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Building Energy Efficient Communities: A Research Agenda for California

UNIVERSITY OF CALIFORNIA - BERKELEY
COLLEGE OF ENVIRONMENTAL DESIGN

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Executive Summary

This white paper explores the links between community design and energy efficiency, and establishes a research agenda for the new Center for Resource Efficient Communities (CREC) at UC-Berkeley. The paper describes the context of resource efficient design in California (especially with respect to climate change), and identifies *five links* between community design and energy efficiency:

- 1 The Transportation-Land Use connection**
- 2 The Street Design-Transportation Connection**
- 3 The Urban Heat Island Effect and Cool Communities**
- 4 Solar Access and Building Energy Use**
- 5 Community Resource Use and Embedded Energy Management**

For each of these areas, the paper summarizes the major findings in the research literature and identifies major research gaps. In addition, it discusses development code barriers and other institutional impediments to resource-efficient community design, and briefly summarizes the literature on the property value implications of resource efficient design features.

Overall, the white paper argues that dramatic reductions in carbon emissions – on the order of 88 percent per capita by 2050 – are necessary throughout California’s economy, and that community design must play a central role in achieving them. Community design sets the physical context for the energy demand associated with both surface transportation and building operations, which collectively produce about 60 percent of CO₂ emissions in the state.

Reducing transportation energy demand will require widespread substitution of automobile trips by mass transit, walking and bicycling. The research shows that this will require clustering trip destinations much more closely together by increasing density and mixing land uses. However, to achieve the large reductions in vehicle miles traveled (at least 40 percent per capita) that will likely be necessary by 2050, these measures must be carried out to a greater degree than even “smart growth” developments have generally proposed.

In addition, major improvements in the pedestrian and bicycling environments will be necessary, both as a direct substitute for car trips and to improve access to transit stops. Research shows that path connectivity, safety, comfort, and enjoyment are all key factors in shaping people’s propensity to walk or bicycle. However, current transportation models and “level of service” calculations used in transportation planning do not consider most of these factors, and as a result, generally disadvantage pedestrian-friendly infill projects in local planning and development review processes.

Thermal comfort is an important and understudied component of willingness to walk and bicycle, especially in the warmer, inland portions of California where most growth is likely to occur in coming decades. Thermal comfort and building energy consumption issues are exacerbated by urban heat islands. “Cool community” strategies such as lighter-colored roofing materials, more reflective pavements, and widespread tree planting, are thus a key component of resource-efficient communities. Modeling the effects of these strategies on street microclimates, and assessing their cost-benefit ratios in a wide range of California communities, are key research tasks.

Community design in California should also consider the importance of solar access and embedded energy considerations in land use planning. The State of California is calling for “zero-energy” new commercial and residential buildings by 2030. Achieving this goal will require careful attention to preserving the solar access of buildings in urban settings, a complex planning task with important urban design implications. In addition, vehicles have significant amounts of embedded energy – as much as 60 percent as much as total operating energy in the case of cars. Avoiding car use therefore has the added benefit of reducing the large energy consumption associated with manufacturing and maintaining cars and their support infrastructure.

Finally, the paper argues that significant barriers to resource efficiency exist in development codes, planning processes, and project review processes in California. These range from physical design standards that prevent construction of resource efficient streets and public spaces, to environmental review processes that focus only on

immediate local impacts such as traffic, rather than regional impacts such as urban sprawl. Removing these barriers requires two research tasks: understanding the origins and evolution of physical design codes and standards so that more flexible ones may be created without increasing the liability of local governments; and developing better regional transportation planning and street design criteria so that pedestrian and bicycle infrastructure can be dramatically improved.

California is once again choosing to lead the nation in research and policy related to energy efficiency and climate change. The challenges facing the state are complex, and carbon reduction goals must be achieved with unprecedented speed and thoroughness. Nonetheless, the white paper demonstrates that the necessary knowledge exists, or can be obtained, to build a more resource-efficient state for future generations. Using seed funding from the California Energy Commission, the CREC intends to embark upon several research projects dedicated to achieving this goal.



1. Introduction

The State of California is at a moment of extraordinary promise – and challenge – with respect to energy use and community design.

On the one hand, state legislation is calling for dramatic improvements in community resource efficiency to combat climate change and build upon California’s well-earned reputation as a national energy efficiency leader. The landmark global warming bills AB 32 and SB 375 both establish processes to set binding targets for greenhouse gas emissions reductions, including for those stemming from land use patterns and community design. These targets will require substantial improvements in energy efficiency, in everything from regional transportation systems



to sidewalk design. New federal regulatory mandates may soon add to these requirements as well.

On the other hand, the rapid growth that has been a hallmark of California’s history is likely to continue over the coming decades, despite recent economic distress. The Department of Finance (2007) estimates that the state’s population will approach 50 million by 2030, from about 37 million today. New homes and businesses must be built to accommodate these millions, in existing communities and in new ones. This development will mostly occur in the hotter, inland portions of the state where populations are growing fastest and land is affordable. If it employs the same planning and design techniques used today, there is little chance of the state meeting its overall energy use and emissions goals.

“Community design” is the practice of creating the places Californians inhabit, from the regional to the neighborhood scale. It involves planners, architects, landscape architects, regulators, engineers, developers, and builders, all of whom make critical choices about the physical design of places. Ultimately, it is these physical design choices – shaped and complemented by laws, prices, and behavioral incentives – that determine the resource efficiency of communities.



Thus, the mission for California today can be stated simply: the communities we already have must become more energy efficient, and the communities we have yet to build must be planned and designed with energy efficiency and emissions reduction as central goals.

Recognizing this mission, in July 2009 the California Energy Commission provided seed funding for a new research center at the University of California, Berkeley called the Center for Resource Efficient Communities (CREC). Housed within the College of Environmental Design, the goals of the CREC are to

- Assess and produce inter-disciplinary research that identifies the best strategies in the development of resource efficient communities;
- Engage and inform members of the public, private, and non-profit sectors, including other academic institutions, in developing and implementing strategies and standards for resource efficient communities; and
- Articulate resource efficiency in regulatory and economic terms as an integrated component of community development in California.



This white paper is intended to help meet this challenge and to establish a research agenda for the Center for Resource Efficient Communities. It has four main purposes:

- To place resource efficient community research, planning, and design in the context of efforts to implement AB 32 and SB 375 at the state and regional levels.
- To summarize briefly the existing research and knowledge on the relationship between community design (e.g., land use planning and urban design) and energy efficiency;
- To assess the major codes, standards and guidelines in planning and design that impede resource efficiency, and suggest others that could advance it;
- To identify gaps in the existing research, and prioritize research needed to provide planners and designers with practical tools to improve community-scale energy efficiency and reduce carbon emissions.



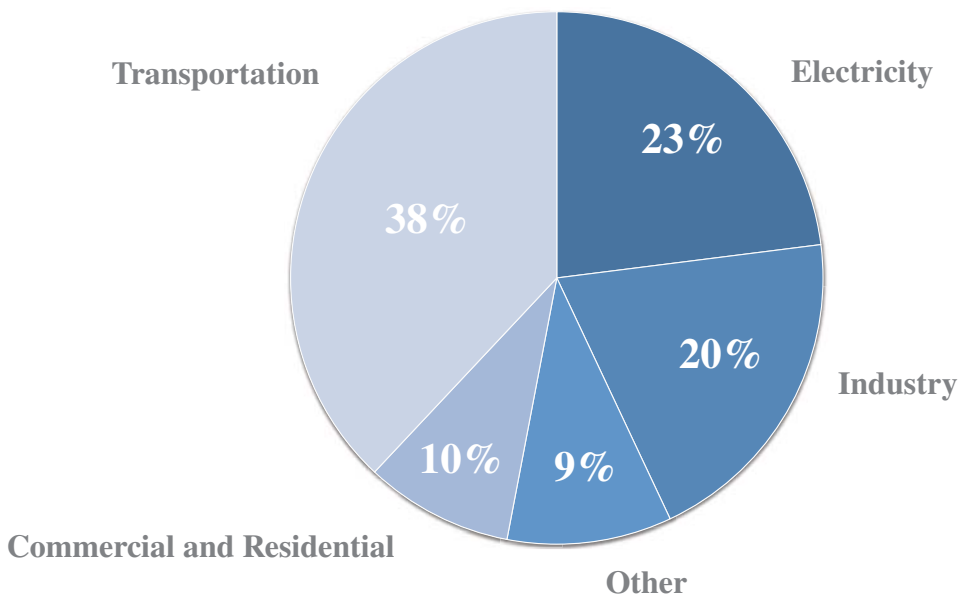
The challenge of climate change and resource efficiency

Consensus has emerged among scientists that the world must limit global temperature increases to 3.6° F (2° C) to avoid the worst of the possible consequences of climate change (IPCC 2007). Numerous policy and management efforts have concluded that this will require cutting global greenhouse gas emissions 60 to 80% below 1990 levels by 2050 (IPCC 2007). California, alone among American states, has accepted this challenge and written it into law and regulation. Gov. Schwarzenegger’s Executive Order S-3-05, signed in 2005, sets an official state target of achieving an 80% reduction below 1990 levels by 2050. Assembly Bill 32 (a.k.a. AB32), passed in 2006, requires the state to return to 1990 emissions levels by 2020, and establishes a cap-and-trade mechanism to implement deeper reductions later.

Carbon emissions have already risen another 10% since 1990 in California (EPA 2007). Hence, a goal to achieve 80% reductions below 1990 levels by 2050 actually means cutting emissions roughly 82% from current levels. Furthermore, these must be reductions in absolute carbon emissions. Since population continues to grow, per capita emissions must be cut even further. The California population is projected to reach 60 million by 2050, an increase of 62% over today’s estimated population of 37 million (Cal. Dept. of Finance 2007). Accounting for population growth means that per capita emissions in California must be reduced by 88% from today’s levels – in just 40 years.¹

The AB 32 Scoping Plan (Cal. Air Resources Board 2008) shows that GHG emissions arise predominantly from four economic sectors: transportation, electricity, commercial/residential and industrial (see Figure 1). Transportation is the

Figure 1. California’s Greenhouse Gas Emissions (2002-2004 Average)



¹A different numerical approach by Schiller (2007) found that emissions reductions must be 86 to 91% by 2050, depending upon growth rate assumptions.

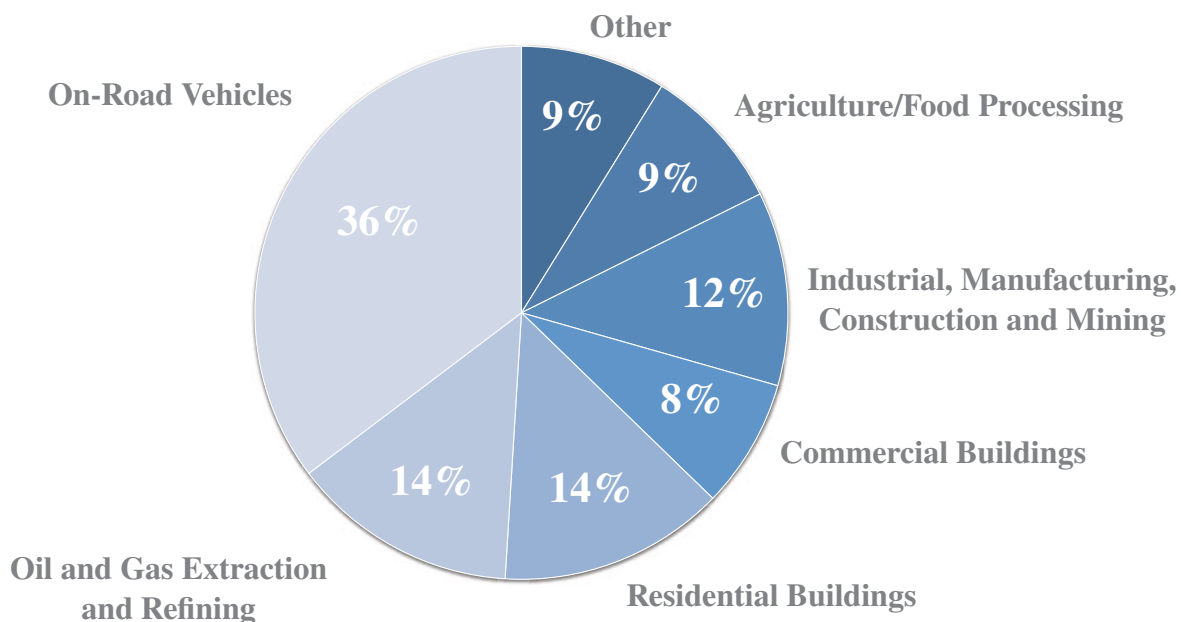
largest single generator of emissions in California, at about 38% of the total, with electricity second. Much of the electricity is actually used within buildings, so the total share of GHG emissions attributable to buildings for heating, cooling, lighting and other electrical needs is actually about 22% (see Figure 2). Thus, transportation and buildings account for about 60% of all GHG emissions, and likely closer to two-thirds of CO₂ emissions.

These facts have two important implications. First, because transportation and buildings collectively represent the majority of energy use and carbon emissions in the California economy, community design must be absolutely central to any effort to fight climate change. The operational efficiency of vehicles and buildings is critical and must be dramatically improved. But the overall energy demand inherent in vehicle and building use is strongly shaped by the physical context

in which they are operated. Even an efficient car will emit a lot of carbon if it has to be driven large distances. An efficiently designed building will still have to use too much imported energy if it is not sited and oriented correctly. These operational contexts are largely established by the practice of community design.

Second, it is worth reflecting upon the sheer magnitude of required emissions reductions. Having to achieve 88% per capita reductions economy-wide means that all major sectors must achieve approximately that much reduction if the overall target is to be met. Simply put, required reductions that deep leave very little wiggle room for tradeoffs among sectors. For the sake of illustration, let us suppose that the transportation sector is able to achieve “only” a 75% per-capita reduction by 2050, still an arduous political and technological challenge. That would mean that all other sectors – including all buildings, industry, and

Figure 2. California’s Greenhouse Gas Emissions - A Demand-Side View



Figures 1 and 2: Source: California Air Resources Board. 2008. Climate Change Scoping Plan: A Framework for Change. Issued pursuant to Assembly Bill 32. Sacramento: Air Resources Board.

agriculture – would have to achieve about a 96% reduction over 40 years for the economy to meet the overall emissions target.²

Even the least of these targets will require efficiency improvements and demand reductions far beyond any previous precedent. And because the overall emissions reduction must be so large, even a “miracle breakthrough” in one sector will not relieve the other sectors of their burden to meet these extraordinary goals. Fighting catastrophic climate change truly will require transformative changes in every sector of the U.S. economy – including community design.

The five links between community design and energy efficiency

This paper focuses on five major links between community design and energy efficiency. (Additional resource efficiency issues are discussed in the sidebar “Comprehensive Resource Efficiency and Cradle-to-Grave Benefits”). Creating more energy efficient communities will require improving performance in all five areas. Though all five links are important, they are not equally well studied and have different implications for the reform of planning and development practice. The five links are as follows:

1. The land use and transportation connection.

A large body of research has established that higher development densities and a good mix of housing, retail, and employment land uses are associated with reduced per capita automobile use, as long as appropriate transit infrastructure exists. These relationships exist at regional, city-wide, and neighborhood scales.

