alternative modes of transportation are available to the elderly when they are no longer able to travel by personal automobile, their making use of those modes depends upon acquiring a good working knowledge of the available options, preferably well before they stop being able to drive (Haustein 2012, Waldorf 2003).

4.2.15 Transportation-Behavior Modeling Techniques

Most conventional travel behavior models consist of four sequential steps, based on the assumption that 1) people decide to make a trip, 2) they decide what the destination of that trip will be, 3) they decide what mode they will use for the trip, and 4) they decide what route the trip will follow. However, a better reflection of reality might be modeling these decisions as being simultaneous, since they may not always be made in the same order. Unfortunately, just like most other modeling techniques that produce a closer representation of reality, modeling people as making multiple decisions at the same time would be very complex, difficult, and time-consuming, resulting in a necessary tradeoff between accuracy and expediency (Hasan and Dashti 2007, Newman and Bernardin Jr. 2010).

One particular limitation of conventional transportation modeling is the assumption that destination decisions necessarily come before mode decisions, which implies that people are more likely to change their minds regarding their mode of travel than regarding their destinations. In this way, modeling destination decisions as being made before mode decisions is a technique best suited for use in large metropolitan areas wherein the transit system is good enough to be competitive with automobile travel and there is a large number of people who both have the option of traveling by either transit or automobile and consider each of those modes to be a viable option. In areas that do not fit this description, modeling destination decisions before mode decisions could potentially represent transit ridership rates as experiencing larger changes in response to level-of-service changes in the transit system than actually occur. On the other hand, if mode choices are not made until after destination choices, different modes can be taken to be compared on the basis of actual travel times. Few studies have so far examined the possibility of modeling mode choices before destination choices (Newman and Bernardin Jr. 2010).

Another possible shortcoming of current travel behavior models is that the number of trips people make ("trip generation") is not taken to be affected by changes in the capacity of the transportation system, even though increased capacity in the transportation system implies increased accessibility to various desirable destinations, which could potentially motivate people to make more trips. Including this consideration in a model would be very complicated and very difficult to generalize to the point where it could be applied to more than one transportation system. Also, this theoretical link between transportation system capacity and trip generation has not yet been proven. Therefore, most models regard the number of trips into and out of a given zone as a function of sociodemographic characteristics and land use patterns, and not as a function of system capacity (Kitamura 2009).

Assuming that all people make their transportation-related decisions in the same fashion, such as everyone having the same perception of the opportunity cost of time spent traveling, is not realistic. Therefore, transportation behavior modeling would benefit from dividing travelers into various categories, based on combinations of socioeconomic characteristics and travel purposes. Ideally, the travel costs perceived by members of each category would be affected by the travel behavior of each of the other categories. This, too, is a technique that would increase the complexity of the modeling process (Hasan and Dashti 2007).

A key concept in the forecasting of travel behavior is travel-time budgets. Under this concept, demand for travel is assumed to be incidental to demand for the things that one travels for; thus, there is only so much of a given person's time that they are willing to spend traveling and the given person will adjust their travel behavior in such a way as to avoid exceeding that budget. In models, this budgeting of time spent on travel is sometimes combined with the budgeting of money spent on travel. One problem with travel budgets, though, is that they are typically assumed to be constant, rather than being affected by any of the outcomes of the models they feed into (Kitamura 2009). An illustration of the effect of modal decisions on travel-time budgets may be seen in Figure 3 and travel-time budget surpluses may be seen as an input to car-only person-miles traveled per person per day in Figure 2.

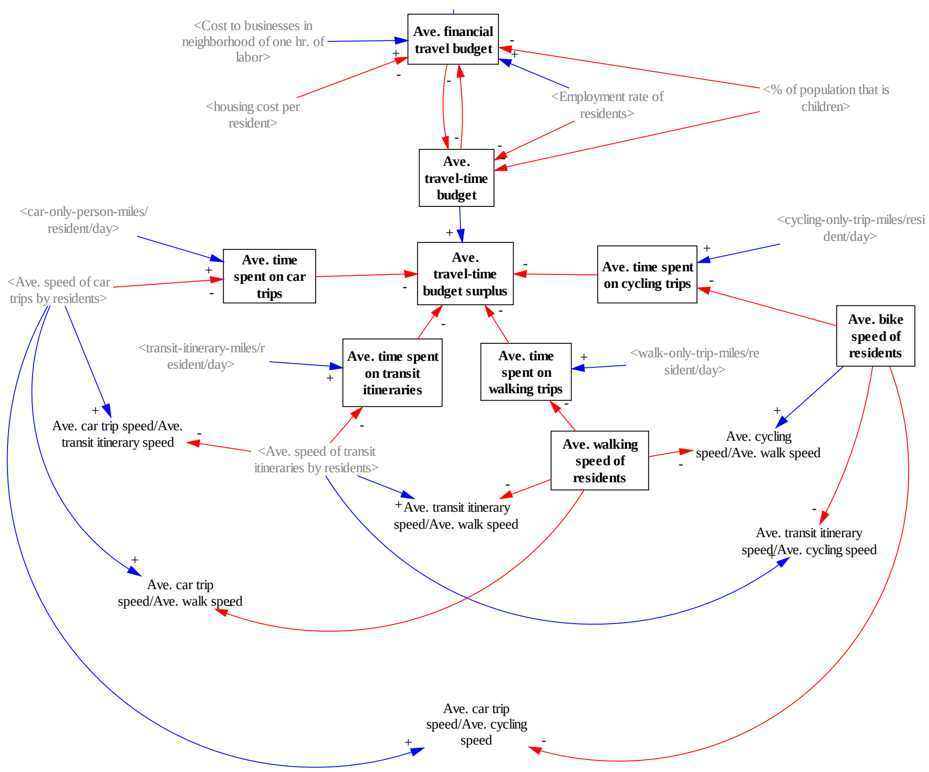

Figure 3: System-dynamics diagram of the effect of modal decisions on travel-time budgets. Red arrows are negative relationships and blue arrows are positive relationships.

Modeling entire tours, wherein someone travels from a given origin point to any number of destination points and then back to the origin point, can be more informative than modeling individual trips. Typically, people decide what mode of transportation they will use for an entire tour prior to commencing. For example, a person is less likely to take public transit somewhere if they know that they will not be coming home until after the transit service day has ended and will be unlikely to travel home by some means other than automobile if they left home in a car that they are now responsible for also getting back home. However, the mode of walking may be used for a few small legs within a tour that is otherwise dominated by some other transportation mode. If a tour has one primary destination and some number of “extra” destinations that will be stopped at some time prior to returning to the origin point, the mode choice for the tour is unlikely to be greatly influenced by land-use patterns around any stops but the origin point and the primary destination. As stated earlier, though, there has so far been little research on the effect of land uses around somebody’s place of work on their travel behavior. If people are presented with high-enough-quality non-automobile mode options, and use those options, a greater proportion of their tours will probably only stop at one destination before returning to the origin point (Frank et al. 2008).

Most travel behavior models do not give much consideration to the time of day at which a person departs on a trip, and most of the models that do give this consideration only narrow down departure times to one of a series of broad time periods, usually a couple hours in duration. Greater precision would be required in order to study variations in traffic congestion within a given peak travel period, which is currently considered a high-priority research area. Issues of complexity and prohibitively long computer runtimes have limited the number of large-scale models including departure-time choices (Kristoffersson and Engelson 2009).

When modeling the effects of crowding on public transit vehicles, some models treat it in the same manner as road congestion, as a function of demand volume and system capacity. However, on a crowded transit vehicle, perceived travel time may more greatly exceed actual travel time than it would on a congested roadway, due to the disutility of boarding a crowded vehicle. As a result of this complication, many models that describe the behavioral effects of transit crowding do not feed those effects back into the model as drivers. Another limitation of such models is the difficulty in calculating transit crowding effects in between a specific origin point and a specific destination point. In spite of these shortcomings, in those locations where transit vehicles reach capacity with significant frequency, modeling the behavioral impacts of transit crowding could be an important aspect of testing the potential outcomes of changes in the capacity of the transit system (Zorn, Sall, and Wu 2012).

In the study and modeling of nonmotorized transportation, different methods and considerations are needed than in the modeling of automobile traffic and public transit use. Since nonmotorized modes (especially walking) are consistently far slower than motorized modes, comparing motorized and nonmotorized travel times would be a meaningless exercise. Also, since people of the same age and height generally walk at similar speeds regardless of the respective environments in which they walk, using travel distance, as opposed to travel time, in disutility functions makes more sense for travel by foot, along with other barriers to nonmotorized transportation such as steep slopes, precipitation, the dark of night, and environments that are generally perceived as less safe than others. Furthermore, because the average nonmotorized trip is significantly shorter than the average motorized trip, the analysis of nonmotorized travel requires a finer scale of analysis than what most transportation models provide. Achieving an analysis with the necessary resolution to consider nonmotorized modes could potentially be done with the help of GIS software and data on the latitudes and longitudes of specific origins and destinations, assuming the provision of sufficiently detailed demographic and employment data. Finally, accounting must be made of such correlations as the fact that curvilinear streets and cul-de-sacs (which discourage nonmotorized transportation) are more common in hilly terrain (which also discourages nonmotorized transportation) (Cervero and Duncan 2003).

4.2.16 Data Availability for Modeling Travel Behavior

Many small and medium-sized towns, including those located near larger cities, do not have enough money at their disposal to carry out the surveys necessary to gather data from which to calculate trip generation rates for travel-behavior models. In such towns, identifying alternative data sources that could be used with confidence can be helpful. Trip-generation rates applicable to various communities were published by the National Cooperative Highway Research Program (NCHRP) in 1998, but only for communities with at least 50,000 residents. For those communities that are smaller, the option exists of adapting national-scale data to their purposes, such as from the Nationwide Personal Transportation Survey (NPTS). Also, in some parts of the country, including South Carolina and Oregon, generalized reusable transportation models have been created that are to be applied to many different small and medium-sized communities. Finally, communities may choose to simulate travel data for their jurisdiction on the basis of local socioeconomic data and patterns observed in travel surveys from other, nearby, larger communities. If a small or medium-sized community that cannot afford a travel survey and a large community that can afford such a survey are sufficiently close together and sufficiently interconnected, data may be transferred from the larger community to the smaller one for the purpose of creating trip generation rates. To determine if such a practice actually could be justifiable would require additional research specific to these communities. If it does turn out to be a valid practice, though, the implication would be that, at least sometimes, conducting a more extensive travel survey of a smaller area (that can be applied to additional locations) may be better than collecting a less certain dataset for a larger area (Horner, Stone, and Huntsinger 2008).

4.2.17 Specific Resources and Tools for Determining Travel Behavior Outcomes

- The U.S. Environmental Protection Agency's Smart Growth Index (SGI) is a GIS-based planning tool used for modeling base and alternative land-use and transportation scenarios for a single point in time and comparing them on the basis of pre-programmed indicators that span the three dimensions of sustainability, including indicators of travel behavior (U.S. Environmental Protection Agency 2013d). To model the effects of the built environment on travel behavior, the SGI uses Ewing and Cervero's 5 D's. It incorporates the built-environment characteristic of density in the form of activity density, which is the sum of the residents and jobs located in an area divided by the number of square miles in the area. The built environment characteristic of land-use diversity is incorporated in the form of the ratio between a given area's jobs-to-housing balance and the jobs-to-housing balance of a larger region that the given area is within. The SGI also incorporates the transportation-system design elements of street-network density, sidewalk coverage, and route directness, which is defined as the ratio between the distance someone travels between two points and the straight-line distance between those points (Ewing and Cervero 2010).

- The Simultaneous Transportation Equilibrium Model (STEM) is a travel behavior model wherein the trip generation rates are taken to be affected by the model's own outcomes. The Multiclass Simultaneous Transportation Equilibrium Model (MSTEM) is based on the STEM model, but with the added element of dividing travelers into classes according to their socioeconomic characteristics, their purposes for traveling, and the use of either single transportation modes or combined transportation modes, with each class making transportation-related decisions on the basis of different criteria. Because the cost attributed to using any particular link of the transportation system is taken to be dependent upon the traffic flows on that and all other links, different classes of travelers may be calculated to take different routes between the same origin and destination. This model also combines the trip-generation step with estimating people's decisions regarding departure time. The downside of the MSTEM model is that its use requires a lot of time, money, and effort (Hasan and Dashti 2007).
- CONTRAM is a route-choice model for given origin-destination pairs. It is used in many different cities, in various countries (Kristoffersson and Engelson 2009).
- The Unified Mechanism of Travel (UMOT) model is a transportation behavior model based around the idea of unchanging household travel budgets that can be applied in situations across both space and time. In this model, the constraints on travel activity are taken to be daily travel time per traveler and money spent on transportation per household. The model assumes that whenever someone experiences travel-time savings, they will use that extra time for more travel. The UMOT model has the advantages of being simple and having low data requirements, but also some limitations, including a car-ownership component that has been called "simplistic" and the use of some questionable elasticities between the cost of using a given mode of transportation and the rate at which that mode is actually used (Kitamura 2009).
- Origin-Destination travel survey data exists for almost every metropolitan area in the United States, often coming from up to three surveys per metropolitan region, taken at intervals of approximately ten years. Typically, the Metropolitan Planning Organization (MPO) of a given area (the local organization through which federal transportation funding is distributed to urban areas with populations of 50,000 or more for the purpose of keeping transportation projects and policies coordinated) will match up this survey data with information on their area's transportation network and patterns of land use. Taken together, all of this information could form a very useful database. However, the data is often not well-archived, not well-documented, and not easily available to researchers (Kitamura 2009).

4.3 Air Quality Issues and Related Tools, Resources, and Indicators

Transportation sources significantly contribute to global, regional, and local air quality impacts. Air emissions occur from fuel combustion, fuel and fluid evaporation through engine operations and leaks, abrasion from brake use, tire wear, and re-entrainment of dust from road and other transportation surfaces. Transportation sources emit criteria pollutants, air toxics, greenhouse gases, and multiple chemical and physical forms of particulate matter.

Many methods have been employed to reduce air quality impacts from transportation sources. These methods typically include reducing emissions through regulations and standards and/or reducing motor vehicle activity. Investing in and deploying public transit, increasing costs for personal vehicle use (e.g. congestion pricing), and improving facilities for walking and biking have all been employed in efforts to reduce motor vehicle activity. Recent development practices have been initiated in many parts of the world to promote the reduction of vehicle activity, and subsequent impacts on air quality and the environment, through compact growth and infill development. The goal of these "smart growth" practices is to make transportation more accessible, convenient, and with a reduced impact on the environment. However, these practices often also bring people in closer and longer contact with transportation source emissions. Exact differences in exposure to near-road air pollution depend on many variables, including the manner in which air pollutants are transported, which is an area of significant research needs.

Recent research has demonstrated a link between adverse human health effects and exposures to air pollutants from traffic emissions near large roadways and other transportation sources. The Health Effects Institute (HEI) recently completed a review of a large number of health studies, concluding that near-road exposures "are a public health concern." This is because of the toxicity of the small particles and chemicals emitted and the emission of these particles and chemicals close to the ground, where they are not well dispersed (http://pubs.healtheffects.org/view.php?id=334). Although the link between adverse health effects and near-road exposures has been made, the science has not yet progressed to an understanding of how some key elements affect these associations, such as the type and size of roads of concern, the vehicle fleet mix, activities leading to highest exposures, and the distance from the road at which near-road health impacts subside. Most studies on traffic and health focus on roads with high levels of traffic (for example, counts of 100,000 annual average daily traffic (AADT) or higher). A few studies have reported health effects associated with smaller traffic volumes, with one study showing effects at volumes as low as 10,000 AADT in an area (HEI Panel on the Health Effects of Traffic-Related Air Pollution 2010). While the health studies reviewed by HEI focused on exposures to traffic emissions, other transportation sources such as rail yards, rail lines, airports, and marine ports have comparable concerns due to similarities in the type and characteristics of air pollution emissions.

For most transportation sources, air pollutant concentrations are generally highest closest to the source, with concentrations lowering with distance from the facility. However, the magnitude and extent of these increased air pollutant concentrations can vary based on a number of factors related to emissions, including the source, meteorological and topographic conditions affecting pollutant transport and dispersion, and the influence of roadway design and roadside features on pollutant transport and dispersion. Traffic emissions may vary depending on the total number of vehicles using a road, the level of congestion on the road, and the number of heavy-duty trucks present. For rail operations, the number of trains, cargo weight, maintenance activities, and line/yard configuration will influence emissions and exposures. Ports and airports will generate emissions from the ships/planes using the facility, as well as support equipment permanently present. For marine ports, large numbers of heavy-duty trucks may also be present on local roadways to move goods from the port; rail activity into and out of a marine port may also be substantial. Air pollutant concentrations near transportation facilities will also be affected by wind direction, wind speed, and atmospheric stability. Changes in local topography from natural or roadway-design features will also affect air pollutant transport and dispersion, which can lead to varying exposures for nearby populations. Thus, air quality may vary based on surrounding terrain and features, such as cut sections, noise walls, vegetation, or combinations of these features (Baldauf et al. 2009).

International consensus has emerged that people living, working, and going to school near high-traffic-volume roads face increased risks for a number of adverse health effects (HEI Panel on the Health Effects of Traffic-Related Air Pollution 2010). These health effects have been attributed to acute and chronic exposures to elevated levels of air pollution near these roads, including particulate matter (PM), gaseous criteria pollutants, and air toxics (Karner, Eisinger, and Niemeier 2010). Field measurements conducted throughout the world, including the U.S., have shown highly elevated air pollution levels near high volume roadways. Pollutant concentrations are often highest within the first 100-150 meters, with increased concentrations of some pollutants of as much as an order of magnitude. Pollutant concentrations from traffic emissions can remain elevated 300-500 meters or more from the road (Karner, Eisinger, and Niemeier 2010, HEI Panel on the Health Effects of Traffic-Related Air Pollution 2010).

With increased urbanization occurring world-wide, the number of people exposed to traffic emissions near high-volume roadways will continue to increase. One factor contributing to this trend is that a growing portion of public transportation and land use policies and practices supporting sustainable development patterns promote compact growth in infill locations along major transportation corridors. Transit-oriented development, offering a mix of housing and supportive land uses located near transit and with accessibility to jobs and services, nonetheless offers a variety of benefits. This development pattern is intended to capture the benefits of location efficiency, which is strongly correlated with household transportation spending. As land use development patterns affect travel behavior, air quality and global climate conditions are indirectly affected by urban form. While sustainable development practices increase the population's access to services and transportation options and promote regional reductions in vehicle miles traveled (VMT) and air pollution, they also often bring people closer to sources of air pollutant emissions, including from traffic activity. Accordingly, there is a growing need to reduce air-pollutant exposures for people residing and working near high-volume roadways.

The U.S. Environmental Protection Agency (EPA) is implementing a number of policies to address these impacts of major roads on nearby air quality. Recent revisions to monitoring rules for the National Ambient Air Quality Standards (NAAQS) require monitors for PM, carbon monoxide (CO), and nitrogen dioxide (NO_2) near high-traffic roads in large metropolitan areas. The Environmental Protection Agency's transportation conformity rule requires modeling of $PM_{2.5}$ and/or PM_{10} "hot spot" concentrations in the immediate vicinity of large federal highway or transit projects involving high levels of heavy-duty diesel vehicle traffic. Projects are required to model concentrations at or below the NAAQS, or show that concentrations with the project built are modeled lower than concentrations without the project built.

The complexity and multitude of factors affecting air pollutant concentrations near transportation sources makes it difficult to recommend a strict set of guidance for “safe” distances from these source types, particularly given the potential for unintended consequences. Decision-makers considering one or more sites in close proximity to major transportation facilities should consider a range of approaches to mitigate or avoid potential exposures. When evaluating potential sites that may be located near a highway or other major transportation facility, several factors should be considered:

- Are there other sites in the community at further distances from the source that are also being considered? Urban areas may be limited in their ability to find appropriate sites away from major roads, major goods movement facilities, and other transportation sources; thus, careful consideration should be given to near-road and other transportation-source sites before eliminating them if the only alternatives involve siting schools, for example, much further from the communities being served. Unintended negative consequences of moving schools away from these communities may include increased pollutant exposures during longer bus or personal car commutes, increased traffic on local roads to access schools further from their communities, lack of walking, biking, or other alternative commute options to school, and the inability to meet many of the other smart growth objectives described in this document.
- What options might be feasible for mitigating pollutant concentrations at the site from off-site sources (Baldauf et al. 2009)?
    - Studies suggest that roads in cut sections (i.e. road surface below surrounding terrain) or that have combinations of noise barriers, vegetation, and/or buildings near the roadside may reduce downwind air pollution concentrations.
    - Building design techniques may be employed to reduce exposures at near-source locations, such as encouraging activity as far from the source as possible (e.g., entrances, playgrounds, gathering places) and locating air intakes at locations not affected by off- or on-site transportation-related air pollutant sources.
    - Installing or preserving barriers such as trees, buildings, and noise barriers may reduce air pollutant exposures.
    - Filtration devices as part of HVAC design can be used to improve indoor air quality as described in other sections of this guidance.
    - Adding controls or redesigning transportation facilities to reduce pollutant emissions and air concentrations. Examples of this practice include: replacing or retrofitting port and rail engines/equipment with cleaner technologies, reducing idling at terminal facilities, re-routing existing or projected traffic away from populated areas (e.g., truck-only lanes), and adoption of high-density development and transit alternatives.