The literature on the land-use/transportation connection shows clearly that increasing development density and mixture of land uses will reduce car use by bringing trip origins and destinations into tighter clusters that can be more efficiently served by non-automobile transportation. These relationships exist across a range of scales. At the regional or city scale, these factors must exist for public transit to substitute for car use. At a neighborhood scale, sufficient residential density, land use mixture, and sidewalk connectivity must also exist to allow walking and bicycling to substitute for short-distance car trips. Large tracts of single-family homes that do not contain stores or workplaces will strongly discourage walking, simply through the sheer distance required to reach a destination.

These land-use/transportation relationships form a major basis for the planning profession’s recent emphasis on “smart growth” and transit-oriented development. Many new developments have already been built in this fashion, and many more neighborhoods embodying these principles remain from the pre-automobile era. Neither type has been particularly well studied for their success or failure in actually encouraging real-world walking and bicycling. Such studies are particularly important to improve transportation modeling, which has enormous influence over planning and environmental impact assessment, but contains powerful biases against infill and non-automobile-oriented development.

2. The street design and transportation connection.

Several design factors at the street scale, including thermal comfort, sense of safety, visual interest, and social opportunities, affect people’s willingness to walk or bicycle for short-

²Again approaching the problem slightly differently, Schiller (2007) has pointed out that for California to achieve 80% reduction by 2050 means “essentially eliminating carbon from virtually all electricity production and non-aviation transportation” and “eliminating about 2/3 or more of the carbon from all other applications.”



distance trips rather than use cars. This includes trips from the home or the workplace to regional transit stops.

The street design/transportation connection has been less emphasized and less researched than broader land use issues. But the choice to walk or bicycle involves considering more than just trip distance. The quality of the street experience is also important, especially for relatively long trips. The temperature and humidity, the visual quality of the environment, the sense of safety, the chance of encountering friends and neighbors, and other potential factors, all influence one's choice to walk or bicycle. All of these elements of the streetscape can be strongly shaped by planners and designers. Planning for street trees is especially important due to their many positive effects on microclimate and visual quality. But the relative importance of the factors that make up a quality street environment, and their collective importance compared to distance in determining transportation choices, are not well understood.

The street design-transportation connection is critical to resource efficient communities because walking and bicycling are the most energy-efficient means of transportation, and tend to reinforce themselves by making their own environment more suitable and pleasant. Moreover, more than a quarter of all trips in the U.S. are less than one mile (Killingworth and Lamming 2001), and the use of public transit usually involves a short-distance trip from home or work to the station, and vice-versa. Researchers have already begun to quantify certain desirable features of the pedestrian environment, but little research or modeling has been done to quantify the conditions of thermal comfort. This is an especially important gap in areas with difficult climate conditions, such as the hot inland portions of California.

3. The urban heat island effect and cool

communities. Buildings and pavement absorb solar radiation and re-radiate it locally, raising ambient temperatures and increasing the need for cooling energy in buildings. The “heat island effect” worsens air pollution and makes the outdoor environment less comfortable, affecting people’s willingness to walk or bicycle. In extreme cases, it can even contribute to acute respiratory illnesses and heat death.

Research indicates that the use of less absorptive, more reflecting paving and roofing materials, plus shading of buildings and pavements, can decrease the heat island effect substantially. Improved modeling of heat island dynamics in real environments is needed to allow more targeted implementation of these “cool communities” efforts. In addition, comprehensive cost-benefit analysis of “cool communities” strategies is important for more widespread implementation throughout California.

4. Solar access and building energy use. The solar orientation and thermal context of buildings influences the temperature and radiation levels of the building envelope and thus its overall energy performance. The position and orientation of buildings relative to the sun, to breezes, to shade trees, and to other buildings has a large effect on their potential energy performance. The size and shape of land parcels also affects the ability to build multi-family housing and other “shared-wall” structures, which are typically more energy efficient than detached structures.

Solar access also strongly influences the potential for “zero-energy” buildings that produce as much energy as they consume, an increasingly important focus of energy policy in California. Indeed, with the need to achieve very large efficiency and emissions improvements in building performance,

the question of optimizing solar access in urbanized settings – and potentially creating entire net-zero neighborhoods – should be a critical focus of research.

5. Community resource use and embedded energy³ management. Water, food, and various solid materials must “flow” through cities in order to sustain human life at urban densities. Producing or capturing these critical inputs off-site, then transporting them to urban populations, is an energy-intensive task. Community design can take steps to reduce these energy costs through conservation, re-use and sourcing strategies that take embedded energy into account.

Embedded energy management in the public environment involves implementing targeted sourcing, re-use and conservation strategies for water and building materials. In the realm of private consumption, standards for food and consumer goods can be developed by public entities or ratings agencies. The costs and benefits of these strategies will vary on a case-by-case and location-by-location basis. Energy-intensive importation of water to southern California, for example, can be reduced by improved efficiency, local stormwater harvesting and wastewater recycling. Additional research is required to quantify the embedded energy savings that might be achievable by various metropolitan regions around the state across a range of critical urban inputs. Existing findings already have important implications for community design, however, suggesting that there is greater leverage to reduce embedded energy in the transportation sector than in the building sector.

The structure of the white paper

After this introduction, chapters two to six will discuss the five community design and resource efficiency links noted above. Each of these chapters summarizes relevant research findings, and discusses conclusions and research needs pertinent to each of these five areas of concern. Chapter seven reviews the economic dimensions of resource efficient communities. Reshaping California’s urban landscape requires both investment and incentives for change. The chapter reviews the methods for assessing economic benefits of the components of resource efficiency, the major finding regarding those components, and identifies research gaps. Chapter eight analyzes the existing codes and standards that impact all aspects of community-scale energy efficiency. It identifies codes and standards that impede resource efficiency and the research needed to develop feasible alternatives to present standards. The white paper concludes with chapter nine that assesses overall research opportunities regarding resource efficient communities.

Improving community-scale energy efficiency is a difficult technical and political task. But California has set an example for the world many times before with bold and innovative responses to daunting resource management challenges – from air pollution to habitat conservation. With climate change looming as the 21st century’s biggest environmental problem, California again finds itself in a position to lead – by showing the world how to improve community-scale energy efficiency through intelligent planning and design. This white paper is intended as a first step down that path.

³ “Embedded energy” refers to the total energy consumed in the extraction of raw materials and their subsequent processing, manufacturing, transport, and eventual construction into a commodity or structure. Some definitions also include energy consumed in disposal of products.

Comprehensive resource efficiency and cradle-to-grave benefits

Climate change is not the only resource efficiency arena in which the state has recently established new policy. In February 2008, Governor Schwarzenegger directed state agencies to develop and implement a plan to achieve a 20% per capita reduction in water use by 2020 (Schwarzenegger 2008). This policy initiative comes in response to a serious statewide drought, an escalating ecosystem crisis in the state's most important fresh water source (the Sacramento-San Joaquin Delta), and decades of oversubscription of the state's water supplies. Indeed, over the next half-century, California faces water supply challenges that are just as serious as its energy use challenges.

Water-efficient community design will be critical. While agriculture uses four times as much water as cities in an average year (Cal. Dept. of Water Resources 2005), the urban sector is still important because significant efficiency opportunities exist there. Efficiency improvements in indoor water uses (e.g. washing machines, dishwashers, toilets, etc) have already achieved substantial market penetration, especially in southern California. Urban landscape irrigation, on the other hand, is still often unregulated, and consumes about half of total residential water use in the state (Cal. Dept. of Water Resources 2005). Moreover, most of this irrigation is still done with drinking-quality water, often imported from far-flung areas at great energy expense.

Water-efficient urban design and xeriscaping ordinances that require the use of water-efficient native plants can reduce overall demand. For the water that must still be used to irrigate trees and other landscaping, there are myriad opportunities for stormwater harvesting, greywater re-use, and municipal water recycling to replace "first use" water. Not only does this improve water efficiency, but in many cases it also saves the energy required to import water from distant sources like the Delta and the Colorado River, and reduces stress on those ecosystems (Cohen, Nelson and Wolff 2004).

Much the same lessons apply to the solid materials and food supplies that must flow through cities to sustain urban populations. Efficiency of use within a community reduces the impacts upon both the "source" landscapes from which these materials originate, and the "sink" landscapes that must accommodate the wastes and by-products. It also reduces the energy required to manufacture, transport, and dispose of these products and materials. Community design can encourage this efficiency through purchasing specifications, use of recycled materials, and other measures.

In each case, "efficiency" is really shorthand for a low-impact material life cycle that reduces energy use and environmental damage at every stage of production, use and disposal (McDonough and Braungart 2004). Community design sets the physical context in which such materials flows occur. The choices and policies of developers, designers, and regulators therefore have major effects in shaping energy use and environmental impacts far beyond the community's borders.

2. The Transportation - Land Use Connection

Planners have long realized that there is a strong link between community design and the transportation behavior of community residents. The combination of low-density development, single-use zoning, and generous federal funding of interstate highway infrastructure create sprawling urban landscapes that virtually require extensive automobile use (Burchell et al 2002). By contrast, compact development with higher population densities and fine-grained mixture of land uses, combined with funding for public transit, is associated with substantially reduced levels of car use, increased public transportation, and more walking and bicycling (Newman and Kenworthy 1999). These two poles are exemplified by American and European styles of urbanism, which have markedly different per capita energy intensities, despite similar levels of economic development (Beatley 1999). Figure 3 shows a general relationship between residential density and gasoline consumption worldwide.

Over the last twenty years, researchers have quantified the general relationship between land use and transportation. That body of research is now being brought to bear on the task of achieving carbon emissions reductions goals under AB 32 and its companion legislation, SB 375 (see sidebar). The major findings of the research reinforce the central importance of compact development for community-scale energy efficiency. Significant improvements in transportation-related efficiency are indeed achievable through land use changes alone.

However, the findings also reveal some of the limitations of existing transportation planning methods, and the need to reform these to achieve even greater energy use and emissions reductions. In short, compact development in isolation is

not enough. New compact developments must leverage existing urban fabric into a community landscape that optimizes transportation efficiency. In addition, this effort must be harnessed to major improvements in walking and bicycling environments at the neighborhood scale to maximize use of these carbon-free transportation modes.

Transportation energy and climate change

As already noted, transportation generates approximately 38% of GHG emissions in California (Bartholomy et al 2007). Transportation-related carbon emissions are the product of a “three-legged stool” with the following terms:

$$[\text{Fuel efficiency of vehicle}] \times [\text{Carbon content of fuel}] \times [\text{Vehicle miles traveled}]$$

Put another way, the overall amount of carbon emission is simply the emissions per mile (fuel efficiency times carbon content of fuels) times the total number of miles traveled. Both fuel efficiency and carbon content of fuels are characteristics of the vehicles themselves, but vehicle miles traveled is a function of community design.

Past experience in the United States has shown that improvements in fuel economy and carbon content can be overwhelmed by continued increases in VMT (Ewing et al 2008). Simply put, nothing is gained if people drive for ever-greater distances in slightly more efficient cars. In recognition of this fact, the AB32 Scoping Plan (Cal. Air Resources Board 2008) requires that five million metric tons of CO2 equivalent (MMTCO2E)



must come from land use changes, as opposed to improvements in automobile technologies. As of this writing, a series of Regional Technical Advisory Committees are defining how much of this reduction must be achieved by each major metropolitan region in California under SB 375.

The AB 32 and SB 375 land use/VMT goals are to be achieved by 2020. It is equally important, however, to think ahead to 2050 in establishing an evaluative context for research results. As noted in the introduction, California must achieve at least an 88% reduction from today's levels in per capita carbon emissions economy-wide.

Each of the major energy end-uses, including transportation, must reach approximately this level of emissions reduction if the overall emissions goal is to be reached.

How much must VMT be reduced?

For the transportation sector to reduce emissions by 88% per-capita, how much must come from VMT?⁴ The answer depends upon what one assumes about trends in the other two legs of the “three-legged stool.” An 88% reduction in per capita emissions could theoretically be achieved in a variety of ways. For instance, if improvements in fuel efficiency and

Figure 3. Petroleum Use versus Population Density in Industrialized Cities

A commonly used study of 32 cities by Newman & Kenworthy in 1989 concluded that there was a strong link between urban development densities and petroleum consumption.

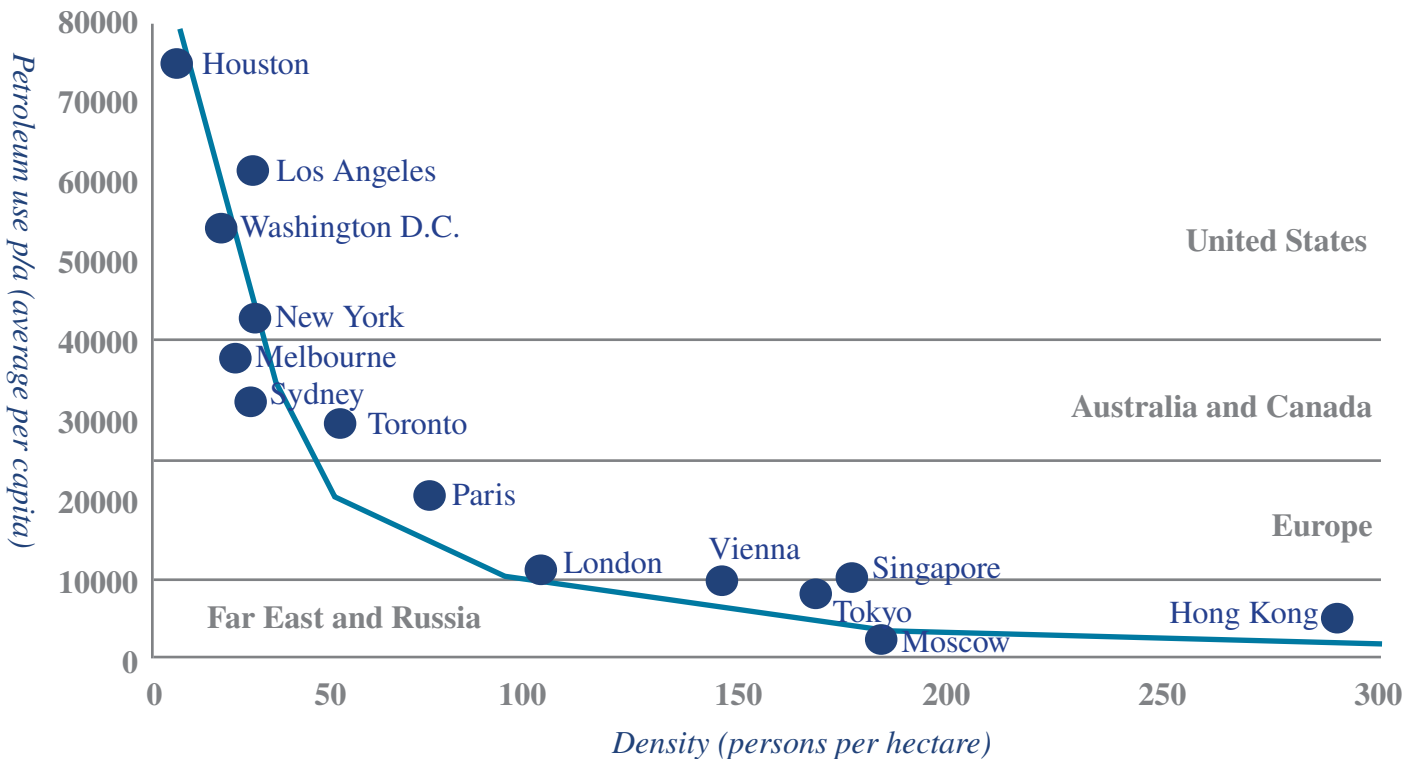


Figure 3: Annual petroleum use per capita adjusted to US MJ (1980). After Andrew Wright Associates, small section taken from ‘Towards and Urban Renaissance,’ Urban Task Force Partnership, 1999, (c) DETR, 1999.

fuel carbon content could combine to reduce the emissions per mile by 88%, then merely holding overall VMT per capita constant would achieve the overall target. That would involve converting virtually the entire vehicle fleet to zero-emissions vehicles⁵, and ensuring that virtually all source energy (e.g. to charge electric batteries or to refine hydrogen) was generated in a carbon-free manner.

Unless a complete fleet conversion of this kind is achieved, however, VMT reductions will need to be quite significant. Though the fastest in the nation, current regulatory progress in California is still not on a course to reach such dramatic efficiency improvements. Even with full implementation of California's Low Carbon Fuel Standard and the AB 1493 GHG emissions standards for light-duty vehicles (a.k.a. the Pavley standards), "further efforts would be needed to reduce the transportation sector's fuel consumption and greenhouse gas emissions to their 1990 levels by 2020 as required by AB 32" (Bartholomy et al 2007, 18). Even looking ten years farther out, "the CEC estimates that fuel and vehicle efficiency standards implemented to comply with AB 32 will result in GHG emissions from transportation that are 15% above the required level in 2030 instead of substantially below, as needed in order to reach the levels mandated by 2050" (Binger 2009, 5).

In addition, there is good reason to conclude that complete conversion to zero-emissions vehicles will not be an adequate response to the climate change crisis. For one thing, such vehicles still must be manufactured, and there is as yet no practical way of building cars in a near-carbon-free manner. (See chapter 6 for a discussion of

the embedded energy of automobiles). Secondly, continuing to rely on automobiles for transport requires sustaining a vast infrastructure of paved roadways, parking lots, and fueling/charging stations, which are themselves energy-intensive to build and maintain. Though such networks will undoubtedly still play some role in a clean-energy future, a full-carbon-cost accounting of the entire automobile infrastructure may well reveal it to be uncompetitive (on the local scale) with inherently low-carbon transportation modes such as walking and cycling. Any cap-and-trade system at the state, federal or international level will eventually "price in" these systemic carbon costs as the cap is gradually lowered (Cal. Air Resources Board 2008). Large areas of pavement also impose other costs on communities, such as contributing to urban heat islands (see chapter 4), and exacerbating stormwater management challenges (Ferguson 1998).

For all these reasons, substantial reductions in VMT per capita must be a significant part of resource-efficient communities. As Figure 4 shows (page 16), even an 80% reduction in emissions per mile – a quintupling of overall automotive carbon efficiency – would still mean that VMT per capita must decrease by 40% in order to reach the overall 88% per-capita emissions reduction target. Achieving "only" a 50% reduction in emissions per mile by 2050 would require a 76% decrease in VMT per capita.

In fact, the VMT-reduction challenge is even greater than this. Based on figures from Nelson (2006), Ewing et al (2007) have estimated that about one-third of the development that will exist in 2050 already exists today. Assuming this

⁴ This discussion is limited to the urban transportation sector, and does not include airline travel, trucking, or other forms of transportation. As with the larger energy use sectors, each of these components of the transportation sector will have to make very deep reductions in emissions if the sector as a whole is to reach its 88% per capita reduction goal. For the sake of simplicity, the ensuing discussion assumes that urban transportation will have to reduce emissions by 88% per capita by 2050.

⁵ Examples include electric and hydrogen fuel cell vehicles.

surviving infrastructure is roughly representative of all of today's development, it will continue to be a major source of VMT per capita. If we are to reach our overall carbon reduction goals, the new development built between now and 2050 will not only have to "pay its own way" in carbon efficiency, but will also have to help make up for the inefficient legacy of the past.

As the research findings will show, per-capita VMT reductions of this magnitude will require major changes in how we design and build communities in California. In general, the engineering and planning professions have not yet fully grasped the magnitude of this challenge. The American Association of State and Highway Transportation Organizations, for example, is calling for a 50% cut in the growth of vehicle miles traveled (Ewing et al 2008) – when what is needed is an absolute reduction of large scope. A stakeholder-driven regional "blueprint" processes in Sacramento that is a national model of best planning practice at the regional scale is expected to achieve VMT reductions relative to sprawl of approximately 15% (Bartholomy et al 2007), still far short of what is needed.

Even the mandates of SB375 and AB32 – as indispensable as they are – are only a good start on what will ultimately be required.

Research findings

Hundreds of studies have investigated the links between land use patterns and transportation behavior, including VMT per capita. The major findings include:

1. Compact development can reduce VMT per capita by 20 to 40%, relative to sprawl.

As Ewing et al (2007, p. 55) point out, dozens of

Senate Bill 375

Senate Bill 375, passed in 2008, aims to reduce transportation-sector greenhouse gas (GHG) emissions attributable to inefficient land use patterns. While other aspects of California climate policy seek to reduce emissions through technological changes, SB 375 is an attempt to achieve reductions through better community planning. The bill coordinates transportation, land use, and environmental planning processes in order to produce regional smart growth policies that decrease driving. It also seeks to create incentives for local governments to comply with these policies.

Under SB 375, the Air Resources Board (ARB) will determine GHG reduction targets for each of California's 18 metropolitan areas with populations over 200,000. In these areas, metropolitan planning organizations (MPOs) are responsible for creating regional transportation plans (RTPs), which outline all regional transportation projects and policies over the next 20 years, and for updating these plans every four years. In the past, RTPs have dealt exclusively with transportation projects and policies, but beginning in 2012 they must also include a sustainable communities strategy (SCS), which is a long-term land use plan that acts alongside transportation plans and policies to reduce driving and meet the targets established by ARB.

If ARB approves the SCS, the MPO must allocate federal and state transportation revenues to projects that conform to the strategy. However, SCSs are... subject to federal requirements that regional plans be consistent with existing local land use plans and growth patterns. If an MPO determines that these requirements prevent it from meeting ARB's targets, it may instead create an alternative planning strategy (APS) in which it proposes additional measures that the region could take to lower



studies have converged on the overall conclusion that “compact development has the potential to reduce VMT per capita by anywhere from 20 to 40% relative to sprawl.” While the precise definition of “compact development” varies from study to study, it is always used to connote (at least) increased residential density, greater mixture of land uses, and tighter clustering of potential trip destinations.⁶

A few sample findings illustrate the consistency of this overall finding.⁷ A major study by Ewing, Pendall and Chen (2003) ranked 83 metropolitan areas in the U.S. by a “sprawl index” that included population and employment density, mixture of land uses, strength of activity centers, and connectedness of the street network. The study found that residents drove about 25% less in the more compact regions, even once socioeconomic

Figure 4. VMT reductions required to achieve CO² emissions reductions, under automotive efficiency scenarios

	Vehicle CO ² / Person / Year	=	Carbon Emitted / Mile	x	VMT / Person / Year
Scenario 1	2 tons CO ² / Person / Year	=	0.0002 tons CO ² / Mile	x	10,000 mile / Person / Year
	↓ 88% emissions reduction with...		a doubling of carbon efficiency...		...requires a 76% reduction of VMT per capita.
	0.24 tons CO ² / Person / Year	=	0.0001 tons CO ² / Mile	x	2,400 mile / Person / Year
Scenario 2	2 tons CO ² / Person / Year	=	0.0002 tons CO ² / Mile	x	10,000 mile / Person / Year
	↓ 88% emissions reduction with...		a quintupling of carbon efficiency...		...requires a 40% reduction of VMT per capita.
	0.24 tons CO ² / Person / Year	=	0.0004 tons CO ² / Mile	x	6,000 mile / Person / Year

Numbers are rough approximations for the sake of illustration

Figure 4: Illustration by the Center for Resource Efficient Communities, 2010.

⁶ Density is most frequently expressed in dwelling units per acre (DU/ac), though there are several ways to measure it (Forsyth 2003). Sprawling suburban development, though becoming somewhat more dense in expensive land markets such as California, has generally been built at densities well below four DU/ac. Pushkarev and Zupan (1977) found that public transit use begins to rise significantly once density reaches seven DU/ac, and that at 60 DU/ac, more than half of all trips occur by public transit. More recently, Holtzclaw (1997) has found that eight DU/ac is necessary for minimal bus service, 20 DU/ac is necessary for a transit station such as light rail, and 30 DU/ac is necessary to support high-frequency transit service (waiting intervals of 10 minutes or less). While study data on walking are scarcer, retail research has suggested that a density of seven DU/ac is necessary to support a convenience store, or 18 DU/ac to support a nearby supermarket (LGC 2003).

⁷ The methods used in these studies are summarized in Appendix A.

differences and other potential confounding factors were accounted for.

A meta-analysis of household travel behavior studies found that areas with double the density, diversity of uses, accessibility of destinations, and interconnection of streets saw inhabitants drive about 33% less than similar residents of sprawling areas (Ewing et al 2008). Another meta-analysis of 23 regional growth simulations found that compact development scenarios could be expected to generate on average 33% fewer miles traveled than the “business-as-usual” scenarios for the same regions (Bartholomew 2007). Finally, an influential project-level study (Walters, Ewing and Allen 2000) compared the likely VMT generated by the Atlantic Station development in downtown Atlanta to the projected VMT from an equivalent amount of residential and commercial space in three conventional suburban locations. It found that the Atlantic Station location would generate about 36% fewer VMT than the suburban sites.

2. Destination accessibility is the most important factor in achieving VMT reductions, suggesting that central cities and other destination-rich locations are the best sites for new development.

Researchers have identified “the five D’s” that influence travel behavior: density, diversity (i.e. land use mix), destination accessibility, distance to transit, and design. Ewing and Cervero (2001) calculated travel elasticities for four of the traditional D factors (distance to transit was excluded) to examine the reduction in VMT that would result from doubling each of them. They found that destination accessibility had by far the largest effect – doubling it results in a 20% reduction in VMT. Doubling density or diversity would yield a five percent reduction, and doubling the design factor reduces VMT by three percent.

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GHG reductions. Since an APS is not required to be consistent with local plans and growth trends, it cannot be part of the RTP, and therefore does not condition transportation funding as an SCS does. However, both an SCS and an APS carry the same weight with respect to the amendments that SB 375 makes to the California Environmental Quality Act (CEQA) and Regional Housing Needs Allocation (RHNA) process.

CEQA outlines a rigorous review process under which government agencies must analyze many potentially significant impacts of a proposed development. The CEQA process has posed challenges for the type of infill and mixed-use developments that are likely to be part of an SCS, in large part because local agencies are generally responsible for CEQA review, and these projects primarily provide benefits at the regional level (Barbour and Teitz 2005; see Chapter 8 for more discussion). SB 375 offers three paths to CEQA relief in order to help implement projects that are contained in an SCS:

- 1) Projects that are primarily residential and are consistent with the SCS/APS are exempt... from analyzing cumulative traffic impacts, growth inducing impacts, and GHG emissions from passenger vehicles, and are not required to analyze a lower-density alternative as a way of mitigating these impacts.
- 2) High-density “transit priority projects” that are primarily residential, consistent with the SCS/APS, and located within a half-mile of a transit station with frequent service are eligible for a streamlined CEQA review that focuses on project-specific impacts instead of cumulative ones.



In the Ewing and Cervero study, “design” is defined as street network density, sidewalk coverage, and route directness. Other studies define it as the physical connectivity of the sidewalk network or the frequency of intersections (often as a proxy for the availability of route choice). In other words, the word “design” is used in this literature simply to indicate the presence of a path network that physically permits walking and bicycling, but says nothing about the visual, social or thermal quality of that environment (see Chapter 3 for further discussion).

A critical conclusion of Ewing and Cervero (2001, 71) is that “the elasticity of VMT with respect to destination accessibility is as large as the other three combined, suggesting that areas of high accessibility – such as center cities – may produce substantially lower VMT than dense mixed-use developments in the exurbs.” Even a large mixed-use suburban development can only contain a small fraction of the jobs, businesses and other destinations that the residents will need. Apart from the trips that can be captured internally by these mixed uses, residents will still be forced to drive for almost everything else.

Some of the VMT reductions that arise from compact development are simply a product of trip origins and destinations being located closer together, which reduces the sheer length of trips. But opportunities to substitute non-automobile transportation modes, such as mass transit, walking and bicycling, for car use are also much greater in compact, mixed-use communities. As Ewing et al (2007) note, almost 75% of all urban trips include an individual’s home at one end or the other, but the average trip length is 6.8 miles, well beyond the boundaries of the local neighborhood. This means that the characteristics

of the built environment in both the home neighborhood and the destination neighborhood may be important in determining the potential use of non-automobile modes.

Moreover, between 40 and 60% of all trips are part of multi-stop “tours,” meaning that the ability to chain together multiple destinations conveniently is also important to mode choice. This suggests that mixture of uses is also important in potential substitution for car trips. According to a study by the Natural Resources Defense Council (2000), the mode share of walking can rise above 20% in mixed-use neighborhoods even when no transit service is available. Cervero (1996, p. 69) has also found that “walking varies as much with the degree of land use mixing as with local densities.”

3. Existing transportation models are misleading because they do not consider the characteristics of the travel environment in projecting transportation behavior.

The findings summarized above support the general conclusion that compact development will reduce VMT per capita. But a general conclusion is not sufficient when municipalities and citizens must assess the expected impacts of specific project or plan proposals. In these cases, assessment must rely on models that estimate the transportation behavior expected to result from new development.

Most such forecasting is done by what are known as “four-step models.” These models begin by assessing developing traffic demand models based on current population, employment, and travel costs, among other factors. Then data on future conditions are fed into the model to forecast future travel demand. The “four steps” are the forecasting of trip generation, trip distribution, mode choice,

⁸ Achieving VMT reductions relative to the overall current average is more difficult than achieving them relative to sprawl, because the current average already includes the effects of existing non-sprawling areas.

and trip assignment, which ultimately yields estimated traffic volumes that can then be modeled over a road network to identify potential bottlenecks (MWCOC 2009).

These models have significant limitations. As Ewing et al (2007, 80-81) note:

Conventional models can simulate land use and transportation system effects on travel at the gross scale of a region, but not at the fine scale of a neighborhood. In particular, they cannot account for the micromixing of land uses, interconnection of local streets, or human-scaled urban design. Most do not even consider walk or bike trips, adjust vehicle trip rates for car shedding at higher densities, or estimate internal trips within mixed-use developments.