Transportation sources impact air quality through three major pathways: vehicle operating emissions of gaseous and particulate contaminants, secondary formations during plume transport of gases and particles, and mechanical processes that abrade particles from brakes, tires, and the road surface.

Carbon monoxide (CO), nitric oxides (NO_x), and volatile organic compounds (VOCs), as well as PM constituents such as polycyclic aromatic hydrocarbons (PAHs) and black carbon (BC) are among the numerous compounds that have been identified at elevated concentrations near large roads (Venkatram et al. 2007).

Emission reduction programs implemented by government agencies throughout the world have significantly reduced emission rates of air pollutants from motor vehicles. Since 1970 in the U.S., average per vehicle emissions have been reduced by over 90% for VOCs, and over 80% for PM_{10} and NO_x. In spite of these reductions, motor vehicles still significantly contribute to pollution in urban areas, often due to large increases in vehicle use offsetting per-vehicle emission reductions (Dallmann and Harley 2010). Furthermore, emissions from some vehicle-associated sources (e.g. brake and tire wear) are not regulated, and pollutants generated from these sources may also increase in the future with increased vehicle use.

Populations near roads are exposed to this mixture of primary emissions and secondarily formed pollutants. Approximately 30 to 45% of urban populations in the U.S. are likely exposed to elevated pollution levels near roads (Zhou and Levy 2007, U.S. Environmental Protection Agency 2013c). In many countries with densely populated urban areas this figure is likely to be even higher.

4.3.1 Specific Resources and Tools for Determining Air Quality Outcomes

- The Community Multiscale Air Quality (CMAQ) model version 5.0 employs a 3-dimensional Eulerian modeling approach to address air quality issues such as tropospheric ozone, fine particles, acid deposition, and visibility degradation (Byun and Schere 2006). CMAQ is process-based and employs first-principal relationships to the greatest extent possible. The model is a multiscale, multipollutant, "one atmosphere" system that includes a meteorological component to describe atmospheric conditions, emission models for anthropogenic and natural emissions that are released into the troposphere, and a chemical-transport model (CTM) to simulate chemical transformations, atmospheric transport, and fate. Most anthropogenic and biogenic emissions are parameterized as emission factors and activity rates, or are represented by hourly estimates of temporally and spatially allocated emissions from point, nonpoint, and mobile-source inventories. CMAQ operates on a five-minute timestep, but results are usually produced hourly. The model simulates regional-scale air quality issues via a set of rectangular grids ranging in size from 1 km^2 for small domains to 100 km^2 for hemispheric-scale simulations. The one-atmosphere approach supports a comprehensive, system-wide technique for analysis of complex sustainability issues spanning air, land, and water media. CMAQ regional air quality simulations at the community scale rely heavily on detailed inventories of transportation-related emissions. A description of the mobile on- and off-road source emissions input to CMAQ is provided at http://epa.gov/ttn/chief/emch/2007v5/2007v5_2020base_EmisMod_TSD_13dec2012.pdf. Transportation emissions include on-road vehicle, on-road refueling, nonroad (construction and agriculture), rail, and marine emissions. Marine emissions are particularly important contributors to overall particulate loads in cities that house large commercial seaports. Except for California, all on-road vehicle and on-road refueling emissions numbers are generated using an emissions modeling framework (SMOKE-MOVES, http://www.epa.gov/otaq/models/moves/index.htm) and hourly meteorology. This system differentiates emissions by process (running of the engine, starting the engine, vapor venting, etc.), vehicle type, road type, temperature, speed, hour of the day, etc. to produce a set of emission factors. Emissions for a county are the result of multiplying these factors by vehicle miles travelled or vehicle population (activity). California emissions are provided by the California Air Resources Board (CARB) using their EMFAC model, designed specifically for California fleets.

- EPA maintains the MOtor Vehicle Emission Simulator (MOVES) model for estimating air pollution emissions from all on-road motor vehicles including cars, trucks, motorcycles and buses. MOVES allows motor vehicle emissions to be analyzed at various scales: national, county, and project, using different levels of input data. The project scale allows the prediction of air emissions from traffic activity on a specific road or intersection to be estimated. In addition to MOVES, EPA has several other calculator-style tools that can be used to estimate emissions of specific types of vehicles. EPA maintains guidance for using MOVES for regulatory purposes of state air quality plans and transportation conformity determinations; however, MOVES is also EPA's best tool for developing on-road greenhouse gas (GHG) emission inventories at the state and local level, with guidance for using MOVES to estimate GHG inventories. For access to MOVES and these other tools, as well as guidance for use and interpretation, please refer to www.epa.gov/otaq/stateresources/tools.htm.
- The EPA Office of Transportation and Air Quality (OTAQ) has guidance for estimating the air quality benefits of various control measures and accounting for them in a state air quality plan or an area's transportation conformity determination. Subjects covered by this guidance include transportation pricing, land use, and commuter programs. Please refer to www.epa.gov/otaq/stateresources/policy/pag_transp.htm for a list of the full range of measures on which guidance is available.
- EPA OTAQ has developed an approach for estimating emission reductions, of both criteria pollutants and GHGs, from "travel efficiency strategies," those emission reduction strategies that affect travel activity, such as travel demand management (e.g., telecommuting, transit subsidies), public transit fare changes and service improvements, road and parking pricing, and land use/smart growth. This approach is described in a series of documents, found at www.epa.gov/otaq/stateresources/ghgtravel.htm.
- EPA OTAQ has guidance for completing quantitative hot-spot analyses for individual highway or transit projects, required for certain projects in PM and CO nonattainment areas. The PM hot-spot guidance covers estimating emissions using MOVES, estimating air quality concentrations using EPA-approved dispersion models (e.g., AERMOD), determining the background air pollutant concentration, and calculating the resulting design value for the project. Policy and technical guidance for hot-spot analyses, as well as training and other resources, can be found at http://www.epa.gov/otaq/stateresources/transconf/projectlevel-hotspot.htm.

- Fuel composition is regulated to achieve air-quality goals under the authority of the Clean Air Act. Releases to the environment occur through the use of fuels for transportation, the production of both fossil fuels and biomass-derived fuels, leaks from pipelines, spills during the transport of fuels, and leaks from storage tanks. The EPA is developing a model, called PVIScreen, to account for the transport and fate of fuel components in soil gas and groundwater. Volatile components of leaked fuels, including vehicle fuels, diffuse through the soil gas and in some cases cause indoor air contamination (called vapor intrusion). The composition of the fuel, subsurface properties, building properties, oxygen availability in the soil gas, and the location of the leaked fuel determine the magnitude of the impact. Care must be taken to mitigate high concentrations of petroleum vapors that enter buildings from acute fuel releases. Field data have shown, however, that many impacts from less severe releases are mitigated before the vapors reach the bottom of a foundation (McHugh et al. 2010, Lahvis et al. 2013).

4.4 Energy Use and Climate Change Issues and Related Tools, Resources, and Indicators

Energy use in the transportation system, including both passenger and freight transportation, is of key interest at the global, national, state, and local levels. At the national level, approximately 28% of total energy consumption in the U.S. is for transportation, including light and heavy duty vehicles, airplanes, buses, trains, barges, and ships (U.S. Energy Information Administration 2013a). Personal transportation in light-duty vehicles (including cars, minivans, light-duty trucks, SUVs, motorcycles, etc.) accounted for the majority (59%) of total transportation energy use (highway and non-highway) and 72% of highway transportation energy use in 2010 (from Table 2.5 in Davis, Diegel, and Boundy (2012)). Energy use is also closely coupled to a number of other environmental outcomes, particularly air quality and climate change. Economic factors also play an important role in assessing transportation energy production and use, whether the consideration involves household and individual expenditures on transportation fuels or broader national issues of energy security and reliability of the transportation system in terms of fuel supply.

Transportation energy use can be broken down into a set of key indicators, which can then inform policies and decision-making regarding ways to reduce overall energy use and, by extension, greenhouse gas (GHG) emissions. These indicators include: end-use travel demand (often expressed as vehicle-miles traveled or VMT), vehicle efficiency or fuel economy (gallons per mile), mode of travel (expressed as a percentage modal split or VMT per mode, which can then be used to assess VMT and fuel economy on the basis of the vehicle fleet of interest), and overall system efficiency of the surface transportation system (such as congestion levels). Each of these will be discussed here, while highlighting selected tools, resources, and indicators related to travel demand, travel mode, and fuel economy. Taken together, these elements can inform assessments of the key driving factors of transportation energy use.

Climate change is closely interrelated with transportation energy use due to the combustion of petroleum-based fuels. Given this close relationship, energy use, climate change, and the measures taken to address these issues will be discussed together in this section. As a major consumer of fossil fuels, the U.S. transportation sector is also a major source of GHG emissions (33% of 2011 CO_2 emissions from fossil fuel combustion), the second largest contributor following the electricity sector (U.S. Environmental Protection Agency 2013b). Most of these emissions are tailpipe emissions of CO_2, although there are also non-CO_2 emissions such as methane (CH_4) and nitrous oxide (N_2O), as well as hydrofluorocarbons (HFCs) from vehicle air conditioning units.

If the goal is to avoid or reduce the implications of serious climate change, deep reductions in total U.S. GHG emissions will be necessary, ~~and would~~ includinge major reductions from the transportation sector. ~~In the context of climate "stabilization wedges", s~~Several analyses have applied the concept of climate "stabilization wedges," from ~~Pacala and Socolow (2004)~~Pacala and Socolow (2004), to the transportation sector, specifically. Wedges are defined as activities that would avoid a specific quantity of cumulative emissions in a given period~~over time,~~ and are generally depicted visually as triangles of avoided emissions that grow linearly over time. An analysis by the EPA's Office of Transportation and Air Quality ~~(2007)~~(Mui et al. 2007) showed that approximately nine U.S. transportation-sector wedges could be applied and scaled for different levels of analysis. Out of the nine wedges, half of them would flatten emissions from passenger vehicles, while others would reduce emissions from freight, aviation, marine, rail, and non-transportation mobile sources. The analysis also explored the system impacts of combining vehicle technology, fuels, and transportation demand management (TDM) strategies to achieve the largest emissions reductions from the transportation sector.

More recent analyse~~i~~s have applied the wedge-based approach to also estimate health co-benefits from U.S. climate-change mitigation ~~(Balbus, Greenblatt, et al., 2014)~~(Balbus et al. 2014). This approach underscores the broader sustainability benefits of climate-mitigation activities, quantified as risk reduction and positive economic ~~ben~~effec~~i~~ts from health co-benefits~~, from climate mitigation activities~~. Benefits from ~~the~~ transportation wedge activities – including both light-duty and heavy-duty vehicle fuel efficiency and reductions in light-duty vehicle demand – suggest monetized health co-benefits on the order of tens of billions of dollars. Wedge-based analyse~~i~~s are a clear conceptual approach to compare mitigation ~~approache~~strategies and may be an approach that can be scaled to the community level, taking into account those strategies that communities consider to be within their scope. In addition to comparing climate mitigation activities, wedge analyses~~they~~ could also be use used as a metric to assess the sustainability co-benefits associated with the implementation of either individual wedges~~,~~ or more holistic strategies that combine wedges. Finally, the analysis of climate mitigation wedges has~~ve~~ highlighted the need to pursue multiple strategies and transportation options together. This is ~~also~~ underscored in an article by ~~Mashayekh et al. (2012)~~Mashayekh et al. (2012) that considers the extent to which sustainable transportation in cities can alleviate climate-change~~s~~ impacts. Their conclusion is that transportation strategies can be "mutually reinforcing" and that "GHG emissions reductions goals could be attained by aggressively pursuing both existing policies and the four strategies discussed [in the paper]: fuel/vehicles strategies, travel demand management, land use change, and renewable power." ~~(Mashayekh et al., 2012).~~

As suggested by the wedge-based approach and other analyses of transportation strategies, there is~~are~~ a range of options for both achieving reductions in energy use and meeting climate mitigation goals.

Methods and tools that reduce *total demand* for transportation energy, whether in the form of liquid transportation fuels (fossil or renewable) or electricity, will generally translate into reductions in carbon dioxide (CO_2) emissions. However, different *sources of transportation energy*, including~~namely~~ gasoline, diesel, and, increasingly, electricity, are used to meet the total transportation end-use demand, and these fuels have different carbon contents, affecting total CO_2 emissions. Switching to lower-carbon or biomass-based fuels can represent an additional measure to reduce the carbon footprint of transportation fuels. However, when assessing the use of renewable fuels derived from biomass or of electric vehicles powered from the grid, additional factors need to be considered in order to capture the full greenhouse gas impacts of these alternatives. In particular, in order to assess the greenhouse gas implications of alternative fuels, quantifying the upstream impacts associated with the production of those fuels is important (U.S. Environmental Protection Agency 2010e). Moreover, transportation fuel choices, whether gasoline, diesel, compressed natural gas, propane, ethanol or biodiesel, will have important implications for the vehicle fleets and fuel distribution infrastructure that are part of a community's landscape. While there is a range of studies regarding specific issues (e.g., underground storage tanks for ethanol blends), there do not appear to be tools or resources that look systematically at how transportation fuel infrastructure fits within the broader sustainable communities context.

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While research on life-cycle impacts (cradle to grave implications) has often focused on upstream impacts of fuel and electricity production, there are also GHG and other environmental impacts related to material flows in production. Although their total contribution to GHG impacts and energy use may be small, the production of vehicles and vehicle components, as well as of larger transportation infrastructure (e.g., concrete production), may need to be considered in terms of other environmental endpoints, which would consequently be counted among the impacts of automobile dependence. To illustrate, some studies have found that the GHG emissions for lithium-ion (Li-ion) battery materials and their production may account for only 2–5% of total life-cycle GHGs (Samaras and Meisterling 2008). However, different battery systems (e.g., NiMH (Nickel Metal Hydride) or Li-ion) will have varying impacts for other endpoints, such as metals depletion and ecotoxicity (Majeau-Bettez, Hawkins, and Stromman 2011). Some of these related issues may become relevant to communities' materials management and suggest the need for better end-of-life recycling for electric and plug-in hybrid vehicle batteries. Another example of materials issues related to fuel production is the production of biodiesel and the fate of the glycerol by-product produced (Steinmetz et al. 2013). This could be a significant waste stream that communities would need to manage, but it may also have reuse potential in other applications that could result in some additional air emissions, as well as offsetting benefits. These examples represent the type of potential problem-shifting that would need to be avoided as more sustainable transportation energy solutions are pursued by communities, and argue for a greater need for systems approaches when assessing solutions. The EPA's Sustainable and Healthy Communities Research Program is in the process of producing another synthesis paper on sustainable waste and materials management, which may be looked to for further insights on these issues.

4.4.1 Transportation Demand

One of the critical indicators of transportation energy consumption is vehicle-miles traveled (VMT) per capita (or potentially average trip length, transportation mode shares, or some other descriptor of people's transportation behavior) (Black, Paez, and Suthanaya 2002). At a very basic level, trends in overall transportation demand for a particular region or community are driven by the combination of population growth and person-miles traveled per capita. Population growth can be a major fundamental driver increasing pressure on transportation energy use. For example, the Annual Energy Outlook projects substantial increases in VMT in regions such as the Pacific Coast and the South Atlantic Region, which includes most of the east coast states from Florida to the Carolinas and up to Maryland (U.S. Energy Information Administration 2013b). On the other hand, VMT in the New England States and Midwest is anticipated to grow at a more moderate pace. These projections result from trends in population growth and changing demographics, including trends such as the migration of population to regions such as the southeastern U.S. These are larger national and regional trends, which are often beyond the scope of a community's decision making. However, the way in which these broader changes in population growth and VMT play out at the community scale is closely linked to land use change and urban form. Some communities have been able to document important energy and GHG reductions achieved through urban design (Portland, OR is one example, see Rose and Burkholder (2009)). This topic is addressed in greater depth in other sections of this document. However, some examples of potential relationships between energy use and measures that are aimed at reducing transportation demand in a given urban area are provided in the following paragraph and bullet points.

Past research suggests a number of correlations which provide potential performance measures for reductions in energy use in the transportation sector in a given urban area based on linkages between population density, mode share, and other factors affecting VMT, and thus demand for transportation energy. These include the following elasticities taken from data on major cities around the world over a period of multiple decades (Sinha 2003):

- A 1% increase in population density is associated with a 0.64% decline in private-transportation energy use per person per year.
- On average, a 1% increase in transit boardings per person per year is associated with a decrease in transportation energy use per person per year of 0.54%. However, this elasticity varies with the magnitude of the input variable.
- On average, a 1% increase in the number of parking spaces per worker in a region's Central Business District is associated with a 1.27% decline in transit boardings per person per year. However, this elasticity varies with the magnitude of the input variable.

The overall indication of the data is that increases in population density and employment density are associated with fewer roads and parking spaces, decreases in the use of single-occupant motor vehicles, and increases in public transit use and non-motorized transportation, all of which are trends that in turn lead to less per-capita energy consumption in the transportation sector (Sinha 2003). However, these associations do not distinguish between causation and correlation.

4.4.2 Travel Mode Choice and Public Transit

Closely related to travel demand reduction, there are a number of options available to communities to influence their modal split, many of which are addressed in other sections of this paper. In general, moving away from single-passenger vehicle travel to transit buses, rail, or non-motorized transportation (walking, biking, etc.) can represent a gain in terms of reducing the energy intensity of travel (e.g., energy use per passenger-mile, Btu/mile). However, these options need to be assessed on a case-by-case basis at the community level, given that there are wide variations in the energy and carbon intensity of different passenger transportation options, which depend largely on the efficiency and ridership of public transportation options. The energy intensity of light rail transit systems, for example, can range from approximately 2,500 Btu/passenger-mile to over 30,000 Btu/passenger-mile (Davis, Diegel, and Boundy 2012). In some cases, the energy intensity of a passenger-mile traveled on public transit can actually be higher than for travel in a private vehicle (e.g., when a bus with a low miles-per-gallon rating is kept in operation all day long on a public-transit route that very few people use). Therefore, the energy-use and GHG reductions resulting from transit mode-share options must be carefully assessed to understand the true magnitude of potential benefits, which requires understanding and modeling changes in both travel demand and operational aspects of public transit. A number of methods are outlined in Transportation Research Board of the National Academies (2013) that highlight tools for energy and GHG emissions analysis, many of which incorporate transit options. Choices regarding public transit can also have impacts on the deployment of alternative vehicle fleets and alternative fuels in a community, as will be discussed more below. Cleaner-burning, alternative-fuel transit fleets can have important air quality benefits. However, near-source issues, discussed in the previous section, must also be considered prior to the implementation of public transportation options, as these options may in turn be constrained by air and exposure issues affecting major transit corridors.

4.4.3 Fuel Economy and GHG Standards

While total travel demand and modal split are critical drivers of energy use, the most effective tool for reducing the energy use and GHG emissions of the transportation sector is the setting of fuel economy standards for light-duty vehicles, known as the Corporate Average Fuel Economy, or CAFE, standards. Fuel economy standards in the U.S. were first set in 1975 as a mechanism to reduce imported oil in response to the 1973 oil embargo. The standards have continued to evolve over the years, most notably in 2010 with the joint development of the Model Year 2012-2016 Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corporate Average Fuel Economy Standards by EPA and the National Highway Traffic Safety Administration (NHTSA) (U.S. Environmental Protection Agency 2010d). This represented the first time that GHG standards, under the authority of the Clean Air Act, were established along with the fleetwide average fuel efficiency standards. In 2012, a joint rulemaking extended the GHG and fuel economy standards to include model years 2017 to 2025 (U.S. Environmental Protection Agency 2012e, U.S. Environmental Protection Agency and National Highway Traffic Safety Administration 2012).