Fundamentally, these models create trip generation projections based on the characteristics of the travelers, not the characteristics of place. If two households living in different neighborhoods have identical socio-economic characteristics, their transportation behavior will be projected to be the same, regardless of the physical characteristics of the neighborhoods. In addition, the possibility of “trip chaining” – visiting multiple destinations in a consecutive tour – is not considered in these models (Ewing et al 2008). The outputs of four-step models can sometimes be improved by “post-processing,” wherein the estimated trips in each travel mode are modified based upon particular characteristics of the region or community under study. However, post-processing methods are inexact and require high-quality data about the locality.

There are other types of models that do a better job of projecting non-automobile

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- 3) Transit priority projects that include at least 20 percent affordable housing units and create sufficient open space are exempt from CEQA altogether.

In order to create a more predictable environment for development, SB 375 also allows local governments to adopt a uniform set of traffic mitigation measures for high-density residential projects instead of determining them on a case-by-case basis. All of the CEQA incentives described above are optional, and though regional plans form the basis for where they may be applied, local governments ultimately have the authority to decide whether or not to apply these incentives.

SB 375 also seeks to better coordinate transportation and land use planning by aligning the RTP with the regional housing needs allocation (RHNA) process. Under state law, cities must update the housing element of their general plan every five years in order to accommodate projected growth in housing demand. Since most MPOs update their RTPs every four years, these processes have been out of sync, which means that transportation investments may not necessarily serve the increased demand created by new housing growth. SB 375 requires that regional agencies update their housing element every eight years and that it be consistent with the SCS/APS. It also introduces new provisions to help housing advocates challenge the housing element if local governments are unwilling to zone for affordable housing.

The impacts of SB 375 will not become clear until 2012, when MPOs produce the first round of RTPs that include SCSs or APSs. On one hand, the bill does align



transportation behavior, but they are currently used in only a few select locations. Activity-based transportation models are an alternative to four-step models that, as the name implies, project travel behavior based on anticipated activities (and the locations of those activities) rather than simply the traveler's demographic characteristics. The models therefore theoretically have the capacity to model travel between closely clustered activities as potentially using a mode other than automobiles and could, if reliable data were available, introduce weighting factors for the likelihood of walking and bicycling in a given location based on the characteristics of the environment. This is a very data- and calculation-intensive modeling process, however, and activity-based models currently exist in only a small handful of California localities. Converting the transportation models of existing regional agencies in the Central Valley and other high-growth locations in California to activity-based models is likely to take a decade or more.

Mixed-use trip generation tools are also growing in sophistication. The most advanced of them, developed by Fehr and Peers in collaboration with the Environmental Protection Agency (EPA) and the Institute for Transportation Engineers (ITE) uses a "5 D's" technique to measure the interactivity within the site, and then combines these findings with conventional modeling methods. These mixed-use methods have yet to achieve widespread acceptance or application in planning processes or environmental impact statements, and at the present time still define "design" primarily in terms of connectivity rather than overall environmental quality.

4. Because of modeling limitations, regional transportation planning processes generally do not account for, or prioritize, streetscape-level improvements.

Though local governments have final say over land use decisions, regional agencies coordinate transportation planning. Federal law requires that in all metropolitan areas with a population over 200,000, metropolitan planning organizations (MPOs) must create 20-year regional transportation plans (RTPs), which they must update every five years. During each update, an MPO assesses regional transportation needs and projected revenues, and then compiles projects proposed by local governments into fiscally constrained investment scenarios that meet the region's transportation needs.

In the past, RTPs were limited to transportation projects and policies and land use decisions were left to local governments. However, concern over the lack of coordination between transportation and land use planning led to Senate Bill 375, which links the two (see sidebar). Few of California's MPOs currently have all the modeling tools needed to evaluate the impacts of smart growth policies and count these policies toward their GHG reduction targets under SB 375. This is important because local governments typically use refined versions of regional travel models to evaluate transportation planning decisions.

The travel models currently used by MPOs were developed primarily to evaluate highway investments, and are not always capable of assessing the benefits of smart growth policies, particularly at the street level (DKS Associates and University of California, Irvine 2007, Regional Targets Advisory Committee 2009). In order to simplify computations, regional travel models include highways and major arterials, and seldom include local streets on which the majority of walk trips occur. In a recent survey, only two of the eighteen MPOs subject to SB 375's planning requirements rated their travel models as having "reasonable sensitivity" to changes in



the pedestrian environment (Regional Targets Advisory Committee 2009). These MPOs use simple measures of walkability like intersection density or proximity to transit (DKS Associates and University of California, Irvine 2007), and aren't capable of capturing the impacts of new sidewalks or "road dieting" strategies that reduce traffic speeds for the sake of pedestrian safety. Until models improve, it will be difficult for MPOs to count design improvements at the streetscape level toward their GHG reduction targets under SB 375, and for the local governments that use versions of these models to evaluate the impact of planning decisions on pedestrians and bicyclists.

5. Urban infill development proposals are politically disadvantaged by existing transportation and traffic level-of-service models.

After calculating trips generated by a project using the models described above, agencies apply those estimates to calculate a new traffic level of service (LOS), expressed on an "A-F" scale based on the amount of vehicle delay at intersections. Since streets in built-out areas are often already congested, and the projected additional traffic only worsens the LOS, this analysis favors development at the urban fringe, where there is more road capacity to handle new trips. Many cities have set minimum LOS thresholds, and automatically disapprove any projects that diminish LOS below these thresholds. Furthermore, LOS measures only vehicle speeds, which means that it registers the negative effects that improvements to the pedestrian environment or to transit access may have on speed, but not the positive impacts that these improvements will have on accessibility (see Chapter 3). This method of impact assessment makes it difficult to develop more housing and improve transportation options in destination-rich infill locations (San Francisco County

Transportation Authority 2003, 3).

The California Environmental Quality Act (CEQA) also plays an important role in these evaluations. Though CEQA is intended to protect the environment, several reports and surveys (Landis et al 1995, Olshansky 1996, Barbour and Teitz 2005) have suggested that CEQA has become a vehicle for protecting local quality of life rather than regional and global environmental quality. The lead agencies that create EIRs are typically local governments, which may not be well-suited to assess the regional benefits that infill developments produce, such as farmland or habitat protection. The tendency of EIRs to focus on local impacts has been further exacerbated by the inclusion of impact categories that fall well outside of the traditional definition of "environmental quality," such as noise and traffic. As a result, it is more common for the EIR process to result in noise and traffic mitigation or a lower-density project alternative, rather than measures to preserve air and water quality (Johnston 1991). For these reasons, a recent study by the Public Policy Institute of California concluded that CEQA "does not mesh effectively with wider,

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three previously separate planning processes toward the goal of reducing GHG emissions. On the other hand, it relies on incentives to implement these plans, and does very little to alter the balance of power between regional planning agencies and local governments (Higgins 2009, Fulton 2008). Analysts suggest that the measures contained in the bill are no substitute for collaborative efforts with stakeholders, which have been the hallmarks of successful regional planning (Barbour and Teitz 2006). Others have already recommended new provisions to improve the law (Binger 2009).

more comprehensive planning, and in fact may be counterproductive” (Barbour 2005, p. 18).

The environmental benefits of infill developments often only become apparent at the regional scale. The lead agencies “have little ability on their own to determine how impact thresholds or mitigation measures actually translate into larger regional consequences” (Barbour and Teitz 2005, 33). EIRs typically assume that new developments induce new growth instead of displacing growth that may occur elsewhere in the region (Lefcoe 2006). The impacts of a new infill development are typically evaluated against a no-build or lower-density alternative at the project site. The EIR will therefore show that the project increases the local share of VMT, instead of diminishing the regional share (Cervero et al 2004).

EIRs are costly to prepare, the public process they require delays projects, and the costs of mitigation are unpredictable. As a result, project sponsors are much more likely to pursue a negative declaration stating that the project has no significant environmental impacts are therefore does not need to undergo an EIR. A 1990 survey found that local governments issue almost 20 times as many negative declarations as they did EIRs (Olshansky 1996). But resource efficient growth projects are more likely to draw the type of scrutiny that may lead to an EIR. If a relatively inexpensive improvement to the pedestrian environment is found to have a significant impact, for example, the cost of the EIR may well dwarf project costs (San Francisco County Transportation Authority 2003). Furthermore, if a project does have to undergo an EIR, the report is likely to reflect less favorably upon a smart growth project than upon a conventional one. Local residents commonly oppose infill projects on the

grounds that they will increase congestion. Partly as a result, EIRs are more likely to require traffic impact mitigation than mitigation in any other category.

The combined effects of four-step and LOS modeling are critical impediments to creating resource efficient communities. These models drive transportation infrastructure planning and capital investment priorities, as well as the evaluation of individual plans and projects. If these models are unable to account for potential walking and cycling behavior associated with compact and urban infill developments, they will always overestimate the likely automobile traffic impacts of these developments and disadvantage them in approval and environmental impact assessment processes.

Conclusions and research needs

Overall, the literature on the transportation – land use connection shows that important reductions in energy use and carbon emissions are possible through improved land use practices. Reductions in VMT of 20 to 40% relative to sprawl are certainly an improvement over current development practices. Ultimately, however, California likely must achieve VMT reductions of much more than 40%, and these reductions must be achieved relative to our overall average VMT per capita, not just relative to sprawl.⁸ California therefore needs to push toward even more compact development, in appropriate locations, in order to shorten trips and achieve more widespread substitution of car use with other modes of travel.

The major research needs to achieve these objectives are:

1. Identification and prioritization of appropriate locations for infill development.

The literature shows that regional destination accessibility has the highest elasticity with respect to transportation mode choice, and that land use mixture is critical for walking mode shares to rise to reasonable levels. These facts suggest that the greatest transportation-related energy savings for new development are to be found where there is a pre-existing urban fabric of streets, retail and employment. Efforts to reduce carbon emissions through land use should focus on leveraging and growing high-accessibility areas such as central cities and existing suburban employment centers, rather than creating detached mixed-use developments on the urban edge. Building resource efficient communities should be more about catalyzing under-used urban and suburban landscapes than creating new ones from scratch.

2. Refinement of four-step transportation models to include characteristics of the built environment and remove the “suburban bias.”

Creating the kind of infill developments described above is made much more difficult by current transportation models, which effectively punish infill developments by failing to consider the possibility that new residents will walk and bicycle more frequently, simply by virtue of their location. Mixed-use projects that include both housing and retail, for example, are assumed to generate as many trips as the equivalent amount of housing created in isolation from retail. These models need to be revised to consider the potential “capture” of trips within the development. Moreover, the findings of existing models make traffic and related environmental impacts of infill appear much worse than they are, disadvantaging

them in level-of-service assessments, and therefore in local permitting and political processes. Reform of the transportation models to incorporate the effects of locational characteristics, not just the travelers’ characteristics, is an important research need.

In addition, the quality of the pedestrian and bicycling environment needs to be considered in the models as well. Substantial VMT reduction almost necessarily requires more walking and bicycling for short-distance trips. Furthermore, greater use of mass transit for medium- and long-distance trips will require people to travel from home to the transit stop – a trip that ordinarily can be taken on foot or by bicycle if the street environment is appropriate. The increase in pedestrian trips resulting from various conditions of safety, comfort, and enjoyment (see Chapter 3) should be quantified and used to further develop the “design” component of these models. Fully incorporating street design factors into transportation models would allow planners to quantify the avoided energy use and carbon emissions resulting from changes to street designs -- a major breakthrough in resource efficient community planning under SB 375.



3. The Street Design - Transportation

The land use-transportation connection is of great importance to resource efficient communities. But ultimately, it is only part of the equation. As discussed in Chapter 2, important reductions in vehicle miles traveled are possible through planning compact land uses, but these reductions are likely not sufficient to fully meet the state's carbon emissions challenges. Achieving even deeper reductions in VMT means creating communities where non-motorized transportation is truly convenient, comfortable, safe, and enjoyable.

Reducing automobile trips means increasing walking and cycling trips, either as a direct substitute, or as a means of accessing public transit. But people will not walk or bike if distances are excessive, if they experience thermal discomfort, or if they do not feel safe. As we have seen, ensuring convenience of walking and biking is primarily a matter of concentrating potential destinations in tight clusters close to housing or other trip origins. This is most effectively done in central cities or older suburban areas, where the pre-existing street networks and land uses patterns are often more transit- and pedestrian-friendly than in post-war suburbs. In these situations, new "infill" residential development is often what is needed to achieve a critical mass of pedestrians that will support transit and neighborhood-serving retail. Creating neo-traditional developments at the urban edge – even if they mix uses or are designed for walking – is a distant second best in terms of potential VMT reductions.

But even within the right land use pattern, street design matters. Indeed, the street design – transportation connection is critical to resource efficient communities for four reasons:

- **Walking and bicycling are the most energy efficient means of transport.** Their total energy consumption per mile traveled is far below that of automobiles, or even public transit. Ultimately, the most efficient communities will be those that have the most pedestrians and bicyclists. But walking and bicycling is profoundly impacted by both the overall street layout of the community and the design of individual street segments.
- **More than one-quarter of all trips in the U.S. are less than one mile (Killingworth and Lamming 2001).** The large majority of these trips are still made by car, so the potential for substitution of car trips by walking and bicycling is substantial. Planners have traditionally used one-half mile as the distance that most Americans are willing to walk to retail or transit, but some studies have shown that the average walking trip is in fact longer than that (Ewing et al 2008).
- **The use of public transit usually involves a short-distance trip from home or work to the transit stops (and vice-versa). Even if the larger land use patterns are transit-supportive, there will still be a need to encourage the trip to transit to be taken on foot or on bike, rather than by car.** Resource efficient communities will therefore need to pay special attention to the street environments within one mile of transit stops.
- **Getting more people on the sidewalks and bike lanes creates a self-reinforcing**

Connection

spiral toward greater collective efficiency. More cars just means more congestion. But more walkers and bicyclists usually means more safety, more social opportunity, more community spirit, and more nearby stores – all of which encourages even more pedestrians and bicyclists. Walking and bicycling reinforce themselves, by making their own environment more suitable and pleasant. Mass automobile use makes its own environment less suitable and pleasant, creating a constant need for more capacity to (temporarily) escape the congestion. Community designers should seek out locations where an “upward spiral” of pedestrianism and bicycling can be created.

The literature shows that comfort and safety must exist for people to choose walking and biking on a routine basis. Once these basic (though not always simple) conditions are met, enjoyment and “livability” values of walking become an important additional determinant of mode choice. An attractive visual environment, social opportunity, window shopping, and exercise are all benefits to walking and biking that are not as readily available to drivers. For this reason, “street design” must include not only the design of the public right-of-way, but also the adjacent buildings and spaces. Building setbacks and façade design are potentially as important as trees, land widths, and parking requirements.

Achieving better street design will require rigorously identifying the relationships between these design factors and transportation behavior. Transportation planning is currently guided by

four-step models and motorized vehicle traffic “level of service” calculations that take little account of the characteristics or needs of the pedestrian and bicycling environment. A rigorous research basis for the street design – transportation connection will be the only way to ensure that pedestrians and bicyclists are planned for at least as well as automobiles are – an absolute pre-requisite for resource efficient communities.

Research findings

Studies of pedestrianism and bicycling have yielded suggestive initial findings that will provide the basis for future efforts to quantify important relationships. This recent research has also complemented decades of urban design research that has sought to identify the factors that make



streets and cities memorable and delightful to pedestrians (see e.g. Jacobs 1995, Gehl 2008, Lynch 1960). This accumulated body of urban design knowledge forms an important evaluative context for research results on specific aspects of street quality. Continued research will ultimately be required to make necessary revisions to the transportation models that so powerfully shape design decisions about streets.

1. Given sufficient destination accessibility and path connectivity, the key factors in shaping the willingness to walk are safety, comfort, and enjoyment.

Planners and public health experts have devoted increasing attention in recent years to identifying the physical characteristics that make a neighborhood “walkable.” Southworth (2005) assessed neighborhoods around the world with high rates of walking and found a number of common factors, including a connected path network, multiple destination options, safety from traffic and crime, and a high degree of visual stimulation. Saelens and Handy (2008) conducted a meta-analysis that found that the key correlates of walking are the distance accessibility of destinations, the aesthetic qualities of the environment, and the presence of sidewalks and network connectivity. Zacharias (2001) found that pedestrians choose routes which are “legible” to them (i.e. they give an overall sense of orientation and direction), and that some complexity of form and space within a more regular structure is desirable.

Rajamani et al (2002) concluded that mixture of land uses is associated with increased propensity to walk for non-work trips. They also found that people are more sensitive to delay when walking or bicycling than when driving or taking transit, implying that the directness of available

routes and the length of waits at intersections may be important factors in people’s choice to walk. Lee and Moudon (2006) found that walking for transportation is more affected by physical variables, including distance to amenities, presence of street trees, average block size, and total length of sidewalk, than is recreational walking.

Safety

Safety from both traffic and crime is a critical dimension of walkability. Intuition and research both strongly suggest that people will not walk where they do not feel safe. Moreover, perceptions of safety may be at least as important as the actual likelihood of any harm. Jacobsen (2003) found that in California, both pedestrians and bicyclists were safer with larger numbers, primarily because drivers knew to expect their presence. When there is a steady flow of non-motorized traffic, virtually all drivers employ caution, slow down, and look more carefully. Several studies have shown that average driving speeds rise once travel lanes exceed 12 feet in width, and that higher speeds are associated with more accidents (Lee and Mannering 1999; Potts et al 2007; van der Horst and de Ridder 2007). Narrower lanes therefore have been found to enhance pedestrian safety, as do traffic-calming measures and even street trees planted close to the roadway (Ewing and Dumbaugh 2009). Saelens and Handy (2008) found that sidewalk and traffic safety improvements are associated with increased walking in some studies.

Litman (2008) found that high-traffic streets often effectively act as a physical barrier to pedestrians, due to pedestrians’ fear of crossing. In 2002, nearly 23% of vehicle collisions with pedestrians occurred in a crosswalk, and one-third of these accidents resulted in severe or fatal injury (Ragland and Mitman 2007). A large body of research on

crosswalk design shows that multiple treatments (e.g. striping, signs, flashing lights, raised pavements) are necessary to fully alert drivers to the potential presence of crossing pedestrians (Knoblauch et al 2001; Huang and Cynecki 2001). Some researchers have also found that increased pedestrianism reduces street crime due to more “eyes on the street” (Cozens and Hiller 2008). This may apply more strongly to serious crimes such as assault, in which a perpetrator wishes to minimize the number of potential witnesses (Loukaitou-Sideris 1999).

Thermal comfort

Few studies have explored the direct influence of climate and weather on transportation choices. Attaset et al (2009) found that weather variables accounted for about 10% of the variation in pedestrian crossings at thirteen locations in Alameda County, despite a very favorable climate. Aultman-Hall et al (2009) found that as much as 30% of the pedestrian volume at a single location in Montpelier, VT could be explained by weather (particularly rain) and that these findings held true even when time of day and day of week are controlled. Finally, a study in Maryland by Clifton (2005) found that 42% of men and 44% of women reported reducing their walking in different seasons. These fragmentary results suggest that if sidewalk conditions can reliably be kept comfortable, more people will walk and bike more frequently.

There is a more general literature on behavioral observations in plazas, parks, and other open spaces in response to climatic conditions. Nikolopoulou and Lykoudis (2006) analyzed the findings of the European Union’s RUROS project and found a strong relationship between microclimate (especially air temperature and solar

radiation) and self-reported comfort conditions. They also found that the conditions that people declared to be comfortable could vary quite substantially across Europe – as much as 18° F – in study locations ranging from Athens to England.

The psychological dimension of comfort is an important finding that is supported by other work as well (Nikolopoulou and Steemers 2003). A number of psychological issues have been found to influence people’s judgments of their own comfort, including:

- Expectations of what the environment “should” be like relative to current conditions;
- Recent experience of the outdoor environment, which helps to shape expectations;
- The perception of some degree of control over conditions, which leads people to tolerate wider variations;
- The degree to which a space is judged to be “natural,” which leads people to tolerate wider variations;
- The degree to which people expect exposure to challenging conditions to be short-lived, which makes them less likely to characterize those conditions negatively

In the RUROS findings, expectations, memory of recent experience, and personal choice were all found to be significant factors in self-reported satisfaction.

Bruse (2005, 2007) has modeled human choice of routes through a model environment based on thermal comfort, which is simulated through a two-node model of the human thermoregulatory system (2007, p. 700). Spagnolo and de Dear (2003) have studied outdoor thermal comfort by comparing

microclimate measurements with self-assessments by people using those environments. They found that among respondents in Sydney, thermal comfort is achieved at higher temperatures outdoors than it is indoors.

Enjoyment

Enjoyment of walking often involves the visual appeal of attractive surroundings, social opportunities to run into neighbors or people-watch, and window shopping. The exercise benefits of walking can also play a significant role in helping to create a sense of well-being. Some research suggests that walking for enjoyment can help leverage substitution of walking for short-range car use. Schlossberg et al (2007) found that enjoyment of walking is a significant factor in people's willingness to walk to up to one-half mile to transit stops. Saelens and Handy's (2008) meta-analysis identified six reviews of pedestrian behavior that found that aesthetic qualities of the pedestrian environment were associated with walking. Naderi (2003) found that aesthetic judgments about a place, often involving vegetation, are important determinants of a route choices.

Enjoyment is often directly diminished by car traffic. A classic study by Appleyard (1981) found that contact between across-the-street neighbors was significantly reduced by high-speed traffic. Bosselmann and Macdonald (1999) have found that the design of multi-way boulevards helps mitigate the adverse social effects of high traffic loads. Boulevards contain extensive street tree coverage and high-quality pedestrian spaces, which directly contributed to high resident satisfaction despite the high traffic loads. More

generally, Jacobs (1995) has examined the design qualities that make "great streets" around the world. Surveying dozens of examples, he identifies "places for people to walk with some leisure," physical comfort, visual definition, and trees among the characteristics that make great streets.

2. Current pedestrian level-of-service calculations assume that pedestrians wish to avoid congestion, when in fact higher pedestrian density usually enhances pedestrian experience.

Level of service (LOS) assessments play a critically important role in shaping transportation planning, public investments, and environmental impact assessments. In general, the major objective of transportation plans is to improve overall LOS for automobile traffic. Billions of dollars are invested annually in projects specifically dedicated to that purpose. More generally, the LOS rating is taken as shorthand for the overall quality of a given transportation facility.

Given the importance of level of service, it is critical to understand how it is being formulated. With respect to pedestrian level of service, LOS calculation methods have been profoundly limited and illustrate the ways in which the nature of pedestrian activity has been fundamentally misinterpreted. Pedestrian level of service has most broadly been defined as consisting of three general performance measures (Landis et al 2001): sidewalk capacity, perception of safety, and the quality of the walking environment. To date, however, only the first two have been rigorously incorporated into level of service calculation methods, leading to results that routinely mischaracterize the actual suitability of pedestrian environments.⁹

⁹The 2010 update of the Highway Capacity Manual may begin to incorporate pedestrian quality assessments in a limited way.

Sidewalk capacity

The “sidewalk capacity” measure was originally developed by Fruin (1971), and is still the sole basis for the pedestrian LOS method used by the Highway Capacity Manual (2000), the authoritative standards book for transportation engineering. The key criterion in this measure is simply “space-per-pedestrian,” or the inverse of density (Dowling et al 2008). Better LOS is thought to result from greater space per pedestrian, or lower density. The implicit assumption is that pedestrians, like drivers, want to move through a route as quickly as possible, with as few other users of the facility as possible to obstruct or distract them.

In extremely congested pedestrian locations such as midtown Manhattan or San Francisco’s

Chinatown, such an assumption might be justified. But virtually everywhere else, as the research reviewed above has shown, greater pedestrian density brings an improvement in overall pedestrian quality. This is because more people on the sidewalks usually yields greater safety, more social opportunity, and more retailing – factors that encourage people to walk. An assessment method focused solely on density as a negative factor has no way of including these associated benefits of greater pedestrian density.

Perception of safety

Additional research has examined the role of perceptions of safety (from traffic) in pedestrian level of service, the second performance measure. Landis et al (2001), on behalf of the Florida Department of Transportation, found that lateral



separation from traffic, the volume of motor vehicle traffic, and the speed of motor vehicle traffic are all statistically significant factors in perceived level of safety. They developed a more advanced pedestrian LOS model based on this finding. Petritsch et al (2006) also found that the total width of driveways and intersections can significantly affect perceptions of safety.

The National Cooperative Highway Research Program (2008) has recommended a pedestrian LOS model that is a hybrid of a density model and a model of “other factors” that includes the safety-oriented model (Dowling et al 2008). However, NCHRP recommends calculating both models and taking the worse of the two as the final LOS for a given sidewalk segment. In practice, resource efficient streetscape designs, which would actively seek to increase pedestrian density even as they sought to narrow streets and improve safety from traffic, would still be discouraged by this method.

Pedestrian quality

The third potential performance measure in LOS calculations is the quality of the walking environment. As Landis et al (2001) point out, however, “there is no established approach” for incorporating these factors into LOS calculations. Works by Sarkar (1993, 1996), Khisty (1994), Dixon (1996), and Clemente et al (2005) have sought to create “quality ratings” that include comfort, visual character and other factors compiled in a qualitative rating scheme. These efforts are preliminary steps toward developing robust methods for incorporating experiential variables into LOS calculations, but much more research remains to be done to quantify these design factors and improve LOS rating methods.

3. Travel times, street connectivity, land use mix, and traffic conditions are at least as important as the presence of bike lanes in shaping the willingness to bicycle.

Bicycling is an important low-carbon mode of urban transportation, since bicycles are human-powered and have modest infrastructure needs. Bicycling is also well suited to the scale of American cities. Bicyclists travel at similar average speeds to cars for trips under three miles (Dill and Gliebe 2008), which constitute almost half of urban trips (Pucher et al 1999). During the 1990s, the amount of trips taken by bicycle almost doubled (Federal Highway Administration 2004), and residents of some bicycle-friendly small cities ride bicycles for over 10% of commute trips (Federal Highway Administration 1992). Nonetheless, bicycle trips only constitute 0.8% of all trips in the U.S. (Federal Highway Administration 2004), and few if any American cities have a complete bicycle network.

Researchers have yet to reach a strong consensus on what factors encourage bicycling, due to the lack of good data and the complexity of the question. Like pedestrians, cyclists are less insulated from their surroundings than drivers or transit riders, and the decision to bicycle to a destination is based on a wide variety of variables in the physical environment, including proximity, speed, topography, weather, traffic volumes, bicycle facilities along the route and at the destination, and aesthetics.

According to Moudon and Lee (2003), three factors in the built environment influence travelers deciding whether or not to travel by bicycle: the origin and destination of a trip, the characteristics

¹⁰ It should be noted that these findings could simply mean that communities with more cyclists are more likely to build facilities.

of the are around the route, and the characteristics of the route itself (including the presence of bike lanes). The balance of the research has concluded that the first two factors are equally, if not more, important than bicycle facilities in determining mode share. Travel times, street connectivity, land use mix, and traffic conditions are just as important as bicycle lanes in determining whether or not people choose to ride.

Cervero and Duncan (2003) found that mixed-use development at trip origins and bicycle-friendly design at destinations were the two most important land use factors in inducing travel by bicycle in the Bay Area. Dill and Voros (2007) surveyed Portland residents and found that street connectivity and distance to the city center had a significant effect on cycling for utilitarian purposes during the summer, but that the amount of bike lanes located within one quarter-mile of respondents' homes had no effect on travelers' decision to ride. Gonzales et al. (2004) surveyed cyclists on off-street paths in Rhode Island and found that riders often did not commute on the pathways because of a lack of connecting facilities. Stinson and Bhat (2003) found that the most important factor in study participants' choices of hypothetical routes was travel time, followed by the presence of bicycle facilities and road class.

Dill and Gliebe (2008), using GPS tracking units on actual bikers, found that cyclists were willing to ride 17% farther in order to avoid high-traffic arterials, eight percent farther in order to use a separated bike path, six percent farther in order to use a "bike boulevard" (a bicycle-friendly neighborhood street), and only four percent farther in order to use a road with a bike lane. In other

words, participants were roughly as likely to ride on low-traffic local streets as they were to ride on streets with bicycle facilities.

Some findings have emphasized the importance of bike lanes, however. Howard and Burns (2001) found that the routes taken by 150 regular bike commuters in Phoenix closely resembled the shortest routes, but were 25% more likely to involve roads with bicycle facilities. Shafizadeh and Neimeier (1997) found that some cyclists in Seattle would rather ride longer distances on a bike path rather than shorter distances in mixed traffic. Hunt and Abraham (2007) found that study participants were willing to trade 4.1 minutes in a bike lane and 2.8 minutes on a bike path for one minute of traveling in mixed traffic. Tilahun et al (2007) found that University of Minnesota employees, responding to hypothetical scenarios, said they would travel 16 minutes out of their way to use a bike lane, nine minutes longer to travel on a route without on-street parking, and five minutes longer to travel on an off-road path.

Nelson and Allen (1997) analyzed data from eighteen American cities to build a model that explained 83% of the variation in the number of residents bicycling to work as a function of the combined mileage of bicycle paths and lanes, the percentage of college students in the population, and the number of rainy days per year. Dill and Carr (2003) also found a significant correlation between the density of bike lanes and paths and journey-to-work mode share across 35 cities. According to their model, each additional mile of bike lanes per square mile (an exceptionally large increase for most cities) is associated with a one percent increase in bicycle mode share. In a random survey of biking habits and attitudes in six college communities and six control communities,

Xing et al (2008) likewise found a correlation between the amount of bicycle infrastructure and bike commuting.¹⁰

4. New level-of-service methods for bicycling reflect cyclists' actual experience of routes.

Despite these mixed findings, the predominant bicycle level of service (LOS) calculation method in the Highway Capacity Manual emphasizes the role of bicycle facilities above all the other factors that influence bicycling behavior. As with pedestrian LOS, it focuses on density (and the delay presumed to result from density) to calculate LOS (Dowling et al 2008), even though this is not an important factor in the overall quality of cycling environments. In fact, Dowling et al (2008) found that the LOS method matched observers' subjective ratings of path quality only 15% of the time.