These rules have important implications for the evolution of passenger vehicle fleets in communities over the next 10-15 years. The standards are projected to result in an average industry fleetwide fuel economy of 54.5 miles per gallon (mpg) (if achieved exclusively through fuel economy improvements) for model year 2025 (U.S. Environmental Protection Agency 2012e). These fuel economy targets will mean improvements in gasoline engines and transmissions, vehicle weight reduction, improved aerodynamics, and other vehicle advancements. In addition, increased electrification of the fleet will likely occur through the expanded production of hybrid vehicles, plug-in hybrid electric vehicles, and electric vehicles. These fuel economy changes, and the potential increases in electrification, have benefits for local air quality as well, given the large reductions in fuel use per vehicle-mile traveled.

Although these standards are set at the national level, any analyses or tools used to meet energy or GHG reduction targets will need to account for changing vehicle fleets at the community level. Existing tools used typically for air-quality purposes, such as the EPA's MOtor Vehicle Emission Simulator (MOVES) model, as well as other emissions factor models such as California's EMFAC, can be applied to assess GHG emissions and used in combination with travel demand models to develop a baseline of energy use and GHG emissions (Transportation Research Board of the National Academies 2013). Perhaps more important, however, is the need for communities to understand how they can influence changes in vehicle and fuel technologies at the local level. A key knowledge gap and research need identified by the Strategic Highway Research Program is "the effect of government interventions (e.g. pricing, infrastructure deployment) on technology advancement…many local and state governments are interested in how they can provide incentive to help accelerate the adoption of new vehicle technologies" (Transportation Research Board of the National Academies 2013).

4.4.4 Operational Considerations Affecting Energy Use and Emissions

Changing vehicle fuel efficiency standards has a critical impact on reducing GHG emissions from the transportation sector and from a research standpoint is perhaps the most studied aspect of transportation energy use and GHG emissions. However, the real-world performance of vehicle technologies and their resulting fuel use/GHG emissions will depend on their actual usage. A number of factors can affect the usage and operation of vehicles, both conventional and advanced, and can be considered broadly as system efficiency (Greene and Plotkin 2011). Some of these operational considerations depend on the vehicle owner/driver, including maintenance issues that affect vehicle efficiency (e.g., correct tire pressure) as well as driver behavior and resulting impacts on gas mileage. For example, efficient driving behavior or "eco-driving" can encompass a number of approaches to safer driving, such as smoothing out changes in vehicle speed, and avoidance of aggressive acceleration and starts/stops, as well as minimizing idling time. Understanding the potential for eco-driving in the U.S. to reduce GHG emissions and energy use has been identified as a research need (Transportation Research Board of the National Academies 2013). Support for an eco-driving "ethic" may be a strategy best implemented in the context of sustainable communities, given that it would have other potential community benefits, such as traffic congestion mitigation and safety. Some empirical evidence suggests that this sort of improved driving can improve fuel economy between 5 and 20 percent (various studies cited in Greene and Plotkin (2011)). System efficiency may also be achieved through more efficient trip-making, possibly by utilizing GPS routing to find more efficient routes and to aid in trip-chaining, which can reduce total VMT by combining trips and can reduce the number of cold starts.

There are also measures that can be taken by communities to improve traffic flow, both by promoting speeds that improve fuel efficiency and by ensuring more constant speeds, instead of stop-and-go traffic. These measures will also mitigate congestion, which can affect air quality, as well as quality of life in terms of delays and time lost to commuting. Many congestion-mitigation and traffic-flow-improvement measures are available to communities and can be implemented on roadways ranging from freeways to smaller arterial streets. These can include ramp metering, incident management, congestion pricing, speed limit enforcement, and improved traffic signalization and coordination. These measures can have local, regional, and global benefits. For some heavily-congested facilities, such as Los Angeles freeways, estimates suggest the potential of such measures to reduce CO_2 emissions by up to 30 percent when used in combination (Greene and Plotkin 2011). However, these measures must also be used with caution, as the use of operational improvements may reduce travel times by increasing speeds for single-occupant vehicles, potentially favoring travel in private vehicles over public transit.

4.4.5 Alternative and Renewable Fuels

In addition to measures affecting total demand for transportation energy and the roles of both vehicle and system-level efficiency, looking at the fuel used by a number of different vehicle fleets in a community is also important. At the federal level, the EPA is responsible for the Renewable Fuel Standard (RFS) Program, ensuring that a minimum volume of renewable fuel, which can come from a range of qualified biomass feedstocks and technology conversion pathways, is blended and sold in the U.S. (U.S. Environmental Protection Agency 2010d). This program works to achieve multiple aims by reducing lifecycle GHG emissions relative to petroleum fuels, reducing imported petroleum by displacing gasoline and/or diesel use in the nation's light- and heavy- duty vehicle fleets, and expanding the production of domestic renewable fuels and of feedstocks used to make them (U.S. Environmental Protection Agency 2010d, e).

In addition to some biomass-based renewable fuels, other alternative fuels whose lifecycle GHG and other environmental impacts may be better than those of gasoline and diesel include natural gas, propane, and hydrogen. The rates at which these alternative fuels are adopted in a given community are influenced by a number of strategies that can be implemented by state and local governments. These strategies generally involve either "provision of alternative fuels infrastructure" or "direct purchase of alternative fuel vehicles for agency fleets" (Transportation Research Board of the National Academies 2013). At the community level, much of what is needed is a detailed understanding of different fuel and vehicle options, their associated energy use and GHG reduction benefits, and the factors that are involved in the implementation of new fuel and vehicle combinations. At a basic level, one key implementation issue for a number of alternative-fuel fleets is the need for dedicated fueling infrastructure and for people knowing where that fueling infrastructure is. The Department of Energy's (DOE's) Alternative Fuels Data Center (AFDC) provides excellent information resources regarding alternative fuels, vehicles, and related infrastructures. For example, the Alternative Fuel Station Locator maps fueling stations, is accessible to the general public, and can be updated as new stations come online regardless of the stations' ownership (www.afdc.energy.gov/locator/stations/) (U.S. Department of Energy 2013a). Other resources include the Clean Cities coalitions of stakeholders, which can help interested community stakeholders to understand alternative fuels and to receive technical assistance supporting the deployment of alternative fuels and vehicle fleets (www1.eere.energy.gov/cleancities/) (U.S. Department of Energy 2013b).

In addition to supporting infrastructure deployment, local governmental agencies are responsible for large fleets of government vehicles and the management of public transit investments and operations

(Transportation Research Board of the National Academies 2011). As such, their decisions regarding vehicle purchases can support the penetration of alternative fuels in a community. In fact, local and state governments can often serve as leaders in the deployment of alternative fuels and vehicles by using them for diverse fleets ranging from law enforcement, public transit, refuse collection, school transportation, and shuttle services. Many already-successful efforts are documented as case studies by the AFDC (www.afdc.energy.gov/case) (U.S. Department of Energy 2013a), and those case studies can provide background information for communities interested in pursuing similar strategies.

4.4.6 Vehicle Electrification and Related Infrastructure

Infrastructure for alternative fuels such as biofuels or natural gas is one key link between the transportation sector and energy system in a community. However, perhaps a more critical emerging trend is the growth in vehicle electrification, which couples the transportation sector to the local electric grid. The joint GHG and fuel economy standards, discussed above, will likely result in increased vehicle electrification for light-duty vehicles. The questions of how and where the charging of electric or plug-in hybrid vehicles will occur can be influenced in a number of ways by decisions and policies at the community level. Many of these questions are being heavily researched, but because of electrically powered vehicles' current small share of the transportation sector, there is relatively limited empirical data regarding charging preferences and potential growth in the use of fully electric or plug-in hybrid vehicles.

However, the build-out of electric charging stations is already occurring, with approximately 6,268 electric stations in the U.S., excluding private stations (www.afdc.energy.gov/locator/stations, last accessed July 2013). This represents more than half of all alternative fuel stations in the U.S. (12,197 total), and therefore more stations than all other alternative fuels combined, including ethanol (E85), biodiesel (B20 and higher), liquified natural gas (LNG), compressed natural gas (CNG), liquified petroleum gas (propane), and hydrogen. Already, there are a number of government- and private-sector-provided public charging spaces (836 of the electric-station owners documented by the AFDC in July 2013 were local governments) (U.S. Department of Energy 2013a). Given this growth in stations, research on their impact on energy use and GHG emissions is needed.

There is the potential for synergies between the transportation-related choices made at the community level and broader energy strategies. There are a number of research initiatives attempting to understand the market for electric vehicles and charging patterns for this still-small but growing segment of the fleet, as well as to understand potential impacts on electric-power dispatching. However, beyond that is the question of how communities can promote synergistic solutions between vehicle electrification and energy strategies, and how to quantify their benefits. For example, research has been conducted to look at the question of whether plug-in vehicle buyers want green-power electricity (Axsen and Kurani 2013). This could point to whether there are market preferences that would support a combination of green power and plug-in hybrid or electric vehicles, as well as point to policy and marketing strategies to advance these solutions (Axsen and Kurani 2013). However, there is a lack of tools and resources available to communities to support these types of strategies. Another question is that of at-home charging (occurring primarily at night), and how the built urban environment can support, or perhaps even negatively affect, the prospects of electric-vehicle use and the ease of charging at home. Therefore, vehicle electrification suggests a number of emerging questions related to interactions between the built environment, private vehicle fleets, and the energy system, including the question of what the relative impacts are of direct vehicle emissions and power-plant emissions that result from generating electricity for plug-in vehicles.

4.4.7 Greenhouse Gas Footprint

Greenhouse gas footprint analysis and emissions calculators are approaches that involve estimation of the GHG footprint of an entire system (or community), transportation service, or facility (Transportation Research Board of the National Academies 2013). These can include registry- or inventory-based calculators or life-cycle-analysis calculators (such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, the Lifecycle Emissions Model (LEM), GHGenius, or Economic Input-Output Life Cycle Assessment (EIO-LCA)), many of which are spreadsheet-based, but often are on the Internet or can utilize more complex software (see Chapter 4 of Transportation Research Board of the National Academies (2013)). These calculations can then be used to set and track CO_2 reduction targets such as: (a) annual percent reductions, (b) percent reductions in a future year relative to a base year, or (c) absolute reductions in CO_2 or CO_2-equivalent, annually or for a target year (Transportation Research Board of the National Academies 2013).

At the community level, another approach is visualization of the transportation carbon footprint in order to compare transportation CO_2 emissions to the potential to biologically sequester that same amount of CO_2. Under this methodology, total system fuel use can be used to estimate the amount of carbon dioxide emitted over the course of one year. Data from sources such as state departments of natural resources may then be used to determine how many acres of local forestland would be needed to absorb and sequester that entire sum of CO_2, accounting for the likelihood and rate of sequestered CO_2 being rereleased through combustion or decay. Once this footprint has been established, superimposing it on a map of the community allows a comparison of the carbon-footprint land area with the community's various other land-use needs. If the jurisdiction carrying out this analysis can meet all of its other land use needs and still have enough natural areas to sequester all of the carbon dioxide from its transportation system, that would be one potential indicator of sustainability (Chi and Stone 2005).

4.5 Water Issues and Related Tools, Resources, and Indicators

Transportation sources can impact surface and groundwater quality through deposited emissions from fuel combustion, fluid leaks, and mechanical wear of brakes and tires. These emissions affect watersheds through the atmospheric deposition of air pollutants and by being transported in stormwater runoff along impervious surfaces (such as transportation infrastructure), which also facilitate the movement of non-transportation pollutants into surface and groundwater. Transportation-related projects also have the potential to significantly affect the sustainability of water infrastructure systems.

4.5.1 Runoff from Impervious Surfaces

There has been a substantial body of research linking water quality and aquatic resources to imperviousness, of which transportation infrastructure makes up a significant proportion. The components of imperviousness are made up primarily of rooftops and the transport systems (roads, driveways, parking lots) built to serve development. This transport component makes up the majority of the impervious area created by development. For example, when a study measured imperviousness in 11 typical developments in the Olympia, Washington metropolitan area, the researchers separated the percentage of a site's area devoted to roads, parking, and sidewalks and found that transportation-related imperviousness comprised 63-70% of total impervious cover (City of Olympia 1995). Later, Goetz et al. (2004) found in a GIS study in the Chesapeake Bay watershed that roads accounted for 36% of all impervious surface area and the combination of roads, driveways, and parking lots accounted for over 60% of all impervious surface area. The contribution of transportation infrastructure to imperviousness is even more pronounced in rural and suburban areas, where roads must be longer to reach homes that are farther apart, driveways must be longer to reach homes that are set back farther from the road, and parking lots must be larger to accommodate more cars, since alternative modes of transport are less common or nonexistent (Schueler 1994). However, rural areas still have the lowest overall percentages of their land area covered in impervious surfaces.

Percent imperviousness in a watershed has been linked to overall watershed health in a number of studies (Schueler, Fraley-McNeal, and Cappiella 2009). Currently, the most widely accepted "tipping point" for watershed health degradation is 10% imperviousness. Once imperviousness reaches an overall 10% share of land cover, there is noticeable degradation in the watershed. More recent surveys of impervious-surface impacts on water quality generally find that adverse impacts are detectable when percentage impervious surface is as low as 5% (Brabec, Schulte, and Richards 2002, Schueler, Fraley-McNeal, and Cappiella 2009). More information on impervious land cover and its effects may be found in the concurrent SHCRP Theme 4 synthesis paper on land use.

Imperviousness caps are now being used in city and regional planning. For example, percent impervious caps have been used as a planning tool in Montgomery County, Maryland for the Paint Branch watershed (Montgomery County) and in Fairfax County, Virginia (Fairfax County). Land use controls and stormwater best management practices that promote natural resource buffers and infiltration are now commonplace in land-use site design practices.

4.5.1.1 Mitigation Strategies

There are two basic design strategies for mitigating stormwater runoff. The first strategy is to establish a basin at the low point of a catchment area, holding rainwater until it either infiltrates into the ground, evaporates, or is harnessed for some purpose (such as watering plants). This function may be served by a rain garden, a constructed wetland, or a dry basin. The second design strategy for mitigating stormwater runoff is to route the flow of water from upland areas to lowland areas across pervious surfaces, which slow down the flow of surface water and allow more of it to infiltrate. To enact this strategy, one may create vegetated buffers, including grass swales, downhill from a road or other impervious surface, or one may replace an area of impervious pavement with an area of pervious pavement (Guo et al. 2010).

There are many different types of pervious pavement (Gomez-Ullate et al. 2011, Scholz 2013). Both concrete and asphalt may serve as materials for a pervious surface and water may either flow in between paving blocks or through a series of pores in the pavement itself (Chai et al. 2012, Starke, Gobel, and Coldewey 2010). Beneath the visible layer of a pervious pavement is a layer of aggregate, the thickness of which must be greater in locations that receive more rainfall (Chai et al. 2012). Potentially, pervious pavement could be used for the shoulders of a road, as opposed to replacing the entire road, in which case the thickness of the layer of aggregate would also need to be proportional to the width of the roadway that the pervious shoulders collect runoff from (Chai et al. 2012). Unlike other design elements that mitigate runoff, pervious pavement does not require the use of any more land than what the roadway currently occupies (Starke, Gobel, and Coldewey 2010), although some pervious pavements may become clogged with sediment, reducing their effectiveness (Gomez-Ullate et al. 2011), and the usefulness of pervious pavement is limited in places where the underlying soil is either already saturated or a poor conductor of water (Chai et al. 2012). Like other runoff-mitigation tactics, pervious pavement reduces flooding, improves water quality, aids in replenishing groundwater, and may be equipped with a system for collecting (non-potable) stormwater for more immediate use by humans (Gomez-Ullate et al. 2011, Starke, Gobel, and Coldewey 2010). Pervious pavement also results in more evaporation than impervious pavement and causes evaporation to occur less rapidly following a rain event, both contributing to the reduction of runoff and mitigating the urban heat island effect by producing a density of moisture in the air that more closely resembles that which would be found in a natural environment. However, pervious pavement is unable to produce as much beneficial evaporation as natural soil and plants (Starke, Gobel, and Coldewey 2010). Currently, the use of pervious pavement for transportation-related surfaces is mostly limited to parking lots, driveways, and some minor roads, with no fully permeable pavement ever having been used on U.S. highways (Chai et al. 2012, Scholz 2013). Furthermore, insufficient research has been conducted, both experiment-based and simulation-based, to determine the effect of pervious pavements on roadway design parameters (Chai et al. 2012). Another knowledge gap is whether or not it is advantageous to include a geotextile layer (a polymer-based film) within the structure of a permeable pavement, with the theoretical benefit being the filtering out of pollutants that take the form of suspended solids (Scholz 2013).

4.5.1.2 Assessing the Effectiveness of Mitigation Strategies

In a given catchment area or watershed, impervious surfaces may be divided between those that empty onto a pervious surface and those that are contiguous with the low point and/or discharge point of the catchment area/watershed, meaning that there is no pervious surface in between to mitigate runoff effects. Likewise, pervious surfaces may be divided between those that receive runoff from an uphill impervious surface and those that do not. Each of these two categories of impervious surface and each of these two categories of pervious surface has a different effect on overall stormwater runoff, a fact that is not reflected by simply calculating the percentage of an area that is impervious. Therefore, calculating an area’s “effective imperviousness” may be beneficial, wherein surface areas are weighted according to whether or not they are part of a relationship where an impervious surface empties onto a pervious surface and consideration is given to the ratio of uphill impervious area to downhill pervious area in each of these relationships. Other important measures to consider are the capacity for runoff storage in an area and the ratio of the local soil infiltration rate to rainfall intensity (Guo et al. 2010).

The EPA's Storm-Water Management Model (SWMM) is a useful tool for assessing stormwater runoff impacts from impervious surfaces, able to model runoff volumes from impervious and pervious surfaces in a network of catchments and subcatchments under many different circumstances. The SWMM is primarily geared towards use in urban areas, but it also has nonurban applications (Guo et al. 2010). Another program that simulates the effects of different kinds of impervious and pervious surfaces on infiltration and runoff in a variety of contexts is the commercially-available HYDRUS model (Chai et al. 2012).

4.5.2 Groundwater Contamination from Leaked Fuel

Regardless of whether or not they are transported through stormwater runoff, transportation fuels contain pollutants that leak from vehicles and storage facilities and enter the groundwater. As discussed for vapor intrusion, a source-term model is being developed by the EPA that accounts for the transport and fate of fuel components in soil gas and groundwater. Groundwater contamination results from contact with leaked vehicle fuels and other fuels. Constituents of fuels partition into groundwater and may form plumes which impact either private or public drinking-water wells. The source-term model being developed addresses the mechanisms of weathering (changing composition due to dissolution of components by water, volatilization to air, and sorption to solids) of gasoline, relative to common geologic settings, and serves as an input for related groundwater modeling work. The purpose of the model is to provide a basis for understanding the longevity and behavior of difficult-to-remediate contaminated sites, which contribute to the current backlog of about 90,000 unresolved leaking-tank sites. The groundwater modeling itself is based on transport along streamlines in flowing groundwater that connect sources to receptors.

4.5.3 Relationship between Transportation Infrastructure and Water Infrastructure

Automobile-based transportation and water-service infrastructures coexist spatially in an urban environment. Large diameter water mains are buried underground along main roads leading to population centers, where small diameter pipe branches serve subdivisions and households. Together these two types of infrastructures in a metropolitan area form a spatial network that distributes urban population and economic production, and hence defines physical centers of major production, commercial, and living activities. One consequence of this relationship is that if transportation-system expansion results in the rapid growth of an urban area, the existing water infrastructure may become incapable of providing the needed services and new infrastructure may be required. Another important connection between water and transportation infrastructures is that the stormwater runoff collected by the gutters and drainage ditches along roadways can significantly impact water quality.

4.5.3.1 Water Planning and Adaptation Methods: Implications for Transportation Choices

Water infrastructure in the U.S. has an extensive, far-reaching presence, providing service functions for water supply – water treatment and distribution, wastewater collection and treatment, stormwater drainage and urban flooding prevention. For example, drinking water infrastructure, a major asset of a water utility, includes pipes, pumps, valves, storage tanks, reservoirs, meters, fittings, and other hydraulic appurtenances that connect treatment plants to the taps of household, commercial and industrial users. These drinking water systems are estimated to span almost 1 million miles in the United States (Kirmeyer, Richards, and Smith 1994), with 3,200 miles (21,239 km) of new pipes installed each year, including an estimated 154,000 finished water storage facilities (American Water Works Association 2003). In addition to supplying potable water, water distribution systems must also be able to provide water for non-potable uses, such as fire suppression, street watering, and irrigation of landscaping. In wastewater management, 98% public wastewater treatment works are publicly owned and provide service to 190 million people or 73% of the population. Seventy-one percent serve less than 10,000 people and twenty-five percent of the population are not connected to centralized treatment, but instead use some form of on-site treatment system such as onsite septic tanks. In total there are approximately 600,000 miles of publicly owned pipe in the U.S. (U.S. Environmental Protection Agency 2002b).

The planning and engineering practices for water infrastructure have been developed through many decades, and are now embodied in the planning guidelines and engineering codes. In this long-held practice, water supply and water management infrastructures are planned and designed for peak needs in a projected future state of population and economic activities defined in urban master plans. Urban master plans define how urban population and economic activity are distributed, setting up physical boundaries for transportation choice and planning of water infrastructure services.

4.5.3.1.1 Current Practice

The general community-development planning and engineering sequence begins with the development of urban socioeconomic goals, followed by infrastructure planning and engineering, performance monitoring, and assessment. A general planning-engineering-evaluation sequence is shown in Figure 4. Methods for transportation planning have been discussed in other sections.

For water infrastructure, master plans are commonly developed for a given set of land use and economic projections. Major planning and engineering tools include EPANet and its commercial derivatives (WaterCAD, H2Omap, etc.) for drinking water supply, EPA's SWMM and related stormwater packages for stormwater management and urban drainage, and engineering software platforms (e.g, SewerGems, H2OMap/Sewer, HydraSewer, etc.)

General water infrastructure planning and engineering consists of three major steps, in sequence, as land use and economic projection, analysis of spatial population distribution, and the projection of water demand and wastewater generation. For the economy of scale, an initial monocentric urban form favors a centralized water supply system, and mostly a single wastewater and stormwater management network, if the hydrographic condition permits. A centralized water supply system delivers water from treatment plants through a vast distribution network, in which energy is consumed and water quality changes. In reverse, sewer systems collect wastewater from individual users to a central location for treatment before discharge. Stormwater sewers drain an urban area and discharge overland runoff,

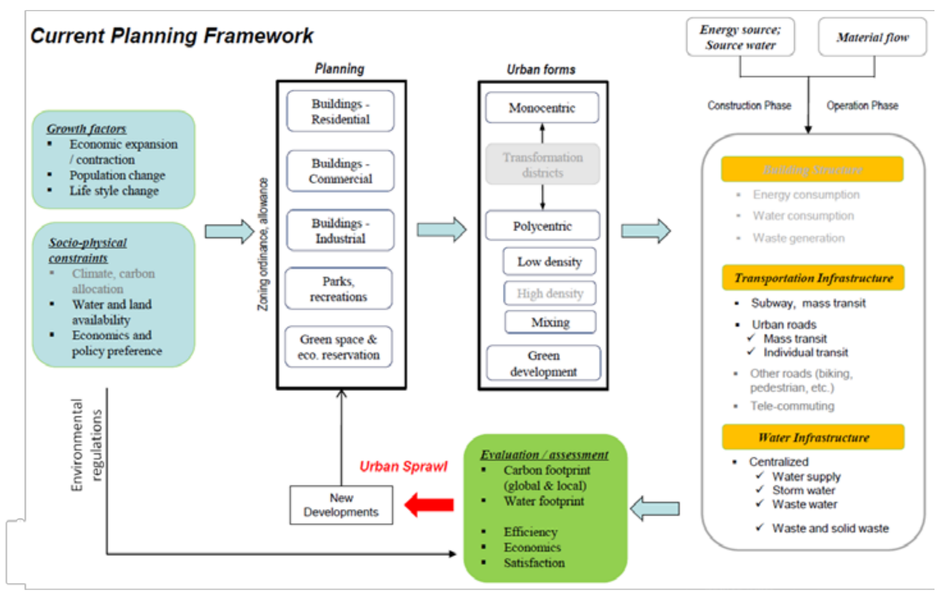

Figure 4: General process of urban master planning and its relations to transportation and water infrastructure engineering.

regulated by the National Pollutant Discharge Elimination System (NPDES) permit program. This arrangement is the most cost-efficient for the water supply and management service of a mono-centrically distributed population. Other factors such as topography, source water, available discharging water bodies, and old combined-sewer systems can also affect specific engineering designs.

Monocentric urban formation is common in the U.S., wherein the population is distributed around a single central business district (CBD), which contains high levels of economic activity. In the absence of extensive transit systems, automobile-based mobility is a precondition to facilitate the form of urban-suburban-exurban arrangement. Examples include numerous, mostly middle-to-large sized, urban centers such as Las Vegas, Cincinnati, and Houston. As a city grows into a large metropolitan center, the population becomes dispersed and the monocentric form evolves into a polycentric formation with connected satellite cities. This is typical for very large metropolitan areas, such as New York City and Los Angeles. Urban form transformation, and its implications for CBD formation, population distribution, and transportation service, have been extensively investigated (e.g., Gordon, Richardson, and Wong (1986), Small and Song (1994), Heikkila et al. (1989), Larson, Liu, and Yezer (2012), Garcia-López (2012), and Zhou et al. (2013)).

The transition of monocentric urban centers into polycentric forms is most relevant for U.S. cities and metropolitan areas. As shown in Figure 4, the master planning process for urban development starts by considering transportation choice and mobility; the improved mobility induces travel demand and further facilitates urban expansion (Ewing 2008, Burchfield et al. 2006). This process commonly involves planning, engineering, outcome monitoring, and simulation against a set of urban developmental goals. Based on given developmental objectives, new developments continue to be planned, leading to further urban sprawl, which can lead to uncontrolled expansion into exurbs and city perimeters (Figure 4). Ewing (2008) examined the mechanisms responsible for this tendency, and concluded that public transportation and improved highway systems are the primary enablers, accelerating urban expansion along their routes or in a “leap-frog” pattern outward from urban centers. This type of “induced demand” was discussed in an earlier section of this report.

Water infrastructure expands accordingly in the urban transformation to extend water services to new developments (Figure 4). This process under the current planning framework is passive and in response to transportation-facilitated urban expansion. Existing water infrastructure is expanded and adjusted in its operation and management in order to meet the expansion-induced new water demand. Usually the legacy of centralized configuration remains intact even after cities are transformed into a polycentric form. Practical examples are numerous, such as the vast centralized water service infrastructure in Los Angles and New York City. This tendency conforms to several notable attributes in urban planning:

- Water infrastructures, mostly buried in subsurface, are planned and designed to meet water demand distribution given by the urban master plans. Once designed and built, the water infrastructures and their functions have created a “lock-in” condition in heavily built urban environment, making it difficult to change or modify the infrastructure framework in the future.
- In centralized water systems, capital-intensive drinking water and wastewater treatment plants are located away from urban centers. New developments can be served economically by expanding the

distribution and collection pipe network at relatively small capital costs, even at the expense of operational and energy efficiency. However, there is a limit to this expansion before the existing system configuration and operations become unsustainable without significant, fundamental changes.

- Water infrastructure has its primary service functions in providing adequate capacity and reliability to meet urban service needs, reduce capital and operational costs, and ensure compliance with applicable Safe Drinking Water Act (SDWA) and Clean Water Act (CWA) regulations. System efficiency and carbon footprints are often a secondary priority.
- Although subject to master development plans, urban water infrastructure is often engineered independently from transportation infrastructures. The two types may become decoupled and uncoordinated. This results in greater inflexibility of both infrastructures to change and adapt to future functionalities and greater incompatibility between them.

Continuous urban expansion toward more dispersed, polycentric forms is a persistent trend leading to uncontrolled urban sprawl. The trade-off in urban efficiency and sustainability of the two infrastructures is under debate on subjects ranging from resource allocation and urban ecology to engineering and operations (Small and Song 1994, Ewing 2008, Heikkila et al. 1989, U.S. Environmental Protection Agency 2006, U.S. Environmental Protection Agency 2007a, Baynes 2009, Ostrom 2010). Notable negative effects have been recognized, such as the challenges to reliable transportation and mobility, as discussed in other chapters. For urban water services, centralized operation and management allows for better control of water pollution and management over water regulations, benefiting from economies of scale. Nevertheless, negative consequences of a centralized water infrastructure can be found in multiple dimensions: excessive energy inefficiency and thus indirect carbon emissions, barriers to resource recovery, and vulnerability to the impact of natural and man-made incidences. Alternative approaches, especially in the form of decentralized water systems, have been increasingly discussed. As monocentric urban form transforms into polycentric form, the centralized water system faces technical and engineering challenges to evolve into a decentralized framework. When this happens, the process requires coordinated urban planning and engineering among transportation and water services.

4.5.3.1.2 Urban Form Transformation: Scenario Planning

The Intergovernmental Panel on Climate Change (IPCC) 3rd Working Group recently studied climate change mitigation and adaptation in urban environments, and concluded that urban form transformation has, by far, the single largest potential for urban efficiency improvement and carbon emission reduction. Several common planning options are listed for urban transformation, including infill, interior redevelopment, mixed land use, and employment centers. They have been applied across U.S. cities (U.S. Environmental Protection Agency 2012d). These urban transformation measures, capable of reversing or at least slowing urban sprawl, require changes in metropolitan transportation and water services. Two approaches in urban form transformation have emerged — scenario planning and urban smart growth.

Specifically, each urban form has a set of characteristic physical layouts in water and transportation infrastructure, with distinct operational properties. Thus each comes with economic costs, energy consumption, carbon and water footprints, and the ability to provide desired services. In scenario planning of existing metropolitan areas, the objective is often to determine the sustainability parameters associated with each developmental option, and thus provide data for informed actions. Water and transportation infrastructure, as the two major urban physical systems, can be planned and engineered through coordinated scenario planning.

In principle, scenario-based urban planning is a systems-engineering approach to examine possible urban development options. Such scenario-based analysis is conducted as a part of urban master planning, involving planning, engineering, outcome assessment and re-planning for new development (Figure 4). The outcome assists city planners and decision-makers to evaluate the capacity and efficiency of existing transportation and water infrastructures, identify future improvement options, and compare their benefits against a set of planning objectives. A technical plan consists of the following major components:

- Population and land use planning and future projections
- Transportation analysis and planning, including a State Implementation Plan (SIP) on air quality conformity
- Water infrastructure analysis and planning

4.5.3.1.2.1 *Urban Population and Land Use Projection*

Population and land use projections in planning scenarios are the most difficult and least quantifiable among the three major components of scenario planning. Future population and land use is a function of urban economic conditions and future economic policy initiatives that are less predictable or quantifiable. As an approximation, cellular-automata Markov chain (CA-MC) simulation in GIS has been used with model boundary conditions representing urban land policy restrictions. Tong, Sun, and Yang (2012) and Sun et al. (2013) successfully projected future land use changes in the watersheds of the Cincinnati and Las Vegas suburbs. Their modeling methodologies incorporated population and land use variables as a GIS model filter in GIS CA-MC simulations.

Recently, ongoing EPA research attempted to simulate land use changes in the resolution of census tracts in the Cincinnati metropolitan area. In this investigation, CA-MC methods supplemented by restraints from water and land use policies were used to generate year 2030 land use patterns and population distributions inside of Cincinnati for four development policy scenarios: 1) current development or baseline; 2) infill; 3) high density development; and 4) mass-transit development. The developed model was successfully calibrated against 1990 and 2000 urban land use and population Census data. However, disruptive urban development policy and events can make the model projections less accurate and useful. The disruption can violate spatial continuum assumptions embedded in the semi-empirical CA-MC methodology. This potential problem and its challenge cannot be under-estimated in urban land use and population projections.

Separately, EPA has developed the Integrated Climate and Land-Use Scenario (ICLUS) tool and projections of housing density and land use categories to the year 2100 under the IPCC Special Report on Emission Scenarios (SRES). This large development scenario covering the entire U.S. is based on a pair of models: a demographic model for population projection, and a spatial allocation model to distribute the projected population into housing units at a 1-ha pixel resolution. Population allocation from a county scale to census tract resolution is technically challenging, because of a set of model assumptions for present, near-term and distant economic growth. For example, the Spatially Explicit Regional Growth Model (SERGoM) is used in population allocation to generate the projections at a spatiotemporal resolution of 10 years and 1 ha. In generating high-resolution population maps, the allocation method may produce model error and uncertainty excessive for infrastructure planning and engineering purposes, although this potential has not been assessed. More details on the methodology can be found in U.S. Environmental Protection Agency (2009b) and U.S. Environmental Protection Agency (2010c).

4.5.3.1.2.2 Water Planning and Engineering

A wide range of tools and models are available for water infrastructure planning and engineering as the result of decades of development. These include EPANET-based distribution modeling and design for drinking water supply, EPA's SWMM and related commercial design packages (e.g., SewerCAD, StormCAD) for storm water drainage, gravity and forced sewer systems. Essential to all tools and models is GIS and topographic-information data-processing that describe urban spatial attributes of infrastructures and their relationships. In urban planning, technical considerations are given to the unique properties of each water infrastructure: gravity flow of wastewater and storm water systems, pressured drinking water supply systems and pressure zone distribution, water treatment, monitoring, and regulation compliance. All have significant implications to the physical components and layout, service functions, energy consumption, and other sustainability attributes.

Noteworthy in water planning and design is that water system expansions are always built on the existing infrastructure framework and physical footprints. The efforts are focused on component optimization, system improvement and capacity expansion, while system-wide redesign and reconstruction rarely happen. Urban form also evolves as the urban area grows, with some developing into polycentric configurations. The transportation-induced redistribution in population and urban activity can subsequently change the existing spatiotemporal configuration of water demand, for which water service functions have to adjust. This continuum of urban growth is widespread across U.S. metropolitan centers, with many experiencing urban sprawl (Figure 4). Under this condition, existing centralized water infrastructure developed for a monocentric formation shows a mismatch with the new water needs and existing water service functions and begins to experience difficulties with required services.

4.5.3.1.3 Urban Form Transformation: Smart Growth and Water Systems Optimization

The second approach in urban transformation is based on smart growth, with the objectives of low-carbon development, high urban density, and walkable and livable environments. The smart growth concept initially developed for these general attributes is now propelled into specific urban and infrastructure planning activities. For example, U.S. Environmental Protection Agency (2012d) reported national trends in smart growth adopted for urban development and urban renewal. Infill and green field residential developments as means of smart urban growth have been gaining applications throughout the U.S. So far, EPA has published a series of reports not only on residential smart development, but also on transportation and water services of a sustainable community (e.g., U.S. Environmental Protection Agency (2006), U.S. Environmental Protection Agency (2009a), and U.S. Environmental Protection Agency (2011a)). Infill development and mixed transportation modes are shown as being capable of reducing transportation-source emissions and improving system efficiencies.

For the urban water sector, infill development (within urban boundaries) and green infrastructure are currently designed around water availability and the cost of providing reliable water services (U.S. Environmental Protection Agency 2006). Less often they are considered as a part of smart urban growth in coordination with transportation systems. Nevertheless, water system optimization is an essential component to enable smart urban growth and reduce energy consumption for CO_2 emission avoidance. EPA research has been developing planning support tools for regional water infrastructure planning (Chang, Qi, and Yang 2012), water usage evaluation in urban planning scenarios (Wang, Burgess, and Yang 2013), and energy optimization in water distribution (Yang, Chang, Neal, et al. 2013). Yang, Chang, Li, et al. (2013) and Yang et al. (2011) further described evaluation criteria based on conjunctive use of the carbon footprint and water footprint indices for urban infrastructure mitigation and adaptation. These two footprint indices detail carbon emissions and water usage against the carbon allocation and water availability of a given urban area.

Life-cycle analysis and Pareto optimization were the techniques used for planning scenario evaluation and selection in Manatee County, Florida (Chang, Qi, and Yang 2012). A total of 20 developmental scenarios in water supply infrastructure expansion were compared against their life-cycle carbon emission and capital/operational cost. Individual structural components were analyzed for their life-cycle impacts under different scenarios of infrastructure construction phases. The analysis was based on a compromise non-linear programming model as the computation technique.

The EPA research programs (e.g., SHC, ACE, and SSWR) are developing other methods for individual water infrastructure components. New developments, such as those in nutrient recovery, leak detections, and green infrastructure, are focused on water infrastructure or its components alone. Restraints from urban transportation, its mode and accessibility, are not yet considered. For integrated planning, however, the smart growth methodology needs to simultaneously consider both types of infrastructures in the evaluation of developmental options.

4.5.3.2 Known Effects of Transportation Decisions on Water Infrastructure Outcomes

In the current urban planning framework (Figure 4), water and transportation infrastructure improvements are frequently made in the period between two adjacent master planning events. The uncoordinated infrastructure work potentially creates a “lock-in” condition in urban water infrastructure, which can hamper future water service optimization and sustainability. These inter-infrastructure interactions were briefly described in the preceding subsections. Alternatively, smart urban growth shifts the development paradigm to adaptive planning, readjusts developmental goals, and enables water service function changes through a combination of gray and green water infrastructures. This systems-approach-process is shown in Figure 5.

Here the impacts of transportation decisions on water services and infrastructure sustainability are outlined. Discussion is made in reference to the existing development framework and the smart-growth transformation shown in Figures 4 and 5, respectively.

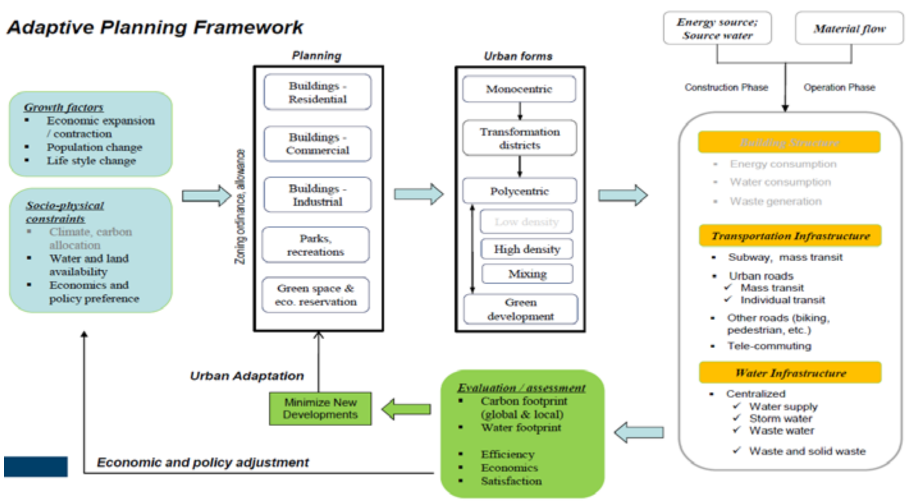

Figure 5: General process of adaptive urban planning and engineering. Compared to traditional master planning (Figure 4), adaptive planning promotes economic and policy adjustment on urban development goals and urban adaptation for high-density, polycentric form through transformation and proper transportation and water infrastructure adjustment.

4.5.3.2.1 City Development Examples

4.5.3.2.1.1 Rapid Urban Sprawl

Many metropolitan areas with rapid growth experience undesired impacts that were facilitated by their transportation choices. The experience of Las Vegas illustrates this. Las Vegas has rapidly increased its physical urban footprint over the past decades. The urban population increased from 273,288 in 1970 to 741,368 in 1990, and approached 1,900,000 by 2010. Correspondingly the urban area increased by 2.9 times from 58 square miles to 170 square miles from 1970 to 1990. The majority of the urban expansion occurred along major highways, US-95, I-15, and I-215 extending from the valley toward Lake Mead. Accompanying this rapid growth, the metropolitan water distribution system has expanded, consisting of >4,500 miles of water pipes, 65 pump stations, and 68 water storage facilities. The network is currently expanding into the Summerlin area to the west, responding to new road and housing developments. Through this history of development, the water distribution system remains centralized, with two water treatment plants and a single distribution network, at significant energy cost for pumping. Lake Mead to the southeast is the primary water source for the city.

Rapid expansion of the centralized water infrastructures met the urban development needs, but also brought technical challenges to the required water service objectives. During the economic depression starting in the late 2000s, vacancy rates were high and water demand was chronically low compared to the preceding housing boom periods. This change led to over-capacity in the water distribution system, and excessively long water ages or water residence time in many parts of the distribution network. A direct consequence was high levels of disinfection by-products (DBPs) (e.g., chloroform) in the tap water, risking violation of the Safe Drinking Water Act (SDWA) DBP Stage-II regulations.