More recent researchers have acknowledged that a wider variety of variables influence cyclists' perceptions of route quality, and have created a more comprehensive model for bike LOS. Landis et al (1997 and 2003) and Petritsch et al (2007) created an alternative method for estimating bicycle LOS based on traffic volumes and speeds, the presence of a bike lane, the effective width of the outside through-lane, pavement condition, and the volume of heavy vehicle traffic. This method is typically able to explain 70 to 85% of the variation in ratings that participants give to routes. This "Florida method" has been applied to over 200,000 miles of North American roadways (Dowling 2008). In a similar effort, the Federal Highway Administration developed a bicycle compatibility index (BCI) (Harkey et al 1998, Federal Highway Administration 1998) to measure route suitability for cycling as a function of the number of lanes, lane widths, traffic volume, traffic speed, median type, driveway density,

sidewalks, and type of roadside development. The model accounted for 89% of the variation in grades given to road segments.

Conclusions and research needs

Pedestrian and bicycle behavior remain relatively understudied compared to other components of the transportation system. It has been suggested that this lack of study may be a product of the small amounts of money that go into pedestrian and bicycle planning, or an assumption that they can "take care of themselves" within existing street networks (Litman 2009). Serious efforts to create resource efficient communities cannot afford to perpetuate this outlook. This is especially the case where they can feasibly substitute for automobile use, as these are the situations where energy use and carbon emissions can be avoided. Generally speaking, these are short-distance trips (less than one mile) originating at the home or workplace, with retail or transit stops as a destination. Pedestrian-oriented land use patterns with appropriate densities and mixture of uses are critical – but so too is the design of the street. There is much research to be done before these factors can be fully integrated into transportation planning.

The major research needs in this area include:

1. Pedestrian and bicycle rating systems that include a credible assessment of the quality of the environment should be created.

Current level-of-service assessments do not adequately consider the quality of the pedestrian environments, instead relying only on measurements of density, delay, and separation from moving traffic. In the case of density, these models entirely mis-characterize what is desirable for the overall quality of pedestrian experience.

The role of comfort and enjoyment in that experience must be much more robustly integrated into these assessments, so that a rating reflects the actual likelihood that pedestrians will use the facility in question. Ultimately, there is a need for a rating system that incorporates all the factors that influence the likelihood and pleasurability of walking, that can be applied to a wide range of streets in many locations, and that has achieved internal validity through field testing.

Bicycling level-of-service rating systems are in better shape. Nonetheless, even the improved bicycle level of service rating system focuses solely on ensuring bicyclists' safety along select routes, without considering whether these routes actually serve destinations. There is also more work to be done in incorporating experiential variables that are likely important to cyclists. Researchers should also do more to take into account the needs of cyclists with low-to-moderate experience levels, who may value different characteristics of the cycling environment than more experienced riders.

2. Street trees are worthy of special research consideration because they contribute directly to safety, comfort, and enjoyment.

Trees create a physical and psychological safety barrier from traffic, create a mixture of sun and shade on sidewalks, protect against rain, and improve the visual character of the street. They also help mitigate the urban heat island effect (see Chapter 4) and filter air pollution. The planting densities needed to create a continuous canopy and a protective "fence" of tree trunks to separate pedestrians from traffic vary by species. According to one proposal by Ewing (1999), trees should be planted no more than 30 feet apart to achieve these benefits, but development codes often call for tree spacing of 50 to 70 feet (see Chapter 8 for further discussion). There is little direct research on how

much street trees and landscaping affect thermal comfort, and whether they influence the decisions to walk.

3. There is a general need for better data gathering techniques, and more diverse site selection, in studies of pedestrianism and bicycling.

Gathering more robust aggregate travel data would help researchers in conducting cross-sectional analyses of different cities or neighborhoods (Macdonald, Sanders, and Supawanich 2008). Moreover, many of the key survey-based studies on pedestrianism and bicycling have been done in relatively benign settings such as the Bay Area, Portland, and Seattle. These are places where the climate is mild, the urban fabric is well suited to walking and cycling, and the quality of urban design is relatively high. While these studies have consistently found that good design makes a difference even in favorable conditions, more research needs to be carried out in locations where conditions are not as favorable, and where resource efficiency improvements are more acutely needed.



4. The Urban Heat Island Effect and Cool

The importance of thermal comfort to pedestrians and cyclists means that resource-efficient communities need to manage microclimates effectively in outdoor environments. Cities are warmer than the countryside that surrounds them, a phenomenon known as the “urban heat island effect.” The heat island effect occurs because the surface area of cities is dominated by man-made pavements and roofs which typically absorb and re-radiate more heat energy than vegetation, thereby raising the ambient temperature of the urban environment.

Community design must strive to mitigate the heat island effect for at least four reasons:

- **Outdoor comfort.** People will be much less likely to walk and bicycle for transportation in warm climates and/or warm seasons when surface temperatures of streets and sidewalks are elevated. Microclimates must be managed to fit into the human thermal comfort zone, not vice-versa.
- **Building energy use.** Both surface and atmospheric heat island effects raise demand for cooling energy in buildings. Since large cities have thousands of buildings, this additional energy use is very substantial in warm climates such as inland California.
- **Infrastructure cost savings.** Surface heat island effects increase peak-period cooling energy demands in buildings, requiring greater peak-period capacity for electricity infrastructure. Surface effects can also accelerate the deterioration of pavement, substantially increasing maintenance and replacement costs over time.
- **Adapting to climate change.** Atmospheric heat island effects are similar in magnitude to anticipated near-term global warming estimates (Stone and Rodgers 2001). Mitigating the heat island effect can be seen as a kind of trial run for climate change adaptation.

Extensive technical research on heat island effects and potential mitigation strategies has already been carried out at Lawrence Berkeley National Lab under the sponsorship of the U.S. Department of Energy and the CEC. The major mitigation strategies include installing cool roofs and pavements that reflect more of the sun’s radiation (before it is absorbed and locally re-radiated), and extensive tree planting on streets and next to buildings. Wind corridors, mist spraying on roofs, vegetated roofs, and advanced materials for vertical exterior building surfaces can also be important in certain situations.

These mitigation strategies should become part of the basic fabric of community planning and development in California. Although technical research should continue on each of these (especially on cool pavements), a primary additional research need is for greater exploration of the economic and policy aspects of “cool communities” implementation in California. Useful initial estimates of direct costs and benefits of cool communities have been created for Los Angeles, but such work needs to be expanded to include additional benefits (such as infrastructure cost savings). Within California, cost-benefit analyses should be carried out for multiple climate zones. Removal of code barriers to planting

Communities

trees along streets and in parking lots, and of aesthetically based code and covenant barriers to installation of cool roofs and pavements, is also important. Finally, continued advances in heat island modeling are also important to provide high-quality input into pedestrian and bicyclist thermal comfort models. This will allow continued refinement of investigations into pedestrian/bicyclist comfort as a component of improved transportation models and level of service ratings.

Research findings

Urban heat island effects have a number of important consequences, ranging from energy use to direct effects on human health. The major summary findings of urban heat island research are:

1. Heat island effects drive up atmospheric and especially surface temperatures, increasing energy use and creating other undesirable effects

Annual mean air temperatures in a city of one million people can be up to 5.4° F above those of its surroundings (Oke 1997). In California, major cities have been warming steadily for several decades, at a rate of about 0.8° F/decade in Los Angeles and San Diego, 0.4° F/decade in Oakland and Sacramento, and 0.3° F/decade in San Jose (Akbari et al 2001). However, these atmospheric averages mask localized surface effects that can be far larger. Daytime surface temperatures of exposed roofs and pavements in cities are, on average, 18 to 27° F above rural surroundings (Voogt and Oke 2003), and can reach temperatures 50 to 90° F above the air temperature (Berdahl and Bretz 1997).

Akbari et al (2001) found that each 1.8° F (1° C) of warming adds about 500 MW – the approximate generating capacity of a large coal-fired power plant – to the air conditioning load in the Los Angeles basin. In addition, peak urban electric demand rises by 2 to 4% for each 1.8° F increase in daily maximum temperature above a threshold of 59 to 68° F (Akbari et al 2001). That forces electricity infrastructure, which is sized to handle such peaks, to be larger than it otherwise need be. Heat islands also contribute to air pollution by intensifying the chemical reactions that form smog. Taha et al (1994) found that each 1.8° F (1° C) of warming above 72° F increased smog incidents by five percent.

2. Cool roofs have been found to substantially reduce peak cooling energy demand in buildings.

“Cool roofs” are composed of light-colored, highly reflective and emissive materials that absorb substantially less solar radiation than traditional roofing materials such as asphalt shingles or tarpaper. Standard black asphalt roofs can reach temperatures of 165 to 185° F during the summer, whereas cool roofs reach peak temperatures of only 110 to 115° F (Konopacki et al 1998). These reductions in surface temperature on the roof directly influence the cooling energy consumption of the building.

A variety of studies have demonstrated the cooling savings that result from cool roofs in California. Akbari et al (1993) found a 34% reduction in overall cooling energy use, and a 17% reduction in peak electricity demand, in a school trailer in Sacramento. The same study found a 69% reduction in overall use, and 32% peak demand

reduction, in a Sacramento residence. Konopacki et al (1998) found that cool roofs reduced summertime average daily air conditioning use by 18% in Davis and 13% in Gilroy. These variations are largely due to site- and building-specific factors, such as insulation levels. Cool roofs also improve indoor thermal comfort. Vincent and Huang (1996) found that cool roofing reduced second-story air temperatures by 4° F in an apartment complex in Sacramento, despite good insulation. Less insulated buildings would experience even greater reductions.

Because cool roofs reflect solar energy year-round, there is a “winter penalty” of increased heating energy demand. In places like Chicago and Philadelphia, the winter penalty almost completely offsets summertime cooling savings, but it is small in California and other warm climates – on the order of 5% in Los Angeles, for instance (Konopacki et al 1997). Early monitoring data from New York City also suggest that the “winter penalty” might be avoided by the use of vegetated green roofs as a heat island countermeasure (Gaffin et al 2009). Vegetated roofs are also beneficial for stormwater management, and can provide aesthetic benefits to neighboring buildings.

3. Cool pavements can significantly reduce both atmospheric and surface temperatures in cities.

“Cool pavements” reflect more solar energy, store less heat and have lower surface temperatures than conventional paving materials. They usually consist of asphalt or concrete combined with high-albedo materials. Standard asphalt or concrete pavements can reach peak temperatures of 120-150° F (Pomerantz et al 2000), which makes outdoor environments uncomfortable and increases cooling energy needs for nearby structures. Cool pavements can reduce those peak surface temperatures by at least 10°F.

Because pavement can cover up to 45% of the land area of a city (Akbari et al 1999), their reflectance and thermal properties are important to the overall urban heat island effect. Studies have shown that each 10% increase in solar reflectance of pavements could decrease surface temperatures in a given location by 7°F, and that a city-wide increase from 10% to 35% could reduce air temperatures by 1°F (Pomerantz et al 2000), resulting in significant cooling energy savings. In addition, cool pavements can yield substantial savings in pavement maintenance. Pomerantz et al (2000b) conducted simulations of asphalt pavements that showed that a 20°F reduction in surface temperature increased the pavement’s lifespan by a factor of 10, and a 40°F reduction increased the lifespan by a factor of 100.

4. Cool roofs and pavements, implemented globally, could be a very important tool in fighting climate change directly.

Pavements and roofs cover about 0.6% of the Earth’s surface. Akbari, Menon and Rosenfeld (2008) calculate that raising the net albedo (i.e. reflectivity) of these surfaces by 0.1 throughout the tropical and temperate world could create a one-time offset of about 44 gigatons of CO2 – more than the entire world’s projected annual CO2 emissions in 2025. This is also equivalent to taking all of the world’s 600 million cars off the road for 18 years. Moreover, the climate-moderating effects of cool roofs and pavements occur instantaneously upon installation, and involve no complex mechanical or financial instruments. Akbari, Menon and Rosenfeld (2008) estimate 44 gigatons to be worth about \$880 billion, at the then-current European market price of \$20/ton for carbon. This economic value has not yet been incorporated into any comprehensive cost-benefit analysis of “cool community” strategies.

5. Tree shading has numerous benefits for urban temperature, energy use and the overall quality

and healthfulness of the outdoor environment.

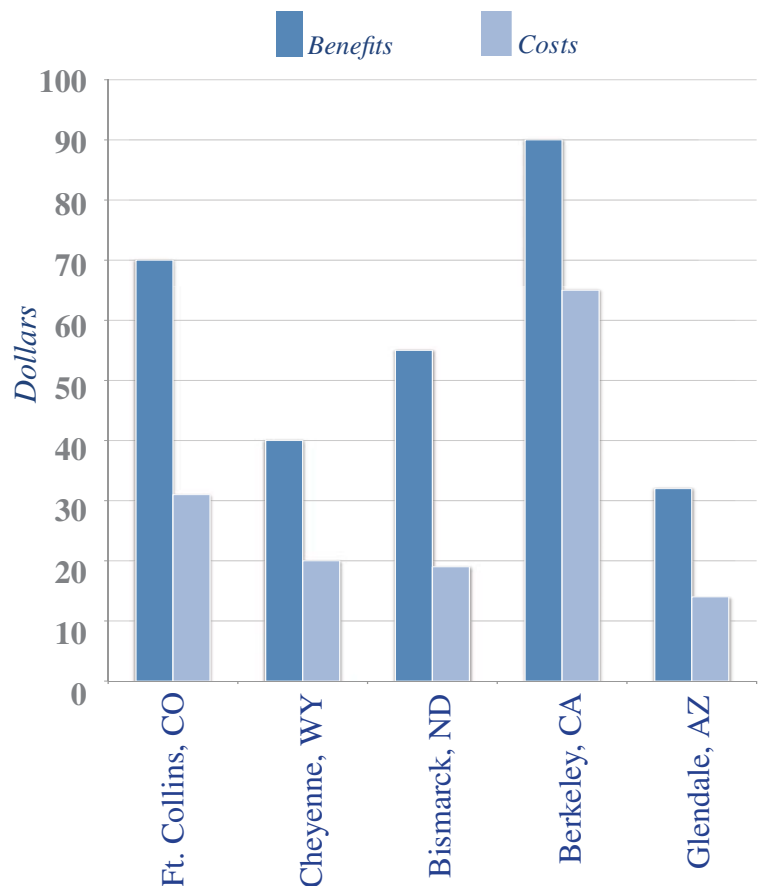
Trees and other vegetation also help cool the urban environment. Tree shading can reduce peak surface temperatures below the canopy from 20 to 45° F (Akbari et al 1997), and vines on the side of buildings have been shown to reduce surface temperatures of the walls by up to 36° F (Sandifer and Givoni 2002). Evapotranspiration from plants also has a cooling effect by using heat from the air to evaporate the water that plants emit from their leaves.