Many metropolitan areas with rapid growth have experienced problems of a similar nature in water supply and water sanitation. A lack of adaptability of centralized water systems to further urban development or changes is a common cause. Such an observation can be made in old industrial cities in the Midwest, such as Detroit, Cleveland, Youngstown, etc., where long periods of economic depression in urban centers are followed by renewed redevelopment efforts in recent years. As an extreme international example, unprecedented urban sprawl in Beijing, China is accelerated by the rapid expansion of car and mass-transit transportation systems along the continuously expanding ring roads around the city center, leading to ecological and water environmental problems (Wang et al. 2007). Because of flat topography in the Beijing metropolitan area, urban drainage and stormwater management becomes a daunting challenge as the monocentric city expands. Inner-city flooding occurred in the last three years with over 86 people killed in flooded roads during a flash flood in October 2012. Although less severe in magnitude, urban drainage problems and investment in runoff control have been a major issue for many U.S. metropolitan areas.

4.5.3.2.1.2 <u>Leap-Frog Development and Small/Community Water Systems</u>

Highway transportation and mass transit have resulted in "leap-frog" new urban development centers — isolated developments, mostly in exurban areas, that exist before further development fills the undeveloped areas between. Sun et al. (2013) show through land use modeling the likelihood and evolution of such development in the Las Vegas metropolitan area. In general, leap-frog development is characteristic of small-community settlement, propelled by highway development and mass transit, in areas away from the urban continuum (Figure 6). Such development can be for the purpose of affordable land, natural scenery, or valuable but low-density estate properties.

Leap-frog development, fueled by transportation infrastructure, has direct implications for the form of water services. Such development often has no existing water and wastewater services from water utilities, tending to be served by small water systems or on-site treatment, like septic tanks. Examples can be found outside Washington, DC. Small-scale, operationally simple, decentralized community or household systems are preferable choices in these areas. As described in U.S. Environmental Protection Agency (2002a) and U.S. Environmental Protection Agency (2007c), these small systems employ less robust water treatment technologies, receive little operational and maintenance attention, and frequently are vulnerable to performance upsets. The environmental consequences have been well documented, particularly nutrient pollution from small wastewater systems. For mitigation, the states of Maryland and Virginia have enacted laws and regulations for these small community water and wastewater systems.

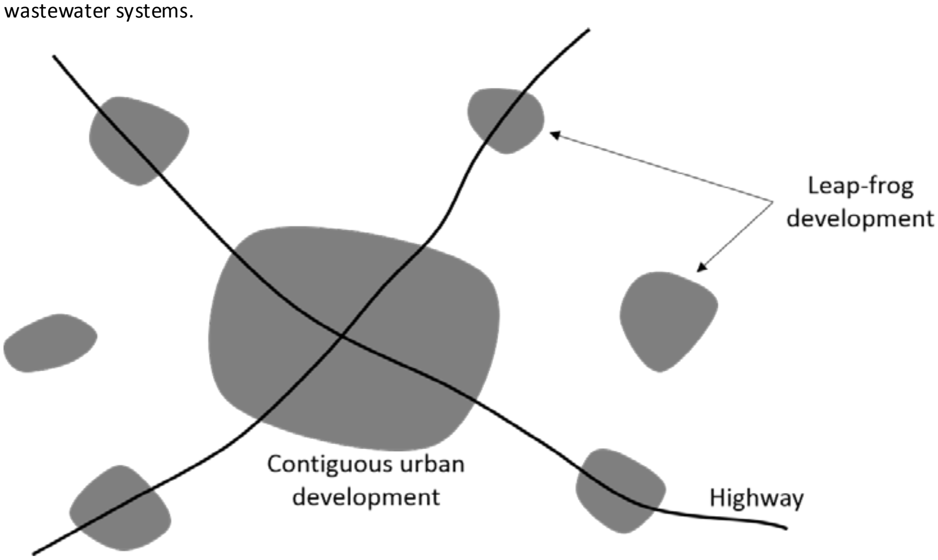

Figure 6: Leap-frog development.

4.5.3.2.1.3 <u>High-density Urban Centers</u>

Urban areas of high population density are developed with the assistance of mass transport. They often are the focus of water master planning and operational adjustment, due to high water consumption and vulnerability to service disruptions. Unique requirements include steady and reliable water supply for domestic consumption by a large population, daily and seasonal variation in commercial services, and high-rise firefighting, in addition to wastewater and storm water management in regulation compliance.

Transportation-supported high-density urban forms can significantly affect water services. In the U.S., many high-density urban centers are also old development districts with aged water infrastructures and compromised pipe integrities. These high-density urban centers are characteristic of old business and urban centers, such as those in New York City. Constant transportation improvement in these cities reinforces their high population density in a geographically restricted area. Many historically deprived high-density urban centers are now redeveloped with the assistance of improved transportation services. These urban centers are characterized by high population concentrations, a high fraction of impervious surface, nearly 100% land coverage, and frequently old and structurally-compromised water infrastructures. Old structures for combined sanitary and stormwater sewers are common in U.S. Northeastern, Eastern, and Midwestern urban centers. Such combined sewers are vulnerable to overflow in heavy rain events, sending raw sewage into waterways, a problem which is exacerbated by runoff from impervious surfaces that is funneled through roadside curb-and-gutter systems.

These conditions make it difficult to improve or redevelop underground water infrastructures. For this reason, mitigation and correction of combined sewer overflow (CSO) problems have proven to be difficult in high-density urban areas.

Another problem for old high-density urban districts occurs in the operation of drinking-water piping, wherein persistently high rates of water loss from drinking-water pipes occurs, particularly between points with a large elevation difference. For these areas, pressure zone management is a challenge to meet the varying water demand in a day, pressure requirement in building fire code, and reduce the risk of damaging aged and structurally compromised underground water pipes.

Urban water and transportation infrastructure improvement can be coordinated to avoid or minimize these problems in high-density urban centers. Urban redevelopment presents an opportunity for integration of the two systems (U.S. Environmental Protection Agency 2009a). One example is the use of green infrastructure (vegetated natural systems instead of "grey infrastructure," or engineered concrete systems) as a part of smart urban growth measures, described below.

4.5.3.2.2 Smart Growth

Smart growth in urban development is often defined differently in literature than in practice. In terms of urban development, smart growth refers to high population density, low carbon intensity, walkability, and green infrastructure, thus creating a livable environment. This premise requires the accommodation of mass transit and other transportation infrastructures, making use of the "Five Ds" of influencing travel behavior through the built environment, discussed earlier. The transportation policies contained in U.S. Environmental Protection Agency (2011a) all aim to increase urban population density, create a walkable and pedestrian-friendly community, and maximize the use of existing infrastructure through infill and redevelopment. U.S. Environmental Protection Agency (2011a) outlined major types of transportation modes with the following sustainability metrics:

- Transit accessibility, for reduced VMT and increased public transportation
- Bicycle and pedestrian mode share
- VMT per capita, to reduce automobile reliance and commute distances
- Carbon intensity (of transportation) per capita
- Percentage land-use mixture in terms of residential and commercial activities

How these changes toward smart growth affect urban water infrastructures and, in return, how the water services facilitate or impede smart growth have received little attention. Many questions persist, ranging from paradigm changes in the water supply and water management, the use and application of green infrastructure, and transitioning the existing grey infrastructure to the new developmental paradigm. Green stormwater infrastructure has been a focus area, wherein EPA has conducted a series of research and site studies, as well as provided significant information on its website. In this context, green infrastructure improves surface water quality (U.S. Environmental Protection Agency 2009a), retards transportation pollutant transport (Baldauf et al. 2008), and enhances the livability of an urban environment.

4.5.4 Transportation Fuel Choice and Impacts on Water Resources

Water usage in biofuel production for automobile fleets also links water resources to urban transportation sustainability. These two categories, on the surface, do not reveal much of the inter-dependency. The relationship, however, may be revealed through close examination of upstream water usage in alternative transportation fuel production. The transportation choice of renewable fuels is driven by U.S. national energy policy. More extensive biofuel use in the future will consume a significant portion of available-but-limited water resources for energy-related biomass production in competition with other beneficial uses. Additionally, associated new transportation technologies will require modification to current fuel supply chains and distribution, travel patterns, VMT distribution, and, importantly, the emission characteristics at the road and in near-road environments. This future state of the transportation system has been discussed and is summarized in preceding sections. Information and data, however, are limited at the present, hampering an informed decision on future urban developmental sustainability.

The use of renewable and alternative fuels in the transportation sector has significant implications in multiple dimensions of water sustainability. EPA Office of Transportation and Air Quality (OTAQ) has been conducting an Integrated Planning Model (IPM) assessment to analyze fuel change impacts both in upstream and downstream environments, with a focus on the power sector. The upstream impacts on water are largely in the form of water usage and wastewater generation during biomass and fuel production. Downstream, the impact is anticipated to be in the form of automobile emission changes for future fleets, urban forms (i.e., buildings, road network, population and activity distribution), and climate conditions.

Water consumption in biomass production for renewable fuels has been extensively investigated and discussed (e.g., National Research Council of the National Academies (2008), U.S. Environmental Protection Agency (2011a), Dominguez-Faus et al. (2009), Berndes (2002), and de Fraiture, Giordano, and Liao (2008)). In a triennial report to Congress, the U.S. Environmental Protection Agency (2011b) described significant water quality and quantity impacts in the production of bioethanol and biomass-based biodiesel. This nationwide large-scale assessment is further supplemented by ongoing research work in EPA's Air, Climate, and Energy (ACE) research program, including detailed region-specific analysis using MARKAL (a model that can optimize energy mixes to accomplish any given function) (Dodder et al. 2011), and by other work on water usage and wastewater generation in the biofuel production process (Lingaraju, Lee, and Yang 2013). This existing pool of knowledge points to a larger water footprint of biofuels than of conventional petroleum counterparts. This impact on water resources, particularly in the form of water-availability competition against both urban water supplies and ecological water needs, is a prominent issue in water-poor regions.

The downstream impacts of biofuel usage on emissions have been studied at national scales (U.S. Environmental Protection Agency 2010a), while the upstream impacts have been reported as well. One significant recent study to address the emission impacts of biofuels is the EPAct/V2/E-89 Tier 2 Gasoline Fuel Effects Study (http://www.epa.gov/otaq/models/moves/epact.htm) (U.S. Environmental Protection Agency 2013f). Numerous published studies (e.g., U.S. Environmental Protection Agency (2002b)) have shown that biofuel combustion in current-fleet engines leads to a meaningful reduction in some pollutants (e.g., particulate matter (PM), carbon monoxide (CO), and hydrocarbons), but an increase in others (e.g., aldehydes and nitrous oxides (NO_x)). Chemical and physical properties of PM emissions also change, but much is uncertain about their implications. These changes are important to near-road air pollutant monitoring and mitigation options (Baldauf et al. 2008). Their potential effects on land use decisions, and hence water infrastructure planning, have not been thoroughly investigated.

4.6 Human Well-Being Issues and Related Tools, Resources, and Indicators

Human well-being consists not just of physical health outcomes, but also of psychological and social health outcomes, economic outcomes (discussed in the next section), and equity outcomes. More information on the effects of transportation projects and policies on human health and well-being may be obtained from the Centers for Disease Control and Prevention (CDC) at http://www.cdc.gov/transportation/default.htm.

4.6.1 Physical Health Outcomes

The transportation sector is increasingly recognized as a critical determinant of human health outcomes. In addition to public health's traditional focus on vehicle emissions and injuries as sources of morbidity and mortality, new areas of investigation are enhancing our understanding of the diverse pathways through which the design and use of transportation systems affect human health. These impacts can be direct or indirect and exert their influence over a wide range of temporal and spatial scales. They not only affect human well-being, but represent a costly externality of the transportation sector that adds additional burden to the rising cost of healthcare in the United States.

4.6.1.1 Direct Impacts

Direct health impacts from the transportation sector result primarily from exposure to environmental contamination or unintentional injuries. Effects may be felt by users of the transportation system or those in proximity to it or its supporting industries.

4.6.1.1.1 Air Pollution

A large body of literature has characterized the adverse health outcomes associated with particulate matter, volatile organic compounds (VOCs), SOx, NOx, carbon monoxide, and ozone that result from tailpipe emissions produced from the combustion of fossil fuels. These pollutants, addressed elsewhere in this synthesis paper, contribute to significant cardiovascular and respiratory morbidity and mortality. While exposure carries well-described risk, factors that determine level of exposure are less clearly defined. Two important considerations for this exposure route are that: children are disproportionately affected, because they breathe in more air for their body size than do adults; and economically-disadvantaged populations are often disproportionately affected by living closer to roadways and other transportation sources (e.g., ports, rail yards) than wealthier populations.

Growing interest in shifting a greater percentage of mode share to active forms of transportation (primarily walking and bicycling) has raised questions about the impacts of such a shift on exposures to air pollutants. While the overall effect of decreased automobile use might be reduced emissions of criteria pollutants and particulates, and thus lower levels of overall population exposure, some have suggested that individuals who choose to walk or bike might receive disproportionately high exposures when compared to motor vehicle or transit passengers. Existing research is inconclusive (Knibbs, Cole-Hunter, and Morawska 2011, Zuurbier et al. 2010, McNabola, Broderick, and Gill 2009). However, some studies have shown that while walkers and cyclists are actually exposed to lower or similar concentrations of pollutants than motor vehicle passengers, the increased gas exchange from physical exertion and travel time associated with active transportation significantly modifies total inhaled or deposited doses for these mode choices (Int Panis et al. 2010). Given strong inverse associations between distance from tailpipe emissions and level of exposure, there is evidence that providing greater separation between bicycle/pedestrian facilities and roadways could modify this effect. Further research is needed to more effectively quantify relative exposure by mode of transportation while properly accounting for associated levels of gas exchange and duration of exposure, in addition to accounting for the substantial health benefits of walking and cycling (see below).

Transportation-associated air pollution extends beyond tailpipe emissions. Pollution, and its associated health impacts, can occur throughout the production of any vehicle fuel source. For example, while increasing dependence on electricity as an energy source for personal and commercial vehicle use (all-electric or plug-in hybrid) may reduce harmful tailpipe emissions, the overall impact on human health depends largely on the fuel stock used to generate electricity. Use of renewable energy sources could reduce air pollution while continued reliance on coal could merely transfer the source of harmful emissions and change the affected population. Comparing the relative benefits and harms to human health of any transportation energy source requires consideration of emissions from the full lifecycle of energy production, as previously discussed in the context of greenhouse gas emissions, and the populations affected.

Air pollution occurs within both the operational and non-operational components of the transportation sector. Operational components refer to pollution stemming directly from vehicle use while non-operational components refer to the manufacture, distribution, and disposal of vehicles and their supporting infrastructure (including roads). Comparison of the relative health impacts of transportation-associated air pollution requires evaluation of emissions from both components. Energy consumption and production of criteria air pollutants from non-operational components of transportation can exceed that of operational components by orders of magnitude. The health impacts of air pollution from non-operational components of the transportation sector could therefore be significant, although this effect will be mediated by both the fuel stock used for energy production and a population's level of exposure.

4.6.1.1.2 Noise

A growing body of evidence has found significant associations between environmental noise and adverse impacts on human health. A World Health Organization study in western Europe found that traffic-related noise was responsible for over 1 million disability-adjusted life years (DALYs), a measure of healthy life years lost, primarily due to sleep disturbance and annoyance (Fritschi et al. 2011). Despite these conclusions, evidence linking sleep disturbance and annoyance caused by road-traffic noise to specific health outcomes is limited (Hume, Brink, and Basner 2012). However, positive associations between road-traffic noise and ischemic heart disease and hypertension have been demonstrated with greater certainty, even when controlling for air pollution as a potential confounder (Davies and van Kamp 2012).

4.6.1.1.3 Injuries

Transportation-related injuries are a leading cause of morbidity and mortality in the United States, with 32,885 individuals killed and 2.24 million injured in traffic crashes in 2010. Fatal and nonfatal injuries among motor vehicle occupants have declined – per 100,000 population and per vehicle mile traveled (VMT) - over the past two decades, largely due to advances in roadway and vehicle engineering as well as interventions targeting seat belt use and drunk driving. Fatal and nonfatal injuries have also declined among pedestrians and cyclists during this time period. Nonetheless, traffic crashes remain the leading cause of death among individuals aged 5 to 24, one of the top ten leading causes of death among all age groups, and the fourth leading cause of nonfatal injury treated in emergency departments (Centers for Disease Control and Prevention). In addition to their devastating emotional toll, traffic crashes cost $99 billion annually in medical expenses (Naumann et al. 2010).

Critical to evaluation of the relative health implications of motor vehicle transportation versus active forms of transportation is an understanding of their associated risks for injury. Unfortunately, comparing these risks is challenging. While many more motor vehicle occupants are killed and injured than pedestrians and cyclists each year, the extent to which this reflects higher levels of exposure versus increased risk is unclear. The absence of an agreed upon, consistent, and appropriately comparable metric for standardizing level of exposure limits current efforts to assess relative safety. Vehicle miles traveled has commonly been used to standardize fatality and injury rates for automobiles. Although various measures have been proposed - including number of walkers and cyclists, number of trips, time, and distance traveled – none is commonly accepted for pedestrians and cyclists.

Experience from Europe demonstrates that pedestrian and bicyclist safety can be enhanced through a combination of engineering, educational, and policy interventions (Fischer et al. 2010). In Germany, Denmark, and the Netherlands, the risk of cycling – as measured by number of fatalities per distance cycled – is three to five times lower than in the United States (Pucher and Buehler 2008). Perhaps more impressively, risks associated with cycling have been so successfully reduced in these European countries that, despite rising levels of cycling over the past four decades, the total number of cyclist fatalities has decreased. The frequently observed inverse association between absolute numbers of pedestrians and cyclists and risk for injury is commonly known as safety-in-numbers (Jacobsen 2003).

Some have suggested that the safety-in-numbers phenomenon reflects a change in driver behavior in the presence of increased numbers of pedestrians and cyclists, and thus provides support for policies that promote walking and cycling as a method by which to enhance safety. However, such interventions may not be justified based upon the primarily cross-sectional data that underlies the safety-in-numbers principle (Bhatia and Wier 2011). Increases in levels of walking and cycling may have occurred in response to interventions that enhanced pedestrian and cyclist safety, or perceptions thereof. Alternatively, if increased numbers of pedestrians and cyclists reflect a shift in mode share from driving to active transportation, decreases in injuries may be due to reductions in traffic volume, a known predictor of crash frequency.

Enhancing pedestrian and cyclist safety is not only possible, but is likely essential to achieving significant shifts in mode share. Although beyond the scope of this review, numerous studies have demonstrated that the design of pedestrian and bicycle infrastructure can both reduce injuries and influence transportation decisions through individuals' perception of safety (de Nazelle et al. 2011).

4.6.1.2 <u>Indirect Impacts</u>

The transportation sector affects human health indirectly through diverse pathways. Transportation system design and access to transportation services influence health behaviors, as well as other critical social determinants of health, such as access to essential services, personal finance, and social interaction. Indirect health impacts also occur through environmental effects operating at a global scale, such as climate change.

4.6.1.2.1 Health Behaviors

Regular physical activity can help prevent or treat many chronic diseases, including hypertension, coronary artery disease, stroke, type 2 diabetes, breast and colon cancer, and osteoporosis and may be protective against depression (Warburton et al. 2010, Teychenne, Ball, and Salmon 2008). Furthermore, physical activity protects against obesity, which is a risk factor for many chronic health conditions. Yet, despite these known health benefits, nearly 40% of US citizens fail to meet recommended levels of exercise through a combination of leisure-time, occupational, and transportation-associated physical activity (Tucker, Welk, and Beyler 2011). The individual and societal price is high. Physical inactivity is responsible for nearly 11% of all deaths in the United States (Murray et al. 2012), and has been estimated to cost the US $250 billion annually in healthcare expenses, workers' compensation, and productivity losses (Chenoweth and Leutzinger 2010).

Recently, many have suggested that decisions within the transportation sector have contributed to and could offer a solution for high rates of physical inactivity in the United States. Greater reliance on the automobile for transportation at the expense of public transit and active forms of transportation has reduced population levels of transportation-associated physical activity. Concerns about safety, tied closely to individuals' perceptions of protection afforded by pedestrian and bicycle infrastructure, are an important deterrent to increased levels of walking and cycling for transportation (de Nazelle et al. 2011). A growing body of literature suggests that efforts to shift mode share from motor vehicles to transit and active transportation could have impacts on physical activity levels and associated health outcomes. Although high quality intervention studies are limited, observational studies of active transportation have identified associations with reductions in cardiovascular disease outcomes (Hamer and Chida 2008) and obesity (Wanner et al. 2012). Walking to and from public transportation can help individuals obtain recommended amounts of physical activity (Besser and Dannenberg 2005). In particular, populations in urban areas with access to rail transit are more likely to meet guidelines for physical activity than other populations (Freeland et al. 2013). Modeling exercises suggest that reducing automobile usage by 1% would result in a 0.4% reduction in the chance of obesity, a 0.3% reduction in the chance of high blood pressure, a 1.3% reduction in the chance of high cholesterol, and a 1% reduction in the chance of heart attack (Samimi and Mohammadian 2010).