Together, shading and evapotranspiration have a significant effect on air temperatures in developed areas. Suburban areas with mature trees are 4 to 6° F cooler than those without mature trees (Kurn et al 1994). Even unshaded grass sports fields can reduce air temperatures above the field by 2 to 4° F compared to the surrounding areas (Kurn et al 1994). The cooling effects of trees and vegetation result in significant cooling energy savings. Akbari et al (1997) found that placing trees around houses in Sacramento to shade west- and southwest-facing windows saved up to 47% of household cooling energy. Another simulation found that creating a 20% tree canopy over a house in various communities around the United States would result in annual cooling energy savings of 8 to 18%, and even some small additional annual heating energy benefits due to wind blockage (Huang et al 1990). Shading also extends the life of pavements. McPherson and Muchnick (2005) found that resurfacing costs for residential streets in central California can be reduced by up to 60% if the pavement is shaded. Tree roots can also cause pavement heaving, so proper species selection and planting practices are important.

Urban vegetation provides a variety of other benefits as well. As reviewed in chapter 3, trees have major urban design and aesthetic benefits

that are important motivators for people to walk and bicycle. As will be covered in chapter 7, trees also improve residential and commercial property values by beautifying neighborhoods. In addition, trees and vegetation filter various particulate pollutants out of the air, reduce the formation and mobilization of VOCs and ozone, reduce exposure to ultraviolet rays, and remove and store carbon (U.S. EPA 2009). These are major public health issues that can have significant human and economic consequences, including increased heat deaths, increased hospitalizations for respiratory

Figure 5. Estimated Net Benefits of Urban Trees in Five Western Cities



Net Benefits were positive for all five cities, ranging from \$21 per tree in Cheyenne to \$38 per tree in Ft. Collins.

Figure 5: Source: U.S. Environmental Protection Agency. 2009. Reducing urban heat islands: Compendium of strategies: Trees and Vegetation. Washington, D. C.

distress, and increased incidence of skin cancer (Stratus Consulting 2009).

Urban vegetation is also critical to stormwater management. Pavements and roofs impede the natural infiltration of water into the soil, which increases the speed, volume and pollution of surface runoff after rainstorms. That increased urban runoff erodes stream channels, harms aquatic ecosystems and in extreme cases causes flooding (Ferguson 1998). Reversing this destructive spiral involves creating vegetated areas where stormwater can collect and infiltrate within the urban environment before entering the storm sewers. Planning urban vegetation to achieve both heat island and stormwater benefits is an example of the multiple-benefit strategies that resource-efficient communities must employ.

When fully accounted, the benefits of urban trees significantly outweigh the costs of installation and maintenance. A five-city study by MacPherson et al (2005) found that net benefits (including property value, stormwater, air quality, carbon, and energy benefits) ranged from roughly \$19 to \$38 per tree (see Figure 5). In California, estimates of annual net benefits have ranged as high as \$85 per tree (EPA 2009).

Conclusions and research needs

Research clearly shows that cool community strategies will save substantial amounts of energy (especially in warm climates), improve public health, and partially mitigate climate change. To accelerate implementation of these strategies, however, the following research needs should be met:

1. Comprehensive cost-benefit analysis is needed to strategize the implementation of cool communities measures.

There is much less literature on the economic and policy aspects of cool communities strategies than on technical aspects, yet economic incentives and appropriate financing mechanisms are likely to be the most important drivers of implementation. There is a need to comprehensively assess the costs and benefits of cool communities strategies in order to properly finance and incentivize implementation. The benefits range beyond local energy use into reducing maintenance costs of shaded pavements, potentially increasing property values through tree planting, and reducing carbon emissions globally. Because various beneficiaries are widely distributed, careful design of equitable financing mechanisms is needed.

Rosenfeld et al (1996) simulated a comprehensive cool community strategy for the entire Los Angeles Basin. The simulation involved increasing the albedo of 1,250 km² of roofs by about 0.35, increasing the albedo of 1,250 km² of pavements by about 0.25, plus planting 11 million street, shade and park trees. They then calculated the direct energy savings, indirect energy savings, and smog reduction benefits of these strategies, along with costs. Direct benefits included air-conditioning energy savings of cooler roofs or shade, and peak power savings accruing to utilities. Indirect energy savings included air-conditioning energy savings and peak power reductions due to overall air temperature reductions. Smog avoidance resulted from a 12% ozone reduction. These gross benefits collectively were appraised at \$535 million.

The Los Angeles study has been widely quoted in heat island research and public communication ever since it was published in 1996, a testament to the importance of such information. Additional costs and benefits have come to light in the 13 years since that study was completed, however, and should be included in future analyses. Major

additional benefits that should be assessed include:

- Property value benefits of trees (Donovan and Butry 2009)
- Avoided heat deaths and other illnesses (Stratus Consulting 2009)
- Avoided carbon emissions (Akbari et al 2008)
- Reduced roof maintenance associated with cool roofs (Levinson et al 2002)
- Reduced street maintenance due to shading (McPherson and Muchnick 2005)

More careful attention to maintenance costs for urban trees, and to opportunity costs for investment capital, is also needed. Many of these additional costs and benefits have been assessed individually, but new comprehensive cost-benefit analyses should be performed for cities in various California climate zones. Implementation likely will be accelerated if state and local policy-makers can look at the full picture of benefits and costs for specific locations. In addition, as the Los Angeles study recognized, benefits and costs are not evenly distributed throughout the community, and may be mis-matched between public and private entities. Analyses of implementation potential should carefully study possible financing structures that ensure efficient and equitable distribution of costs among beneficiaries.

2. The potential rate and cost at which the existing stocks of roofs and pavements in California could be made “cool” in the course of routine maintenance should be calculated.

Roofs and pavements both require significant ongoing maintenance and periodic replacement. Many roofs, for example, are recommended for replacement as often as every twenty years – much faster than the replacement rates of buildings or even many heating and cooling systems.

Pavements not only must be repaired periodically, but are also subject to disruption from repair of underground utilities and other construction projects. These moments of repair or replacement would likely be the most advantageous moment to switch to cool roofing and pavement technologies, so it is important to understand the rate at which such replacement could occur and the associated costs.

3. The effects of cool communities measures on outdoor thermal comfort should be measured.

Although it is apparent that increasing peak temperatures in warm climates reduces comfort for outdoor activities, research directly linking heat island effects to outdoor comfort remains to be performed. Atmospheric effects will influence pedestrian comfort by increasing the overall air temperature, but surface effects will be more powerful. Dark pavements exposed to sun quickly become uncomfortably warm, even on relatively moderate days.

There is a need to analyze the potential for heat islands to impede walking and bicycling by reducing outdoor comfort. Urban microclimate modeling used in heat island research can be used as an input to thermal comfort modeling to examine this issue. The beneficial effects of cool community strategies could likewise be assessed. Ultimately, it may be possible to estimate the changes in transportation mode choice that could result from widespread cool community strategies, with quantification of the associated energy use and carbon avoidance. If so, it would be another quantified benefit of cool communities that would further buttress the argument for their implementation.

5. Solar Access and Building Energy Use

Buildings are a major end-user of energy in California, consuming about 22% of the total. Along with the other sectors, dramatic reductions – on the order of 88% per capita – in the carbon emissions associated with building energy use are necessary by 2050. The emissions associated with buildings are a product of the total energy used and the carbon density of the energy sources; large improvements must be made in both areas. Buildings must use less energy, and the energy used must be from low- or no-carbon sources.

In recognition of these facts, government agencies and the building professions have begun setting ambitious goals for zero-energy buildings – i.e. those that produce as much energy as they consume annually. In California, the Energy Commission and the Public Utilities Commission have adopted policies for all new residential construction to meet zero-energy standards by 2020, and for all new commercial construction to follow suit in 2030 (Center for the Built Environment 2008).

At the national level, the U.S. Energy Independence and Security Act of 2007 created a Zero-Net-Energy Commercial Buildings Initiative within the U.S. Department of Energy to support the goal that all new commercial construction be net-zero energy by 2030. The law identifies an additional goal of having 50% of all commercial buildings be “net zero” by 2040, and 100% by 2050. New and renovated federal buildings are required to be net-zero by 2030. In addition, the Environmental Protection Agency, the American Institute of Architects, the U.S. Green Building Council, and the American Society of Heating, Refrigeration and Air-Conditioning Engineers have all accepted the “2030 Challenge” that advocates that all new buildings and major renovations be carbon neutral by 2030.

The net-zero goal is a useful framework for analysis for two reasons. First, recall that total building-related carbon emissions must be reduced 88% per capita by 2050. The existing building stock that will be carried forward will likely continue to under-perform in carbon terms, even if retrofitted. This will place a greater onus on new development to carry the entire building sector toward deep carbon reductions. Second, “net-zero” provides a clear standard against which planners and designers can compare real-world possibilities. Building energy consumption is a complex subject, and systematic planning-level assessment of the many relevant variables across entire communities is difficult. The net-zero concept integrates those variables into a single, easily-understood, quantified standard.

What does all this mean for community design? The short answer is that solar access for buildings – both individually and collectively – becomes critical. Though reducing the carbon impact of imported energy sources (i.e. through use of renewable sources) will also be critical to this effort, much of the progress toward the zero-energy goal will have to be carried out at the building site. Demand for heating energy can be reduced substantially through passive solar design techniques that permit sunlight into the building in winter but not in summer. Water heating can also substitute passive solar for natural gas. Demand for daytime lighting energy can be reduced through natural daylighting, and other uses of electricity can be at least partially supplied by rooftop photovoltaics.

Along with mechanical efficiency and off-site renewable energy generation, these on-site solar techniques will be necessary to achieve “net zero”

buildings in large numbers. The one thing they all have in common, however, is the need for solar access. Planners and designers must strive to optimize the solar energy potential of buildings relative to other project goals, and there may also be efficiencies in generation and use that are achievable only at a neighborhood scale. Even if solar energy is not part of the current design program, the buildings created will stand for several decades, during which time the value of the on-site solar potential will likely grow.

Research findings

Research into net-zero buildings is relatively new, but findings from earlier research on urban solar access and street orientation are also relevant.

1. All definitions of net-zero buildings require on-site generation and therefore (in most cases) extensive solar access for the building.

To date, there are only a handful of buildings in the U.S. striving for “net-zero” status (U.S. DOE 2009). With regulatory requirements and incentives accumulating, however, they will become far more common in the coming decades. Torcellini et al (2006) have articulated four different definitions of zero-energy buildings. In descending order of difficulty to achieve, these include:

- Net Zero Site Energy – the net energy balance of the building is zero (or negative) when accounted for at the site (i.e. all energy needed is produced within the property boundary)

- Net Zero Source Energy – the net energy balance of the building is zero (or negative) when accounted for at the source (i.e. all energy imported is at least compensated for by on-site production)
- Net Zero Energy Costs – the building owner earns as much money from selling energy back to the grid as they pay for imported energy
- Net Zero Energy Emissions – the building produces as much carbon-free energy on site as it imports from emissions-producing energy sources.



Crucially, all four of these definitions imply both extensive demand reduction, and a significant amount of on-site energy generation (even if the energy supplied is sold back to the grid). This leads the authors to develop a hierarchy of renewable energy “supply” options, shown in Figure 6 (next page).

As the table shows, reducing demand comes first, including measures such as natural daylighting and passive solar heating in addition to mechanical efficiency improvements to reduce HVAC and plug loads. On-site supply options come next, including PV generation, solar water heating, and wind power if available. Last in the

hierarchy are off-site renewable energy supply options, either developed as part of the project, or simply purchased from the utility. For the designer seeking to create such buildings, solar access will be a fundamental determinant of the potential for a net-zero building.

In a companion study on the potential for zero-energy commercial buildings, Griffith et al (2006) found that 22% of commercial buildings could achieve net-zero status using today’s technology, and as many as 64% with anticipated 2025 technologies, but only if each building “was reoriented and elongated along an east-west axis for good daylighting and passive solar design,”

Figure 6. Zero-Energy Building Supply Hierarchy

Option Number	ZEB Supply-Side Options	Examples
0	Reduce site energy use through low-energy building technologies	Daylighting, high-efficiency HVAC equipment, natural ventilations, evaporative cooling, etc.
<i>On-Site Supply Options</i>		
1	Use renewable energy sources available within the building’s footprint	PV, solar hot water, and wind located on the building
2	Use renewable energy sources available at the site	PV, solar hot water, low-impact hydro, and wind located on-site, but not on the building
<i>Off-Site Supply Options</i>		
3	Use renewable energy sources available off site to generate energy on site	Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or waste streams from on-site processes that can be used on-site to generate electricity and heat.
4	Purchase off-site renewable energy sources	Utility-based wind, PV, emission credits, or other “green” purchasing options. Hydroelectric is sometimes considered.

Figure 6: Source: Torcellini, P., S. Pless, M. Deru, and D. Crawley. 2006. Zero-energy buildings: A critical look at the definition. NREL Conference Paper CP-550-39833. Prepared for ACEEE Summer Study, Pacific Grove, CA, August 14-18.

among other measures. Though of questionable practicality, this modeling condition again underscores the importance of solar access.

2. In cities, street orientation is a key influence on building solar access, and outdoor comfort.

Many high-performance buildings are built on large rural sites where the building can be oriented in any direction. In urban or suburban situations, however, there is far less flexibility due to smaller lot sizes and the customary need for building entrances to face the street. The direction of the streets therefore often determines the orientation of the buildings.

The pioneering subdivision Village Homes, built in Davis in the 1970s, recognized this fact, arranging the houses along east-west streets, so that each structure would have a sizable south-facing façade and the potential for passive solar heating (Corbett and Corbett 2000). Paradis et al (1983) found that the optimal street orientation in Quebec City could reduce annual household energy consumption by 16.5%, and maximum instantaneous heating load by 24 to 70% (depending on wind), for a typical single-family bungalow. A study by NBA Tectonics (1988) of low and medium-density estate housing in England found that the modeled passive solar features could save 11% of the space heating in these dwellings with appropriate orientation, but that more than half the savings were lost with a non-optimal site layout (Littlefair 1998). The California Energy Commission has financed the creation of the Subdivision Energy Analysis Tool (SEAT) modeling tool, which will allow planners and developers in California to create street and lot orientations that preserve appropriate solar access (Christensen and Horowitz 2007).

Street orientation also has important consequences

for outdoor comfort and the pedestrian environment. North-south streets will generally be shaded a higher proportion of the time, especially if there are relatively tall buildings (or buildings with short setbacks) flanking the street (Givoni 1998). On the east side of such streets, trees will shadow the sidewalk extensively in the afternoons, when comfort needs are most acute. On the south side of east-west directed streets, pedestrians will be exposed to full sun most of the day even if there are street trees between the sidewalk and the street (unless there are trees or tall buildings to the south); the opposite is true on the other side. In warm climates such as inland California, these considerations may be important in planning comfortable pedestrian and bicycle routes.