Development density, street connectivity, traffic calming features, and pedestrian safety measures are all aspects of the built environment that are associated with higher rates of active transportation. However, research has yet to establish the degree to which these factors affect the overall health of community members (Samimi and Mohammadian 2010). In fact, the amount that people walk and ride bicycles is more greatly affected by the factors of inhospitable topography, darkness, inclement weather, and the demographics of the travelers. The built-environment feature that most strongly predicts more walking is the presence of retail establishments near people's homes. The built-environment features that most strongly predict more cycling are density, mixed land uses, and favorable neighborhood design characteristics, especially when these things are found at the home end of people's trips (Cervero and Duncan 2003).

People are also more likely to travel by active modes in neighborhoods with good aesthetics, safety features, and amenities. Conducive aesthetic features include green space, attractive architecture, and the absence of noise, air pollution, and physical disorder. A safe walking environment is one where both crime and traffic accidents occur at low levels. Amenities conducive to walking include public benches and sidewalk retail and restaurants. Also, pedestrians generally prefer an environment where numerous other pedestrians are around, whereas drivers generally prefer an environment where there are as few other drivers as possible. An advantage of using aesthetics and safety upgrades to promote physical activity is that it takes less time to implement than increasing urban densities or changing land-use patterns. Another advantage is that improvements to aesthetics and safety are easy to convey to community members. Research is still wanting on the relative impacts that various aesthetic and safety features have on physical activity. More research is also needed on how people's demographic and socioeconomic characteristics affect their walking behavior when all other factors are controlled for. Finally, research could shed more light on the degree to which pedestrians regard public spaces as either a destination or an obstruction (Neckerman et al. 2009).

4.6.1.2.2 Social Determinants of Health

A large body of research has characterized the importance of social and economic factors on health and well-being, broadly referred to as social determinants of health (Braveman, Egerter, and Williams 2011). Transportation – itself a determinant of health (Wilkinson and Marmot 2003) – influences other social determinants of health such as access to healthcare, personal finance, employment opportunity, and social interaction. Decisions about transportation, and their ultimate health effects, reflect tradeoffs between the need to access housing, services, and opportunities and the money and time people spend on transportation. The magnitude of this impact is often inequitably distributed, creating a greater burden on those with more limited transportation options such as minority, economically disadvantaged, disabled, and rural populations.

Among those with a usual source of outpatient health care, lack of transportation can be a major factor causing individuals to seek care in an emergency department (ED) rather than with a regular provider (Rust et al. 2008). Seeking care for nonurgent conditions in the emergency department can contribute to worse patient outcomes, ED crowding, and higher healthcare costs (Hoot and Aronsky 2008).

Expenditures on transportation represent the second largest household expense behind housing (Surface Transportation Policy Project 2003). Transportation costs consume a disproportionately large percentage of economically disadvantaged populations' income, an important social determinant of health (U.S. Department of Labor 2012). Those who rely on personal automobiles for commuting are particularly affected (U.S. Department of Transportation 2003a). In efforts to obtain affordable housing, many households accept greater transportation costs associated with commuting, as opposed to choosing to save money on transportation through location efficiency. In addition to higher commuting expense, greater spatial separation from places of employment results in increased commute times that can compromise individuals' ability to find and hold jobs, as well as their time available for other priorities, such as accessing child care. Limited transit options or frequency place a greater burden on those dependent upon public transportation for commuting (Roberto 2008).

Increased commute time can also have an impact on social interactions, another well-described social determinant of health (Holt-Lunstad, Smith, and Layton 2010). Longer commutes have been associated with fewer trips taken for social purposes and decreased time spent with family (Besser, Marcus, and Frumkin 2008, Christian 2012a), as well as decreased time spent in health-related activities (Christian 2012b). Access to transportation also affects levels of social interaction and social isolation, both of which have been associated with health outcomes (Fujiwara and Kawachi 2008, Holt-Lunstad, Smith, and Layton 2010, Dickens et al. 2011). Older populations are at particularly high risk of social isolation and its attendant health risks. Disabled individuals disproportionately report being unable to leave their homes due to transportation difficulties (U.S. Department of Transportation 2003b).

4.6.1.2.3 Air Pollution and Climate Change

As previously discussed, exposure to air pollution emitted by vehicles has been shown to increase risks of adverse health effects for a number of outcomes, including respiratory, cardiovascular, cancer, and premature mortality. These exposures can occur from being close to transportation sources and the emissions from vehicles using transportation facilities, or from more regional air-quality deterioration from the cumulative effect of vehicle emissions within an urban or larger area. These regional impacts can increase concentrations of air pollutants that are directly harmful to human health. While exposure to air pollution increases public health risks, two studies suggest that the risks from air pollution and injury are outweighed by the health benefits of increased physical activity from walking or biking (de Hartog et al. 2010, Rojas-Rueda et al. 2011), although these studies focused on regional air pollution impacts and did not account for elevated exposures near roadways and other transportation sources.

Global climate change is increasingly recognized as a significant public health threat, and, as discussed previously, the transportation sector is a key contributor to greenhouse gas emissions. Climate change is anticipated to affect human health through diverse mechanisms including heat waves, extreme weather events, changes in air quality, impacts on ecological systems that affect food production, vectorborne disease transmission, water quality and quantity, and short- and long-term population displacement due to changing environmental conditions (McMichael, Montgomery, and Costello 2012, Confalonieri et al. 2007). In the year 2000, the World Health Organization estimated that climate change was responsible for 150,000 deaths globally each year (Patz et al. 2005). In the United States between 2000 and 2009, six climate-related events of the type projected to increase with rising global temperatures were cumulatively responsible for an estimated $14 billion in health damages (Knowlton et al. 2011).

4.6.1.3 ***<u>Tools</u>***

With growing recognition of and interest in the diverse health impacts of the transportation sector, a number of tools and processes have been developed to evaluate the potential health effects of transportation planning decisions.

Health Economic Assessment Tool (HEAT) for Walking or Cycling

The World Health Organization's Health Economic Assessment Tool (HEAT) for walking or cycling (Kahlmeier et al. 2011, World Health Organization) can be used to calculate the magnitude of mortality reduction from a given level of active transportation in a population and determine the associated economic value. The tool was designed for transportation planners, among others, in order to inform decision-making around transportation infrastructure projects. HEAT can be used to determine the value of specific levels of walking or cycling at a point in time or before and after an intervention.

HEAT combines existing epidemiological data quantifying the mortality risk reduction associated with active transportation with local data. Users enter the number of walkers or cyclers and time spent per year in either activity. Default parameters such as baseline mortality rate, projected mode share, time over which to average benefits, and locally accepted estimates of value of a statistical life can be modified. Cost information can be incorporated in order to derive cost-benefit ratios.

Currently HEAT only considers savings from mortality risk reductions associated with active transportation since epidemiological data characterizing associated reductions in morbidity is less robust. HEAT does not incorporate potential costs due to changes in numbers of injuries or morbidity and mortality from exposure to air pollution that could be associated with increased walking and cycling. Recognizing this limitation, the tools' creators state that information about air pollution risks to walkers and cyclists is currently limited and the observed 'safety in numbers' phenomenon suggests injury risk could decrease with increased walking and cycling. They cite the two studies mentioned earlier that found that risks from air pollution and injury are far outweighed by the health benefits of increased physical activity (de Hartog et al. 2010, Rojas-Rueda et al. 2011). Given an absence of strong epidemiological data in children or by gender, HEAT can only be applied to adult populations.

Integrated Transport and Health Impact Modelling Tool (ITHIM)

The Integrated Transport and Health Impact Modelling Tool (ITHIM), created by the Centre for Diet and Activity Research (CEDAR), has been developed to evaluate the health impacts of different transportation scenarios and policies via their effects on physical activity, injuries, and air pollution exposure (Centre for Diet and Activity Research). ITHIM uses a comparative risk assessment methodology to model changes in population risk associated with changes in transportation mode share and/or vehicle emissions. Unlike HEAT, which is based on changes in all-cause mortality associated with active transportation, ITHIM models transportation impacts on both morbidity and mortality from numerous chronic conditions, providing an output in disability adjusted life-years (DALYs). The output also includes changes in greenhouse gas emissions with under modeled scenarios.

ITHIM has been used to model the health impacts of transportation scenarios in England and Wales (Woodcock, Givoni, and Morgan 2013) and in the San Francisco Bay Area (Maizlish et al. 2013). Although not currently available as a tool for public use, the Excel-spreadsheet-based model can be obtained from CEDAR.

Health Impact Assessment

Health impact assessment (HIA) is rapidly gaining acceptance as a tool with which to ensure the health implications of decisions like those in transportation planning are taken into consideration during the initial design stages. HIA is grounded in the observation that many health outcomes are influenced less by individuals' interactions with the healthcare sector than by policies and interventions implemented in other sectors. The HIA process is used to evaluate the potential health impacts of a proposed plan or policy and the distribution of those impacts within a population. The process culminates in recommendations by which to minimize and mitigate adverse effects and maximize health benefits. These recommendations are provided to decision-makers in order to inform the design process prior to finalization and implementation (National Research Council of the National Academies 2011a).

HIA is rooted in a process of active stakeholder engagement and, as such, provides an opportunity for communities to participate in the planning process. Although the process consists of numerous standardized steps, the HIA is a flexible tool that can be applied to a wide variety of projects and policies using diverse methodologies and analytic tools. The ability to quantify the direction and magnitude of potential health outcomes is often a reflection of the availability of necessary population data, existing epidemiological data relevant to health impacts of interest, and the feasible scope of analysis that can be conducted within project constraints.

Community Cumulative Assessment Tool (CCAT)

Expected to be available in summer 2015, the Community Cumulative Assessment Tool (CCAT) is a computerized, step-by-step assessment method that leads users through a guided, yet flexible, process to sort through information and develop a "to-do" list of actions to address social, environmental, and economic impacts in their community, primarily focused around human health and ecological/environmental concerns. CCAT was developed by the EPA as part of its Sustainable and Healthy Communities Research Program. CCAT is a component of a larger tool, the Community-Focused

Exposure and Risk Screening Tool (C-FERST), discussed earlier in this paper, which provides a wide range of information, datasets, GIS maps, and guidance to help inform users of potential health and environmental issues in their community.

CCAT provides guidance on how to relate stressors to impacts, and provides an evidence-based scoring method to evaluate and compare a wide range of issues simultaneously and help to prioritize solutions based on the weight of a given impact. CCAT is not an exposure or risk model, but rather a decision-making support tool. CCAT includes a conceptual model builder in its computer framework, where users can assemble cause-effect flowcharts of stressors and impacts related to a particular issue, such as the range of impacts potentially associated with landfills. Transportation-related issues (focused around health and ecological/environmental concerns), for example, could include near-road air, water, or soil quality; mobile-source emissions impacts on sensitive land-use areas related to daycare facilities, schools, or healthcare centers; or an exploration of the benefits and potential impacts of a given transportation-infrastructure expansion project.

When viewed from a local-scale, community-based perspective, sustainable transportation relates to a wide variety of stakeholders and considerations. CCAT allows users to examine and compare a diverse range of issues at the same time, and therefore makes it easier to assemble a to-do list of actions to address these issues. The CCAT framework is general enough to be transferable across communities, yet specific enough to be tailored to each community and application. CCAT draws from cumulative-risk assessment methodologies established by the EPA and the broader scientific community (U.S. Environmental Protection Agency 2003, U.S. Environmental Protection Agency 2007b, National Research Council of the National Academies 2009). The ability to include and compare multiple social, environmental, and economic issues across a range of stressors and impacts provides a suitable context in which to weigh sustainability options when considering solutions to various problems (National Research Council of the National Academies 2011b).

Eco-Health Relationship Browser

The Eco-Health Relationship Browser is an interactive, web-based tool that displays published linkages between ecosystem services (benefits supplied by nature) and many aspects of public health and well-being. The Browser provides information about four of the nation's major ecosystem types, the natural benefits they provide, and how those benefits or their absence may affect human health and well-being. Ecosystems such as wetlands and forests provide a wide variety of goods and services, many of which we use every day. However, some of these goods and services, such as air and water filtration, are not only free of direct financial cost, but also “out of sight,” and so can be difficult to appreciate in terms of their relevance to people’s daily lives. The Eco-Health Relationship Browser reflects a detailed review of the recent scientific literature, with more than 300 citations in its bibliography. The most compelling research findings are summarized for dozens of public health issues. Many of the featured studies do not address causality, but document statistical associations. Plausible, proposed, and known causal mechanisms are also presented. The Eco-Health Relationship Browser is accessible through EnviroAtlas, discussed in an earlier section, and at http://www.epa.gov/research/healthscience/browser/introduction.html.

4.6.2 Social Interaction Outcomes

Transportation infrastructure and the ways in which people use it are able to produce substantial effects, both positive and negative, on how much and in what ways the members of a community interact with one another. Even though theoretical connections have been established between a community's transportation system and social interaction/isolation, the magnitudes of these impacts are challenging to quantify (Kennedy 2002).

If roadways or rail lines are designed with the primary goal of moving people and freight efficiently and at minimum cost, this system is likely to have a significant negative effect on the perceived quality of the public space in a community, leading to less use of that space, and hence less social interaction. This phenomenon is due to traffic noise, pollution, the unaesthetic appearance of the infrastructure, and the tendency of major transportation routes to divide communities into segments by forming a physical and/or psychological barrier to movement by pedestrians and cyclists perpendicular to a major roadway or rail line. Alternatively, transportation infrastructure (including bridges, public transit stops, and bicycle paths) may be designed in accordance with architectural principles that encourage social interaction. A particularly memorable, aesthetically pleasing, and enjoyable-to-use piece of transportation infrastructure may serve as a common reference point within the geography of a community, with the result that people will tend to use it as a gathering place. Regardless of whether a community's transportation infrastructure promotes or discourages social interaction, the effects are liable to be very long-lasting, as it is difficult for major infrastructure elements to be removed in their entirety and replaced with something dramatically different, as opposed to merely being modified or expanded (Meyboom 2009).

Transportation mode choice may have a significant effect on social interaction within a community, as well. Particularly, personal automobiles, more than other modes, represent a choice of private space over public space. As a result, people may become more isolated from one another and have less sense of community, and socioeconomic segregation may be more easily facilitated (Mercier 2009). Furthermore, the noise produced by automobile traffic has been found to discourage sidewalk activity in residential neighborhoods, meaning that automobiles may increase social isolation both for people that use them and for people who do not use them (Kennedy 2002). However, if someone travels for the express purpose of taking part in social activities, the speed, flexibility, security, and comfort of personal automobile travel serve to increase that person's access to opportunities for social interaction, especially in areas that have been developed at too low of a density for other modes to be practical (Kennedy 2002). Regardless, a study in Miami, FL found that residents of neighborhoods with more automobile commuters per land area tend to experience more depressive symptoms and also found that residents of neighborhoods with higher housing densities tend to experience fewer depressive symptoms (Miles, Coutts, and Mohamadi 2012).

Senior citizens eventually reach a point in time when they must either stop driving or greatly reduce the amount that they drive; hence, losing the access to social interaction that driving provided, senior citizens may especially benefit from the availability of alternative transportation modes, especially if they are unable to meet their travel needs by riding with friends and family members (Waldorf 2003). If the non-driving transportation alternatives in a community happen to include good walking environments, the resultant physical activity may also benefit the psychological well-being of older residents (Kim and Ulfarsson 2008).

4.6.3 Equity Outcomes

Issues related to equity are discussed in various sections of this synthesis paper, such as in discussions of pollution exposure, health outcomes, and transportation funding mechanisms. Rather than discuss equitability in the distribution of the effects of externalities, this subsection is dedicated to equitability in the distribution of transportation as a product that the government provides to its constituents. For the purpose of assessing equity among the various users of a community's transportation system, the most appropriate measure by which to compare those users is destination accessibility. Destination accessibility is a function of how fast people are able to travel, how cheaply they can travel, and the number and variety of desirable destinations that are located relatively close to their home or place of business. Destination accessibility is distinct from potential mobility, which merely consists of being able to easily travel a long distance at a great speed. Measures of potential mobility do not consider whether or not the journeys a person is able to make lead to places that are worth the trip. Discussing destination accessibility only in terms of a single mode of transportation would be misleading, as most people have more than one modal option (even if those options are not created equally) and may choose different modes under different circumstances or mix modes within a trip. Furthermore, while a transportation agency may directly influence the potential-mobility component of people's destination accessibility, the distribution of origins and potential destinations within a community (the other component of people's destination accessibility) is mostly outside the ability of transportation agencies to directly influence, making it necessary to also consider as inputs to any model of destination-accessibility equity the local land-use regime, economic-development activities, and the provision of various other services. However, transportation-agency actions still indirectly affect the distribution of origins and destinations, since changes in accessibility produce reactions in the real estate market, which then alter land-use patterns, producing more changes in accessibility. The resulting feedback loop makes long-term transportation equity outcomes difficult to predict. In addition, individual community members make different tradeoffs between accessibility, the cost of housing, and other considerations when they make decisions on where to live, where to work, and how to travel, meaning that a situation that may seem equitable or inequitable through the lens of destination accessibility might actually be the opposite when a wider view is taken. This represents yet another complication to account for in the evaluation of transportation equity (Martens 2012).

While one might be inclined to define an equitable transportation system as one where every user's destination accessibility is roughly equal, the fact that urban areas tend to organize themselves into cores and peripheries (with the core usually having access to more destinations than the periphery) suggests that transportation planners must accept the existence of at least some variation in the destination accessibility of different individuals and groups of individuals. In that case, seeking to simultaneously maximize the average level of accessibility among community members and keep the difference between worst accessibility and best accessibility under a certain limit may be advisable.

Alternate ways of achieving an equitable distribution of accessibility include distribution according to need and distribution according to merit (wherein destination accessibility is considered a "reward" for some "burden," such as living someplace undesirable). Neither of these ways of looking at equity is well-suited to transportation questions, though. Distribution by need would encounter the complication of distinguishing between "need" and "want," as well as differences in need among people who would equally benefit from a transportation project and changes in people's relative levels of need that occur faster than the transportation sector can respond. Meanwhile, merit-based distribution would require making an inherently subjective judgment of what is a "burden" and what constitutes an appropriate "reward" (Martens 2012).

One of the most important indicators contributing to measures of destination-accessibility equity within a transportation system is how much it costs to use the system. Because traveling by automobile is usually costlier than traveling by public transit, low-density cities with automobile-dependent transportation systems are not very equitable; low-income travelers will have to either spend a large percentage of their earnings on automobile transportation or travel on an underfunded and inefficient public transit system (Mercier 2009), bearing in mind that even the public transit systems in cities that are not particularly automobile-dependent do not necessarily serve all of the destinations that a given transit-dependent individual may require (Berechman and Paaswell 1997). Furthermore, the societal costs of traveling by private automobile are not as internalized as those of other modes of transportation, which is another form of inequity (Sinha 2003) (i.e., drivers do not "pay for" the cost to the broader tax base of motor-vehicle infrastructure on their own, or for negative externalities like pollution).

Even when two neighborhoods provide the same amount of access to modes of transportation other than private automobiles, there may still be transportation inequalities between them. If two neighborhoods are equally walkable in terms of their density, land-use mix, street connectivity, and access to transit, the richer neighborhood is likely to have better aesthetics, better pedestrian safety features, and other amenities that make pedestrian travel a more attractive prospect. Though the walkability of a neighborhood (measured in terms of density, land-use mix, street connectivity, and access to transit) is strongly correlated with the amount of physical activity its residents get, reduced aesthetics, safety, and amenities dampen this effect. This may partially account for higher rates of health problems that are associated with insufficient physical activity in high-poverty neighborhoods (Neckerman et al. 2009). In addition, residents of different neighborhoods with comparable access to transportation do not necessarily have comparable access to destinations.

Two other dimensions of transportation equity are the international and intergenerational aspects. For example, even though North America is only home to 5% of the world's population, it accounts for 40% of worldwide transportation energy use (Mercier 2009). Also, the negative externalities of transportation policy decisions are often not felt until a later generation than the one in which they are implemented (Loo and Chow 2006).

More research is still needed on how accounting for racial segregation would change models of future population and employment distribution and models of future land use patterns. More research is also needed on how a given geographic area may derive an economic advantage over another geographic area from the particular mix of jobs that it has, as opposed to its total level of employment (Carruthers and Vias 2005). If verifiable answers are provided to these research questions, which have clear equity implications, those answers could provide additional guidance in the setting of transportation policies that have equitable outcomes.

4.7 Economic Issues and Related Tools, Resources, and Indicators

Before considering the specific case of how transportation-related government actions affect the economy, familiarity with several concepts that may be applied to analyzing the economic impacts of any government action is advisable. The following are some such concepts (U.S. Environmental Protection Agency 2010b):

- *Benefit-Cost Analysis (BCA)*: A method of calculating the net benefits to society produced by a given action, regardless of which specific individuals within society experience the benefits of the action and which ones experience the costs. The results of a benefit-cost analysis are considered to support a particular government action if they conclude that the benefits accrued from the action are greater than the costs imposed, regardless of who experiences the benefits and who experiences the costs. In isolation, this kind of analysis is blind to issues of equity.
- *Willingness to Pay (WTP)*: The greatest amount of money that either a person or a collection of people would be willing to part with in order to either bring about a "favorable" government action or prevent an "unfavorable" government action.
- *Willingness to Accept (WTA)*: If a particular action would be detrimental to a given individual or group, this is the minimum amount of compensation that they would agree to receive in exchange.
- *Baseline*: Describes the future scenario that would occur if no changes are made to the status quo (i.e., "business as usual"). Preferably, any scenario would be projected out to a time when the adjustment periods related to any changes in the status quo have passed and a new state of economic equilibrium has been reached.
- *Kaldor-Hicks Criterion*: This criterion describes a situation that is favorable to initiating a given change in the status quo. The expected beneficiaries of a proposed change may incentivize the expected cost-bearers to compromise and allow the change to take place; in this case, the minimum amount of compensation must be less than the maximum the beneficiaries of the change are willing to provide. Likewise, the expected cost-bearers may incentivize the expected beneficiaries to maintain the status quo; in this case, the minimum value of the incentive must be greater than the maximum the people providing it are willing to sacrifice.
- *Economic Impact Analysis (EIA)*: Disaggregates the analysis of the benefits and costs of a government action to the scale of individual sectors of the economy or individual entities and institutions. This may include looking at effects on specific industries, specific governmental units, nonprofit organizations, individual companies, and the consumers and suppliers of given

products. This kind of analysis delineates which parties benefit from a government action and which ones lose from it.

- *Equity Assessment*: An analysis of the benefits and costs of a government action that are experienced by specific subpopulations, especially those that are regarded as disadvantaged.
- *Standing*: If the potential effects of a particular government action on a given party are significant enough to be considered in the economic analyses of that government action, the party in question is regarded as having "standing." Ideally, an economic analysis would grant standing to all individuals who have any potential of being affected. However, for practical purposes, standing may not be granted to those who are assumed to only be very remotely affected, such as residents of foreign countries.
- *Externalities*: Benefits and costs of an action that are experienced by those who are not directly connected to it (e.g., air pollution is a negative externality, while a pleasant view of green infrastructure would be a positive externality).
- *Opportunity Cost*: The value that would be derived from the best of any of the alternatives to a given course of action (not always reducible to monetary terms). This is the value that someone accepts missing the opportunity to receive whenever they choose between mutually exclusive alternatives. Choosing a given course of action is only advisable if the value derived from that course of action is greater than the opportunity cost (i.e., the opportunity provides more value than any alternative would).
- *Discounting*: An analytical operation that equates the value of some amount of future economic consumption to the value of some lesser amount of present-day consumption. Due to considerations of uncertainty about the future, inflation, and opportunity costs, people generally prefer to receive a given quantity of benefits in the present than to wait to receive that same quantity of benefits sometime in the future, meaning that benefits that occur in the distant future are valued less, or discounted, relative to benefits that occur in the near future. Since the buying power of a dollar generally goes down over time, spending and investing both provide more value than simply saving. If someone owns an object that they do not use and which physically degrades over time (such as an unoccupied house), they receive more value from selling it now than from waiting to do so. An investment that takes one year to turn a profit is more attractive than an investment that takes twenty years to turn a profit, since the profits from the former investment could be reinvested sooner, resulting in more profits (opportunity cost). The longer it takes for an investment to pay out, the more opportunities there are for unforeseen events to reduce the odds of making a profit (natural disaster disrupts operations, economy goes into recession, etc.). However, if anticipated future benefits from a given action sufficiently exceed a theoretical set of near-term benefits, people will regard the two as equally attractive. Since different alternative courses of action yield their benefits and costs over different amounts of time after they are initiated, translating all of them to the amount of present-day benefit or cost they are regarded as being equivalent to enables direct comparisons. They are all converted to their *Net Present Value (NPV)*. When it comes to natural resources that either are nonrenewable or renew very slowly, this practice could become problematic.

- *Cost-Effectiveness Analysis (CEA)*: If a given government action is intended to produce a specific quantifiable benefit, the result of a cost-effectiveness analysis is the ratio of dollars spent on the government action in question per unit of change in whatever measure is used for the quantifiable benefit under consideration (i.e., bang per buck).

When considering a new, altered, or expanded transportation system, several basic questions of an economic nature must be considered, including (Sastry 1973):

- How many people will use the system?
- How will changes to the transportation system alter forecasts of future population distributions and land use patterns?
- Will business activity near the transportation infrastructure be discouraged, encouraged, or otherwise shifted?
- If business activity is shifted, what neighborhoods will respectively suffer and benefit? What will be the effect on the local real estate market?
- What environmental and aesthetic impacts will the transportation system produce that might affect the economy?
- Going beyond just the local area around new transportation connections, what impact will those new connections have on the state of the regional economy?
- What impact will a transportation project or policy have on the size of the tax base for a given jurisdiction and how does that impact compare with any governmental expenditures resulting from the project or policy?

When economic analyses are carried out to address the above questions for a particular transportation project under consideration, varying the extensiveness of the analysis in proportion to the size and cost of the project being proposed is well-advised. Upon carrying out such analyses, which generally require very large datasets, the step of determining economic costs and benefits must be preceded by the step of defining the population and employment bases for which costs and benefits will be considered. Then, costs and benefits must be considered that are both of a quantifiable and of an abstract nature. The most quantifiable items in an analysis of a transportation infrastructure project are the costs of capital, maintenance, and administration, which must be paid by the agency responsible for the project. More abstract costs may consist of environmental and societal impacts, while major components of a project's benefits include increases in travelers' access to various types of destinations (which is independent of how far away those destinations are), their overall mobility across the landscape (which is independent of how many worthwhile destinations occupy that landscape), safety improvements, and the reduction of environmental impacts. However, the most critical source of economic costs and benefits from a transportation project is its effect on area-wide traffic patterns, preferably expressed in the form of link-by-link forecasted traffic volumes for each alternate scenario contemplated. Not only must costs and benefits be identified for the entire area impacted by a transportation project, but also for the entire timeframe of the project's useful life (Shadewald, Hallmark, and Souleyrette 2001).

The potential benefits and costs of transportation projects and policies that are listed above may be referred to as direct economic impacts, which may produce any number of indirect impacts. Both direct and indirect effects must be considered in order for an economic analysis to be complete. One of the most noteworthy indirect effects of transportation projects is when development is attracted to an area by the reduced transportation expenditures that follow from increased accessibility. However, such increases in development activity often result in air pollution, noise pollution, and other such deterrents to development in close proximity to heavily-used transportation infrastructure (Hof, Heyma, and van der Hoorn 2012, Jha and Kim 2006). Land use impacts from transportation projects and policies, as well as other indirect effects, typically come about over a period of years and are difficult to estimate. The long-term, indirect effects of new rail transit projects are especially difficult to predict, since very few case studies exist of such projects that have been in existence long enough for all of their economic impacts to have manifested (Polzin 1999, Szeto, Jaber, and O'Mahony 2010). One reason that the overall economic impacts of transportation projects are so uncertain is that performing benefit-cost analyses runs the risk of some effects being double-counted, as indirect benefits and costs are not necessarily additive (Hof, Heyma, and van der Hoorn 2012). Meanwhile, some effects are simply neglected in the analysis or not quantified.

According to a study of economic models from the Netherlands (Hof, Heyma, and van der Hoorn 2012), direct economic effects from transportation projects may be significantly greater than the indirect effects of the same projects. However, even if this conclusion holds true in other settings and with other models, identifying direct and indirect impacts would still help to keep effects from being double-counted. Models would be useful that feature a “quick scan” function that estimates whether or not a proposal’s indirect effects would be great enough to warrant taking the extra time necessary to produce a detailed estimate of those effects (Hof, Heyma, and van der Hoorn 2012). Other beneficial model attributes include:

- The consideration of travel into and out of the study area (Hof, Heyma, and van der Hoorn 2012).
- The representation of both personal travel and freight travel (Hof, Heyma, and van der Hoorn 2012).
- The anticipation of as many of the reasons for which people travel as possible (Hof, Heyma, and van der Hoorn 2012).
- Accounting for people valuing their time in different ways (Szeto, Jaber, and O'Mahony 2010).
- Showing how changes to the transportation network may result in changes in the distribution of land uses, which results in changes in the distribution of traffic volumes, which may necessitate further changes to the transportation system (Szeto, Jaber, and O'Mahony 2010).
- Modeling the elasticities of housing demand and housing supply for the determination of land use effects (Szeto, Jaber, and O'Mahony 2010).
- Allowances for uncertainties in demand and supply (Szeto, Jaber, and O'Mahony 2010).
- The calculation of tradeoffs between the interests of various parties, including unequal changes in landowners’ profits (Szeto, Jaber, and O'Mahony 2010).

- Modeling activity on the various links within a transportation network instead of modeling all of the paths that may be traveled between origins and destinations within that network, as the use of path-based modeling on large networks is burdensomely complex (Szeto, Jaber, and O'Mahony 2010).
- Making it so that transportation models that address different geographic scales have consistent units, inputs, and assumptions, so that the outputs of large-scale models may be used as inputs for the small-scale models (Hof, Heyma, and van der Hoorn 2012).
- Modeling that is based on empirical observations and describes the path that all relevant measures take from the starting year to the ending year of the model simulation, in contrast to many current models of the economic effects of transportation projects and policies (Hof, Heyma, and van der Hoorn 2012).

4.7.1 Accessibility

Changes in accessibility are considered to be one of the most fundamental economic impacts stemming from transportation projects and policies; the primary purpose of most transportation projects and policies is to decrease the amount of time and money required by people and businesses to meet their travel requirements. A few basic methods exist by which accessibility may be enhanced. First, a transportation project may increase the number of people who have the option of traveling to a given location, such as by extending a new transit line to a previously unserved commercial district and allowing transit-dependent individuals to become customers and workers there. Second, improvements to the transportation system may increase the percentage of the local population that is able to reach a given location within a given travel time, such as by reducing traffic congestion. Third, a transportation project may provide travelers with value in the form of an additional option for how to travel. Even if the new option is not necessarily superior to existing options, simply having an expanded range of choices may be regarded as beneficial (Polzin 1999). Finally, a transportation project or policy may open up a travel option that is not faster, more flexible, or more comfortable than preexisting options, but which is cheaper than those other options and frees up the opportunity cost of paying for them (Kennedy 2002). At the same time, though, travel is not purely a derived demand. While arriving at given destinations in a timely and cost-effective manner is still the primary reason that people travel, they also derive at least some value from the act of traveling itself, meaning that people may be willing to trade some amount of accessibility in exchange for a more pleasant travel experience (Loo and Chow 2006, Polzin 1999). Furthermore, value may be derived from working (or doing some other worthwhile activity) while traveling, such as during the commute to and from an individual’s place of employment, effectively making the commute part of the workday (Gripsrud and Hjorthol 2012).

4.7.2 Announcement Effect

The “announcement effect” is when land prices around a transportation infrastructure project increase before anything has actually been built, in anticipation of a future increase in accessibility. So far, there has been little research on how to calculate the timing of the announcement effect (Tsutsumi and Seya 2008).

4.7.3 Non-Accessibility Benefits from Transportation Projects

The primary intended economic benefits from transportation projects usually consist of providing faster, cheaper, and/or more convenient travel for a greater number of people and businesses, with fewer externalities. However, such projects may also produce other economic benefits, whose influence may be difficult to distinguish from that of the transportation-related benefits. Government intentions to invest in the transportation infrastructure of a given area may convince businesspeople to invest their own money in the area as well, with the first wave of new investors inspiring additional investors. This effect may be enhanced by efforts of the government to promote the economic advantages of the transportation project. However, if the transportation infrastructure in a particular area is built up at too much faster of a pace than nearby land development, the apparent mismatch may discourage private-sector investment (Polzin 1999).

Some transportation infrastructure projects are initiated in conjunction with other policy actions that serve the purpose of making investment in the area around the transportation project more attractive. For example, the government may choose to expedite the approval process for nearby development proposals, reduce relevant fees, change the local land-use zoning map, increase maximum building densities, alter parking requirements, provide tax incentives, or locate other types of government facilities in the same area. The government may also choose to use the power of eminent domain to buy properties near the transportation project for resale to developers who would not have been able to gather the land needed for their planned buildings on their own. Furthermore, the presence of a new transportation project may serve as a rallying point to inspire government actors to institute unrelated improvements in the area. This may include beautification projects, historic preservation efforts, increased public lighting, increased police presence, or increased trash service. In some cases, the complementary policies stemming from a transportation project will affect a jurisdiction far larger than the immediate area around the project (Polzin 1999).

Other non-transportation economic effects may arise unintentionally from the implementation of a transportation infrastructure project. For example, when the government buys land for the right-of-way of a transportation project, the entire property must be purchased, even if only a portion is needed. Selling the part of the property that they do not need can produce an economic benefit. Similarly, public building projects may require that some plots of land be purchased strictly for the temporary purpose of holding construction equipment and materials. This land, too, is likely to be resold when the project is finished (Polzin 1999).

4.7.4 Agglomeration Effects

When a transportation project increases the profitability of doing business in a given area, either by reducing the cost of transportation or other means, more money will likely be invested in that particular area, with new businesses moving in and preexisting businesses increasing their presence. In addition, as a particular kind of business increases its presence in an area, businesses that are complementary may be motivated to locate in the same area, as proximity reduces transportation costs. As businesses become agglomerated in a particular area, whether around a transportation facility or some other initial focal point, greater competition arises between businesses, resulting in lower prices and smaller profit margins. However, if improvements to the transportation system increase the number of businesses within range of the same customer base, those businesses have greater opportunities to differentiate their products from their competitors' products, potentially allowing higher prices and higher profits. Therefore, the same initial event may produce drivers of low prices and drivers of high prices at the exact same time (Hof, Heyma, and van der Hoorn 2012). The concentration of businesses in a given area also increases land-use diversity and destination accessibility within that area, which, as discussed earlier in this paper, are factors that encourage the use of modes of transportation other than the private automobile. However, if businesses become concentrated in one part of a region at the expense of others, regional land-use diversity and destination accessibility may be reduced.

4.7.5 Regional Adjustment Model

Both jobs attract people to an area and people attract jobs to an area, although much is still unknown about the exact nature of this relationship (Kim 2007). Consequently, assessing the economic sustainability of transportation decisions would be greatly aided by the use of a tool that can untangle the connections between population changes and employment changes. A regional adjustment model consists of two separate equations describing the migration of people and jobs in and out of a given area, with changes in population and changes in employment both being functions of the starting values of population and employment and any number of additional variables, such as measures of ecosystem services, infrastructure provision, and beneficial government policies. This type of model uses a positive feedback loop, where jobs and people both follow each other, as opposed to employers locating jobs wherever they like and then counting on workers to move to the area. One of the implications of this dynamic is that non-job-related amenities (which elements of the transportation system may either create or destroy) in a given area may attract more residents and subsequently more jobs (Carruthers and Vias 2005, Kennedy 2002). Under this theoretical construct, the economy is taken to be in a state of partial equilibrium, constantly readjusting towards an ideal spatial distribution of people and jobs, which is never actually reached, on account of shocks to the economic system (Carruthers and Vias 2005). Furthermore, because some people may be willing to accept worse job prospects in exchange for good location-specific amenities (such as natural environments and vibrant communities) and other people may be willing to accept living in an amenity-poor area in exchange for a high income, a state of equilibrium in the distribution of people and jobs would not necessarily appear homogenous (Carruthers and Vias 2005). The mutual causality between population and employment levels has not been firmly established at all geographic and time scales, with the greatest evidence found at the very-large-region scale (i.e., consisting of several states or provinces within a country) (Carruthers and Vias 2005). Most likely, the interactions between population and employment levels vary from region to region, meaning that different regions need to have different models. Ideally, each region's model would consider interrelationships with other regions (Carruthers and Vias 2005).

4.7.6 Models of Transportation-Infrastructure Land Use and Other Land Uses

The Solow and Vickrey model describes the relationship between traffic volumes, real estate values, and the amount of land dedicated to transportation infrastructure in an urban area in simplified terms. Using economic principles, this model concludes that land rents do not typically fully reflect the transportation advantage enjoyed by properties at the center of an urban area. This subsequently affects the distribution of transportation demand throughout the urban area, with the result of an unnecessarily large number of lane-miles of roads being built, most especially at the center of the urban area. A variation on the Solow and Vickrey model, the Legey, Ripper, and Varaiya model, goes on to predict that in a city where a central authority does not allocate land in a manner contrary to market forces, not only will too many resources be dedicated to transportation at the urban center, but there will also be too many resources dedicated to housing along the outer edges of the urban area, a finding which one may interpret as describing market-based drivers of urban sprawl. In another variation on the Solow and Vickrey model, attention is given to the case of a city laid out in a circular pattern. In this scenario, the transportation system would be optimized by a balance between radial roads leading out from the center of the urban area and several progressively larger ring roads that encircle the center and intersect with the radial roads. Meanwhile, another study adapted the Solow and Vickrey model to the scenario of a square city with streets that all intersect at right angles. In this case, the model showed that the amount of land dedicated to transportation infrastructure would be excessive in all parts of the city, with the worst of the overbuilding of roads occurring along the edges of the urban area, instead of the center; at the same time, the center of the urban area would still experience the highest rents. Finally, adaptation of the Solow and Vickrey model shows that if an urban area is polycentric, whichever of its multiple centers is the most central will experience the greatest amount of traffic. Consequently, that particular center will most likely be the one that is the most heavily developed and the one where the greatest amount of land is required for transportation infrastructure (Medda, Nijkamp, and Rietveld 2003).

4.7.7 Market Imperfections

An imperfect market is one in which the price of a product, such as transportation, is either unequal to the cost of supplying it or unequal to the value derived from it by the buyer. Most markets are imperfect and may come to be that way either through government actions (subsidies, taxes, etc.) or through private-sector actors exerting market power that comes from economies of scale. When market imperfections exist, they prevent the theoretical economic effects of a transportation project from being realized in their entirety. For example, zoning laws and other land-use regulations constrict the reaction of the real estate market to changes in the transportation system. Also, if a company either has a monopoly or is part of an oligopoly, they are less likely to pass on to customers the savings from a reduction in transportation-related expenses. However, transportation improvements may also mitigate existing market imperfections. If a transportation project triggers an agglomeration effect, those companies that are consequently placed in more direct competition with one another are forced to make the prices of their products more closely reflect the cost of providing them. Furthermore, a transportation project may create market imperfections, for either good or bad, by way of benefits being derived from something in a non-transaction manner. An example is when a transportation system benefits someone who is not part of the tax base that supports the system, or whose tax payments going to the transportation system are not proportional to their use of that system (Hof, Heyma, and van der Hoorn 2012).

4.7.8 Import Substitution

If one is primarily concerned with the economic well-being of a specific geographic region, such as a metropolitan area, considering the distinction between transportation expenditures that are paid to parties within the same local economy and those that are paid to outside parties is important (for example, depending on location-specific circumstances, one may drive a plug-in electric vehicle whose energy source is a potentially-local power plant instead of driving a gasoline-powered vehicle whose fuel may come from a refinery in a different state, or one may buy a car at a local dealership instead of going out of town to shop for a vehicle). If the latter expenditures are too great, it may contribute to a trade imbalance, hurting the local economy. Furthermore, even if a given area currently has a trade balance with the outside world, a lack of diversity in its exports or an inability to meet its own needs by way of internal sources may still produce a state of inflexibility that will endanger the local economy in the future. If the area in question contains a car factory, for example, a portion of the money that residents spend on automobiles will eventually contribute to the wages of local workers. When it comes to import substitution, public transit has an advantage over travel by private automobile. Wages paid to employees living in the transit system's service area may represent a significant portion of the money that the local government spends on public transit, and the local government may choose to favor locally-based companies when deciding where to buy transit vehicles and other products necessary to the operation of the transit system (Kennedy 2002).

4.7.9 Cost-Effective Use of Government Budgets

In order to spend transportation-related funds in a cost-effective manner, tradeoffs must be considered between different kinds of costs. An example of such a tradeoff is when a government entity spends money to build a bridge across a body of water and is consequently able to end a previous practice of subsidizing ferry service across that body of water (Hof, Heyma, and van der Hoorn 2012). Another important area for tradeoffs is the Level of Service (LOS) that exists on freeways and arterial streets. Urban freeways are expensive to build, requiring large amounts of land and building materials, and are often designed with the primary goals of achieving a high free-flow speed and accommodating heavy truck traffic. Achieving these design goals requires the creation of shoulders on the road and wide traffic lanes. The result is fewer total traffic lanes and a smaller traffic volume that can be accommodated, potentially resulting in economic costs from traffic congestion. If a particular urban area generates very high traffic volumes during the peak travel periods of the day, and a relatively small percentage of overall vehicle traffic consists of trucks, having a greater number of narrower traffic lanes may be more cost-effective than a smaller number of wider lanes, choosing the economic benefits of optimizing peak-travel-period traffic volumes over the economic benefits of optimizing off-peak traffic speeds. Going farther, in some highly congested areas, the travel-time savings of having freeways instead of non-limited-access, unsignalized arterial streets may not produce enough economic benefit to offset the added expense of building freeways. However, freeways also tend to have lower accident rates than ordinary arterial streets, which may save the government enough additional money to make freeways cost-effective (Ng and Small 2012).

Maintaining a transportation system will be far more cost-effective for the government if it takes advantage of economies of scale. If a large number of destinations and transportation-system users are densely concentrated in a small geographic area, their travel needs can be met at a low cost per capita or per ton of freight, such as when companies agglomerate around a major seaport (Hof, Heyma, and van der Hoorn 2012). The cost-effectiveness benefits of high development densities are especially noticeable in the case of public transit systems. There are certain thresholds of development density required for economically feasible operation of fixed-route transit systems (Kennedy 2002). However, more research is still warranted to arrive at better estimates of these thresholds. The question of what minimum development density may justify introducing public transit service may have different answers in different contexts, such as monocentric and polycentric urban areas, or different-size of jurisdictions (Kennedy 2002).

Other economy-of-scale benefits can be derived from the size of the government agency in charge of a given transportation network. If an organization has a frequent need for a specific asset (such as concrete or vehicle-fleet maintenance services), the organization will seek to reduce the uncertainty and transaction costs associated with purchasing the asset. To do this, the organization will tend to favor transitioning from buying the asset on the open market to buying it from a contractor on a standing basis and then transitioning to providing the asset in-house. However, the benefits of reducing uncertainty and transaction costs in this manner are offset by the overhead costs associated with supplying an asset in-house. If an organization is large enough, economies of scale can reduce the overhead cost per unit of a repeatedly needed asset. As a result, providing or producing the asset within the organization becomes more economical, or, if in-house provision is not practical, the organization uses the promise of a large-volume order to get a contractor to agree to a low per-unit price to supply the same asset (Mercier 2009).

4.7.10 Equity in Transportation Funding Mechanisms

Two of the most common ways of perceiving the equitability of how a transportation system is funded include: (1) how proportionate someone's contribution is to the amount of value they get from the system and (2) how regressive the funding scheme is in terms of the percentage of a person's income that is required. Aside from a progressive income tax, most of the ways in which a government entity may collect revenue are regressive, likely requiring low-income people to pay a larger percentage of their earnings than what high-income people must pay. Therefore, if potential transportation funding mechanisms are to be analyzed in terms of their regressiveness, asking whether a given mechanism is more or less regressive than its alternatives may be more appropriate than simply asking whether the cost is regressive at all. Meanwhile, the question of whether or not the amount people pay for the use of a transportation system and the amount of use they receive from it are proportional becomes more relevant in cases where use of the transportation system produces significant negative externalities, such as noise, air pollution, or accidents. If the amount someone pays for a service is little affected by how much they use it, they are likely to use it more than they otherwise would, resulting in an increase in any associated externalities. Common ways of funding surface transportation infrastructure include fuel taxes, vehicle registration taxes, vehicle sales taxes, general sales taxes, and tolls and fares. All of these options are regressive to some extent, but fuel taxes, tolls, and fares are mostly proportional to people's usage of the transportation system. Fuel taxes, though, have a difficult time keeping pace with the demand for transportation-infrastructure revenue, thanks to increases in motor vehicles' fuel efficiency and the phenomenon of fuel taxes being set as a fixed amount of money per gallon instead of a percent of the price of the fuel purchase. General sales taxes are both regressive and blind to the relative amounts that people use the transportation system, placing the greatest cost burden on infrequent users of the system. However, because sales taxes spread the cost of transportation infrastructure across a very large number of individuals, are paid in numerous small increments over the course of a year, and are easy for the government to collect, these are often seen as a more attractive option than road tolls, even by people who would ultimately pay more in transportation-related sales taxes than they otherwise would in tolls and fees. Nonetheless, if a roadway system is funded through tolls and low-income people retain the option of traveling by cheaper means than a toll road or toll lane (such as riding on public transit), most tolls will be paid by middle-income and upper-income individuals, making road pricing potentially less income-regressive than other funding schemes; however, this could still leave low-income individuals traveling by slower means than other people (Schweitzer and Taylor 2008).

4.7.11 Economic Analysis Software for Transportation Planning

The Federal Highway Administration (FHWA) has put out several different software programs that analyze the economic impacts of transportation project alternatives, including the Spreadsheet Model for Induced Travel Estimation (SMILE) and the Sketch Planning Analysis Spreadsheet Model (SPASM). The ITS Deployment Analysis System (IDAS) and the Surface Transportation Efficiency Analysis Model (STEAM) focus on the estimation of system-wide impacts and include default values for the economic costs of parameters such as vehicle emissions, fuel consumption, and traffic accidents (Shadewald, Hallmark, and Souleyrette 2001).

Iowa State University's Center for Transportation Research and Education (CTRE) created an interface between the GIS platform ArcView and the transportation demand model Tranplan. In combination with a program such as FHWA's STEAM, an interface like this can be used in the early planning stages of a transportation project to compare alternative and base design scenarios through visual representations. One may map the economic benefits that an alternative scenario will produce for different districts within a study area, allowing analysis of economic equity issues (Shadewald, Hallmark, and Souleyrette 2001).

5 EXAMPLE APPLICATION OF SUSTAINABILITY PRINCIPLES AND ASSESSMENT TOOLS: COMPLETE STREETS

This section assesses the sustainability of transportation policies and practices related to "Complete Streets" design principles and compares them with more typical urban designs, oriented around personal vehicle use, that have predominated development in the United States for many years. This comparison highlights many of the sustainability principles presented in this paper, as well as the assessment tools described. This comparison also demonstrates the consideration of transportation and other land-use decisions through a systems approach to account for the multiple benefits, and potential costs, of transportation-related decisions, including the indication of tradeoffs, co-benefits, and mitigating factors. The complete streets principles examined here are increasingly used in communities to address growth management, economic development, and multi-modal transportation issues.

When a transportation corridor is designed in accordance with the principle of "Complete Streets," it is designed to accommodate multiple modes of transportation, typically including private automobiles, public transit vehicles, cycling, and walking. This type of design may also include other benefits and amenities, such as green stormwater infrastructure, park-like elements, sidewalk dining, or on-street parking. Design elements that may serve this purpose include frequent intersections, traffic calming measures, other non-automobile-oriented safety features, features that make travel by a given mode more comfortable even if they do not make it safer, a compact development pattern, mixed land uses, and having building set back as little as possible from the property line. However, the most central element of Complete Streets is how much of a transportation corridor's cross-section is available for use by each specific mode and to what degree those modes are kept out of conflict with one another. Due to the development of adjoining private properties, most transportation corridors cannot be widened indefinitely; therefore, the amount of transportation-corridor width dedicated to each mode must be traded off with one another.

One of the most prominent benefits attributed to Complete Streets is safety from vehicle-pedestrian and vehicle-cyclist collisions. Roads that do not include facilities for pedestrians (sidewalks) or cyclists (bike lanes and shoulders) will likely still be used by at least some pedestrians and cyclists, especially those who do not have the option of motorized travel. Pedestrians and cyclists who travel along roadways that are designed only for motor vehicles face a greater risk of being involved in traffic accidents than they would if the transportation corridor's cross-section included segregated facilities for each mode. Furthermore, the replacement of ordinary vehicle traffic lanes with medians, turning lanes, and/or on-street parking makes it safer for pedestrians and cyclists to cross intersections, as it reduces the amount of time they must spend crossing motor-vehicle lanes. The effects of transportation policies and practices on accident rates, as well as other public health outcomes, can be assessed using the Integrated Transport and Health Impact Modelling Tool (ITHIM).

Since reductions in the safety, comfort, and convenience of a given mode inhibit the destination accessibility of individuals who already have limited modal options (for reasons such as household budget or physical disability/infirmity), a transportation system that accommodates as many modes as possible provides an equity benefit.

If Complete Streets practices succeed in making travel by modes other than the private automobile safer, easier, and more pleasant, the result may be increased usage of these alternative modes and decreased usage of private automobiles, especially if capacity constraints reduce the average speed of automobile travel (Figure 2). Verification of these effects may be aided by various transportation behavior models, some common (but not universal) elements of which include travel time budgets (Figure 3) and the conventional four-step transportation modeling process of first determining the number of trips that people will make, then those trips' destinations, then mode choices, then route choices. Some examples of such models include the EPA's Smart Growth Index (SGI), the Multiclass Simultaneous Transportation Equilibrium Model (MSTEM), CONTRAM, and the Unified Mechanism of Travel (UMOT).

As discussed throughout this paper, numerous benefits would follow from such a shift in modal shares, including decreased transportation-energy use, decreased tailpipe emissions (including both greenhouse gases and chemicals that more directly affect human health), increased levels of physical activity, reduced traffic-related noise pollution, and decreased levels of social isolation (especially if the resulting pedestrian facilities are aesthetically pleasing and conducive to personal interaction). However, even if overall emissions of air pollution from motor vehicles are reduced, Complete Streets practices may simultaneously increase exposure to those emissions by encouraging the construction of buildings closer to roadways and placing pedestrians and cyclists (who breathe in more air per period of time than do motor-vehicle occupants) in close proximity to vehicles' tailpipe emissions for the duration of trips that take more time to complete than they would if taken by motor vehicle. Changes in energy use and greenhouse gas emissions resulting from a given shift in transportation behavior may be assessed using the EPA's MOtor Vehicle Emission Simulator (MOVES) model or California's EMFAC, models that consider the composition of the vehicle fleet whose use is being affected. Also useful in this task are assessment tools that use greenhouse-gas footprint methodologies and/or consider life-cycle emissions impacts, such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, the Lifecycle Emissions Model (LEM), GHGenius, and Economic Input-Output Life Cycle Assessment (EIO-LCA). Meanwhile, emissions and transport of a variety of other transportation-related airborne pollutants may be assessed using the EPA's Community Multiscale Air Quality (CMAQ) model. Evaluations of the health impacts of modals shifts to walking and cycling may be aided by the Health Economic Assessment Tool (HEAT) and by ITHIM. Useful tools for assessing a broader range of health impacts from transportation policies and practices may include Health Impact Assessments and the EPA-developed Community Cumulative Assessment Tool (CCAT).

A community may choose to enact Complete Streets policies and practices for economic reasons. If the number of available modal options for reaching a given commercial district is increased, a greater number of people will have an easy time getting there, theoretically increasing their patronage of the businesses within that district. Furthermore, since Complete Streets principles encourage mixed land uses and minimal setbacks of buildings from their property lines, the benefits of agglomeration economies may also be realized. However, if dedicating more of a transportation right-of-way to non-automobile modes too greatly reduces the convenience of automobile travel, travel to a given district by that mode could conceivably be reduced by a greater amount than use of other modes is increased. In that event, economic activity in that particular district could suffer. The assessment of economic outcomes may be aided by the programs SMILE, SPASM, IDAS, and STEAM, all put out by the FHWA, and by the tools of benefit-cost analyses, economic impact analyses, equity assessments, and cost-effectiveness analyses.

Depending on what design elements are incorporated, Complete Streets has the potential to produce benefits that are independent of how people use the transportation system. Trees, grass, and other forms of vegetation may be incorporated into medians and pedestrian facilities. Such features may mitigate the detrimental effects of stormwater runoff from impervious surfaces (such as paved transportation facilities) and absorb a portion of the greenhouse gases emitted during the combustion of transportation fuels. Furthermore, if it would not be practical to use pervious paving materials in the construction of motor-vehicle lanes on a particular roadway, those materials might instead be used for other surfaces within the transportation corridor, such as shoulders, sidewalks, and bike lanes. Finally, because Complete Streets encourages a compact development pattern, it may lead to greater efficiency in the provision of various public services, such as the distribution of drinking water, the collection of wastewater, and the provision of fire and police services. The effects of particular Complete Streets designs on stormwater runoff effects could be evaluated using the EPA's Storm-Water Management Model and the commercially-available HYDRUS. The assessment of water-infrastructure outcomes may be aided by commercial design packages such as SewerCAD and StormCAD, as well as the development of a water footprint index, comparing water usage with water availability. The degree to which vegetation in a transportation right-of-way mitigates CO_2 emissions may be assessed using greenhouse gas footprint analysis.

Other tools discussed in this paper that may aid in the assessment of sustainability outcomes in scenarios that do or do not feature Complete Streets practices include, but are not limited to, LEED-ND, INVEST, and the EPA-developed DOSII, DASEES, C-FERST, Tribal-FERST, TRACI, EnviroAtlas, and Green Communities Program.

6 IMPORTANT INFORMATION GAPS

The following is a compilation of important information gaps described by cited researchers and highlighted throughout this report. This section has been organized to highlight issues raised in the previous discussions rather than consolidate and integrate the research needs in order to provide the summary in order of topics presented and avoid confusion or oversimplification that may occur when consolidating these issues.

From "*Tools, Resources, and Indicators for Assessing Sustainability*" (Opening) Section

- Insufficient understanding of the measurement of sustainability in the regular functions of a transportation agency (Ramani et al. 2011).
- Uncertainty in the inputs of transportation and land use models (Duthie et al. 2010).
- Insufficient understanding of how the built environment affects pedestrian and bicycle travel, as opposed to motorized transportation (Cervero and Duncan 2003).

From "*Drivers of Transportation Behavior*" Section

- Research to date has given little attention to the travel-behavior effects of the land uses that surround a person's place of work, as opposed to those that surround their place of residence (Frank et al. 2008).
- The phenomenon of induced demand is not well understood, would require very complex theories to model, and is not incorporated into standard travel demand forecasts (Kitamura 2009).

- The greatest source of doubt that exists regarding the magnitude of the effect of the built environment on travel behavior is residential self-selection, the idea that a neighborhood built around a particular kind of transportation behavior will simply attract residents who already had a predisposition towards that kind of transportation behavior rather than motivating other people to change their transportation behavior (Ewing and Cervero 2010).
- Little research has so far been conducted on the manner in which parents decide how their children will travel to school (Faulkner et al. 2010).

From "*Transportation-Behavior Modeling Techniques*" Subsection

- Most conventional travel behavior models consist of four sequential steps, based on the assumption that people first decide to make a trip, then decide what the destination of that trip will be, then decide what mode they will make the trip by, then decide what route the trip will follow. However, a better reflection of reality might be modeling these decisions as being simultaneous. Unfortunately, just like most other modeling techniques that produce a closer representation of reality, modeling people as making multiple decisions at the same time would be very complex, difficult, and time-consuming, resulting in a necessary tradeoff between accuracy and expediency (Hasan and Dashti 2007, Newman and Bernardin Jr. 2010).
- A better understanding is needed of systems approaches to integrating behavior choices with other factors in the decision-making process.
- Few studies have so far examined the possibility of modeling mode choices before destination choices (Newman and Bernardin Jr. 2010).
- The theoretical link between transportation system capacity and trip generation has not yet been proven (Kitamura 2009).
- Most travel behavior models do not give much consideration to the time of day at which a person departs on a trip, and most of the models that do give this consideration only narrow down departure times to one of a series of broad time periods, usually a couple hours in duration. Greater precision than this would be required in order to study variations in traffic congestion within a given peak travel period, which is currently considered a high-priority research area (Kristoffersson and Engelson 2009).

From "*Energy Use*" Section

- While there is a range of studies regarding specific issues (e.g., underground storage tanks for ethanol blends), there do not appear to be tools or resources that look systematically at how transportation fuel infrastructure fits within the broader sustainable communities context.
- While research on life-cycle impacts has often focused on upstream impacts of fuel and electricity production, there are also GHG and other environmental impacts related to material flows. Although their total contribution to GHG impacts and energy use may be small, the production of vehicles and vehicle components, as well as of larger transportation infrastructure (e.g., concrete production), may need to be considered in terms of other environmental endpoints.

- A key knowledge gap and research need identified by the Strategic Highway Research Program is "the effect of government interventions (e.g. pricing, infrastructure deployment) on technology advancement…many local and state governments are interested in how they can provide incentive to help accelerate the adoption of new vehicle technologies."
- Understanding the potential for eco-driving in the U.S. to reduce GHG emissions and energy use has been identified as a research need.
- There are a number of research initiatives attempting to understand the market for electric vehicles and charging patterns for this still-small but growing segment of the fleet, as well as to understand potential impacts on electric-power dispatching. However, beyond that is the question of how communities can promote synergistic solutions between vehicle electrification and energy strategies, and how to quantify their benefits.
- Research has been conducted to look at the question of whether plug-in vehicle buyers want green-power electricity. This could point to whether there are market preferences that would support a combination of green power and plug-in hybrid or electric vehicles, as well as point to policy and marketing strategies to advance these solutions. However, there is a lack of tools and resources available to communities to support these types of strategies.

From "*Water Infrastructure*" Subsection

- Methods for projecting population growth and activity modeling.
- The EPA research programs (e.g., SHC, ACE, and SSWR) are developing analysis methods for individual water infrastructure components. New developments, such as those in nutrient recovery, leak detection, and green infrastructure, are focused on water infrastructure or its components alone. Restraints from urban transportation, accounting for mode and accessibility, are not yet considered. For integrated planning, however, the smart growth methodology needs to simultaneously consider both types of infrastructures in option evaluation.
- Smart growth in urban development is often defined differently in literature than in practice. In light of urban development, smart growth refers to high population density, low carbon intensity, and green infrastructure, thus creating a livable environment. This premise requires the accommodation of mass transit and other transportation infrastructures. The transportation policies contained in U.S. Environmental Protection Agency (2011a) all aim to increase urban population density, create a walkable and pedestrian-friendly community, and maximize the use of existing infrastructure through infill and redevelopment. U.S. Environmental Protection Agency (2011a) outlined major types of transportation modes with the following sustainability metrics:
    - Transit accessibility, for reduced VMT and increased public transportation
    - Bicycle and pedestrian mode share
    - VMT per capita, to reduce automobile reliance and commute distances
    - Carbon intensity (of transportation) per capita
    - Percentage land-use mixture in terms of residential and commercial activities

- How changes toward smart growth affect urban water infrastructure, and in return how water services facilitate or impede smart growth, has received little attention.
- Numerous published studies (e.g., U.S. Environmental Protection Agency (2002b)) have shown that biofuel combustion in current fleet engines leads to a meaningful reduction in some pollutants (e.g., particulate matter (PM), carbon monoxide (CO), and hydrocarbons), but an increase in others (e.g., aldehydes and nitrous oxides (NO_x)). Chemical and physical properties of PM emissions also change when biofuels are used. These changes are important to near-road air pollutant monitoring and mitigation options (Baldauf et al. 2008). Their potential effects on land use decisions, and hence water infrastructure planning, have not been thoroughly investigated.

From "Physical Health" Subsection

- Research is still wanting on the relative impacts that various aesthetic and safety features have on physical activity.
- More research is also needed on how people's demographic and socioeconomic characteristics affect their walking behavior when all other factors are controlled for.
- Research could shed more light on the degree to which pedestrians regard public spaces as either a destination or an obstruction.

As the SHCRP program develops, these and other research needs raised should be considered for further evaluation both as individual activities and as integrated programs to enhance communities in their drive to achieve sustainable transportation developments.

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