3. Measuring and planning urban solar access requires clarity about the intended use of the energy.

There is a growing literature on the methods of ensuring solar access in dense urban environments that has much to say about the potential for transformation to carbon-free community design. Compagnon (2004), for example, has developed a method to determine what percentage of building facades in a given urban area are being struck by technically and commercially useful amounts of solar radiation over a selected period of time. The thresholds for a “useful” amount of radiation differ for four solar techniques: passive thermal heating, photovoltaic systems, daylighting systems, and solar thermal collectors. Studying five different layouts for a dense urban redevelopment project in Switzerland, Compagnon found that the best performing configuration was able to exceed the threshold for daylighting over 83% of the total façade area; for

¹¹ The analysis excluded rooftops (where PV is most viable), since the buildings did not shade one another’s roofs.

solar thermal collectors over 82% of the area; for passive solar heating over 52% of the area; and for photovoltaic over 17% of the area.¹¹ Though actually using this energy is the architect’s task, the technique allows planners to optimize the total potential across multiple structures.

Knowles (2003, 1974) has developed a method for identifying the three-dimensional volume (called the “solar envelope”) within which newly proposed buildings must fit in order not to shadow their neighbors above a desired height at selected times. The solar envelope construct can be used to design clusters of buildings that preserve solar access for one another, and for adjacent neighbors. Threshold values for various solar techniques, such as those used by Compagnon, could be used to determine at what locations and times shadowing is unacceptable.

As a cooling strategy, shading is most effective when trees are sited to the south and west of buildings, and tall enough to block summer sun without unduly obstructing the low-angle winter sun (or daylight coming through the windows). This could impede opportunities for active solar energy generation on rooftops. However, a study



by Levinson et al (2009) found that the fraction of insolation lost to tree shading on south-, southwest- and west-facing roof surfaces in selected residential neighborhoods of Sacramento, San Jose, Los Angeles, and San Diego, is only seven to eight percent now, and would be no more than fourteen percent after 30 years of tree growth.

Conclusions and research needs

Solar access analysis is critical to the technical feasibility of net-zero buildings in urban and suburban sites, but may also yield conclusions that conflict with parallel goals to create more clustered and resource-efficient communities. Research should therefore be conducted on the following issues.

1. There may be tradeoffs between the design imperatives of net-zero buildings and the urban patterns that support low-carbon transportation.

A variety of critical questions about urban net-zero buildings have yet to be answered by robust research. Are large numbers of net-zero buildings even achievable in constrained urban or redevelopment sites in California, given potential restrictions on building orientation and massing? How does adequate solar access for buildings affect urban design considerations, including walkability and density? And if these goals are in conflict, which should prevail to ensure that both the building and transportation sectors can achieve the kinds of emission reductions that are necessary in the next four decades?

In general, existing net-zero buildings are less than four stories tall. Above that height, there generally isn’t enough roof area for photovoltaics

to supply electricity demand from within the building (Madsen 2007). Though three- to four-story buildings can provide sufficient density to support robust non-automobile transportation networks, they can only do so with relatively high lot coverages (such as in San Francisco) that may reduce building solar access both individually and collectively. Location-specific research is needed to identify the optimal tradeoffs for collective resource efficiency. Otherwise, net-zero building standards could become a spur to low-density, automobile-dependent growth.

2. There is a need for much more research on the potential to achieve net-zero status across entire communities, as opposed to single buildings.

There are already pioneering net-zero community projects in California, including Sonoma Mountain Village in Rohnert Park and West Village in Davis. These projects make efforts to reduce substantially the consumption of transportation energy, but do not explicitly include that goal within the “net-zero” framework. As these projects have been planned, some research and policy innovations have already been identified, such as the need to reform utility regulations to allow localized electricity networks. There are likely important efficiencies of scale and of resource-sharing at the neighborhood level that are unavailable at the individual building scale; research is needed to clearly identify and incentivize these opportunities. The CEC’s SEAT tool, and other modeling techniques, should be used to examine the magnitude of potential orientation-related efficiency gains of proposed developments. Even more challenging will be the effort to transform existing neighborhoods into zero- or low-energy neighborhoods through building efficiency, cool communities strategies, and local energy

generation. More research on the opportunities and constraints to such transformations is required.

3. The differences between the solar access needs of residential and commercial buildings in California should be further investigated.

Commercial buildings are generally occupied during the daytime, and their energy demand is largely driven by lighting and cooling needs. In a warm climate such as inland California, passive daylighting combined with high-angle shading may be able to bring well-designed commercial buildings close to net-zero status. Residential buildings are more densely occupied in mornings, evenings, and nighttime, when heating and artificial lighting are more often necessary. That may imply that preserving unobstructed solar access and rooftop generating capacity is a higher priority for residential structures.

4. There is a need for more research on the extent to which other community design variables may also affect household energy consumption.

The effect of community design decisions involving density and housing types upon household energy use is a nearly unexplored topic. Ewing and Rong found that households living in single-family detached housing consume 35% more energy for space heating, and 21% more for space cooling, than comparable households in multifamily buildings (Ewing et al 2008), but much of this difference is attributed to the larger average square footage of detached dwellings. More rigorous research involving disaggregated energy consumption data, and planning variables such as density, housing type, and household size, should be conducted to assess the extent to which household energy use is shaped by community design.

6. Community Resource Use and Embedded

Embedded energy, commonly also called embodied energy, is the total energy consumed in the extraction of raw materials and their subsequent processing, manufacturing, transport and eventual construction into a commodity for consumption. Some research extends this definition beyond manufacture and transport to include energy used for disposal (Wackernagel and Rees 1996). Detailed assessment of the energy required for material extraction, manufacture and transportation is a complex task. In some situations, embedded energy is location-specific due to transport-related energy use, heightening the measurement complexity. Embedded energy is less researched, less understood and less optimized than other categories of energy use.

Policy, regulatory and planning efforts tend to focus only on the operating energy of vehicles, buildings, and infrastructure systems. Yet the embodied energy of these systems is also significant, and should be considered in any effort to create resource efficient communities. The human-made physical environment of buildings, roads, infrastructure systems, and vehicles requires vast quantities of materials, virtually all of which are energy-intensive to manufacture and transport. Reducing the demand for such materials and products through intelligent community design will be a critical component of larger efforts to reduce energy use and carbon emissions throughout the economy. Measures that account for embodied energy can assess a development or region's true overall energy requirements – from the design phase to building occupation – based on what that development is constructed from, how it is designed, how it is serviced, and how it will be powered.

In addition to energy use, there is also a critical need to assess and optimize the use of water within California communities. Water is itself energy-intensive to convey, treat, heat, and dispose of (or recycle) within a semi-arid climate such as southern California's. But the state is also facing absolute shortages relative to the growing demands for urban and agricultural water use. These are virtually certain to worsen as climate change takes hold, largely due to the reduction in the Sierra snowpack and constraints in the water delivery system (Cal. Dept. of Water Resources 2006).

Research Findings

Research into embedded energy has yielded some basic findings that have important implications for resource-efficient community design.

1. The embedded energy of vehicles, especially cars, is surprisingly large compared to their operating energy, and has important implications for resource efficient communities.

Though most research and policy efforts dealing with transportation focus on the fuel use of the vehicles, the embedded energy of vehicles is significant. Chester and Horvath (2009) present results of a comprehensive life-cycle energy, greenhouse gas emissions, and selected criteria air pollutant emissions inventory for automobiles, buses, trains, and airplanes in the US, including assessment of the associated infrastructure, fuel production, and supply chains. Disposal phases are not included.

Energy Management

They found that the embedded energy of a car is about 60% as large as the total operating energy it will consume in its lifetime. For rail, embedded energy is 155% of lifetime operating energy, due to the large supporting infrastructure that rail requires. For airlines, the comparable figure is 31% (Chester and Horvath 2009). These findings suggest that reducing the demand for motorized travel (and vehicle purchase) could yield significant additional energy savings throughout the supply chain, in addition to the operational energy savings.

2. The embedded energy of buildings is relatively low compared to their operating energy and related transportation energy, suggesting that building location and efficiency should be optimized prior to any effort to reduce embedded energy.

More research has been focused on the embedded energy of buildings, but data on common construction materials are still relatively scarce. The embedded energy of building, infrastructure and construction materials can be classified into two types: initial embodied energy and recurring embodied energy. Initial embodied energy includes energy used to transport building products to the site, to construct the building and to acquire, process, and manufacture the building materials, including any transportation related to these activities (Canadian Architect 2009). Recurring embodied energy represents the energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems during the life of the building. Recurring embodied energy is distinct from operating energy, which is that consumed over a building's operational lifetime, after construction.

Current research shows that initial embodied energy accounts for approximately 16% of a building's total life cycle energy consumption, 74% is attributed to operating energy, and the remaining 10% is attributed to recurring embodied energy (NTHP 2007). Other studies also show that the "use phase" (i.e. the operating energy) accounts for approximately 90% of the total life-cycle energy consumption of both office (Junilla et al 2006) and residential buildings (Keoleian et al 2001). Thus, much more long-term energy savings can be realized by improving the operational efficiency of a building than by reducing the embodied energy (Jackson 2005). However, the embodied energy of renovation is approximately half of that for new construction (Architecture 2030, 2009). Thus, renovation of existing building stock is more energy efficient than demolition and reconstruction, other things equal.



About 50% of a building's embodied energy is in construction materials (Jackson 2005). Among common materials, wood has a relatively low embodied energy level, while concrete and steel are higher (Dias and Pooliyadda 2004). It is generally possible to reduce the embedded energy of concrete through the use of fillers and volume displacers such as fly ash or recycled pavement. Given that building embedded energy is relatively small compared to operational energy, it is not clear that wood is a preferable alternative when the entire energy impact of a given building is considered. Even assuming the wood is sustainably harvested, concrete and steel structures allow taller construction (and thus greater densities), and may allow for better operational energy performance through better fenestration and ventilation.

In other words, the greater embedded energy of concrete and steel probably "buy" operational efficiency and transportation efficiency improvements that are worth the energy cost over the long term. Wilson and Navaro (2007) have found that for the average U.S. office building, 30% more energy is consumed by workers traveling to the building than is used by the building itself. For the average new office building built to code, transportation energy is more than double operating energy. Given that operating energy is in turn much larger than embedded energy, this strongly suggests that locational benefits can greatly outweigh the additional embedded energy costs of sturdier structural materials such as steel.

A comprehensive life-cycle analysis of high- and low-density residential environments in Toronto supports this general conclusion. Norman et al (2006) found that low-density suburban development is between two and two-and-a-

half times as energy- and GHG-intensive as high-density urban core development per capita, and up to one-and-a-half times as intensive per square meter of living space. They found that transportation accounts for 40 – 60% of life-cycle GHG emissions in residential development, whereas production of building materials account for only about 10% (the remainder is building operations). Thus, location efficiency is at least as important as building operation efficiency, and much more important than building materials, in overall building-related life-cycle emissions.

3. Delivery and heating of water are energy-intensive activities, especially in southern California.

Water systems in California are one of the largest energy users in the state (Wilkinson 2000). About nineteen percent of total electricity use and 32% of natural gas use in California is water-related (Navigant Consulting 2006). Water systems use energy at five separate stages: source and conveyance, treatment, distribution, end use, and wastewater treatment. Due to California's varied geography and uneven natural distribution of water, the total energy embedded in a unit of delivered water varies with location, source, and use within the state. California's water systems are energy intensive, relative to national averages. Nationally, about four percent of all annual electricity consumption is attributed to water and wastewater systems, excluding end-use consumption (EPRI 2002).

Some of the inter-basin transfer systems, such as San Francisco's Hetch Hetchy system and the Los Angeles Aqueduct, are net energy producers because the dams that store water in the mountains also generate hydropower. Others, such as the State Water Project and the Colorado River Aqueduct,

require large amounts of electrical energy to convey water, primarily due to the need to pump large volumes over the mountains into the Los Angeles Basin (Wilkinson 2000).

Thus, despite requiring similar levels of energy for treatment, distribution and wastewater treatment, water supplied to Southern California has more embodied energy (24,133 kWh/MG) than that supplied to Northern California (8,911 kWh/MG) due to the conveyance distance (Navigant Consulting 2006). In fact, the amount of electricity used to deliver water to residential customers in Southern California is equal to one-third of the total average household electric use in Southern California (Cohen, Nelson and Wolff 2004). When the state is viewed as a whole, however, it is the end use stage – where water is heated for clothes washing, showering, dishwashing, and industrial uses – that accounts for more energy consumption than any other part of the conveyance and treatment cycle. The treatment stage of the cycle also consumes energy in both mechanical and biological treatment systems. As a result, the reuse of water is far less energy intensive than any physical source of “new” water other than local surface water (Cohen, Nelson and Wolff 2004). On-site stormwater harvesting for outdoor irrigation and non-potable household uses, which can be done on the individual building scale even in urban settings, avoids virtually all energy use associated with conveyance and distribution of water.

Overall, reducing water demand statewide, but particularly in Southern Californian communities, can save significant amounts of energy. Indeed, reducing the energy consumption associated with each stage of the water system will be critical for the state to meet its energy use and carbon emissions goals. Demand reduction, substitution

with stormwater and re-used local water, and supply of heating energy through rooftop solar access are a few of the strategies that will be critical.

4. The embedded energy of food is significant, and in California may be increased by development of farmland near cities.

Food has embedded energy due to the fact that modern production methods require large amounts of fossil fuel and food must be transported to concentrated urban populations. It now requires between seven and ten calories of fossil fuel energy to deliver each calorie of food energy to the consumer’s plate. About 60% of the food consumed in California is produced in-state, about 25% is imported from abroad, and the remaining 15% comes from other U.S. sources. But California is America’s most diverse and productive agricultural state and is more self-reliant than most. On average in the U.S., food travels 1,300 miles between farm and consumer, powered entirely by fossil fuel energy (Thompson, Harper, and Kraus 2008). In Sweden, which recently began “carbon labeling” of food products, the national government has estimated that



25% of national per capita carbon emissions are attributable to food, and that 20 to 50% of those food-related emissions could be eliminated through different consumer choices (Rosenthal 2009).

Food is a community design issue to the extent that local farmland must be conserved if supply lines are to be shortened. Though circumstances vary in each community, it is evident that the closer food is produced to where it is consumed, the greater the likelihood that getting it to market will use less energy and produce less pollution. One analysis has estimated that 20 million tons of food are grown within 100 miles of the San Francisco Bay Area, but that 12% of this “foodshed” is already developed, and another 800,000 acres (at least one-third of which are high-quality irrigated land) are threatened with development by 2050 (Thompson, Harper, and Kraus 2008). The more California farmland is lost, the longer the distances from which food will have to be imported to major population centers.

Conclusions and research needs

Though understudied, the implications of embedded energy for community design are important.

1. Embedded energy considerations further suggest that reducing car use should be a key goal for resource efficient communities.

In particular, the ratios of embedded energy to operating energy are very different for transportation systems than for buildings. Cars, buses, and trains have a large ratio of embedded to operating energy, ranging from about 0.6 for cars to more than 1:1 for buses and trains. It is important to realize that a high ratio is not

necessarily bad, since it may mean that operational energy use is low. Nor does it reflect the fact that buses and trains carry many people at a time, and therefore are much more efficient on a per-capita basis. But for cars especially (which do not currently operate very efficiently relative to what is technically feasible) a ratio this high is indicative of a very significant amount of embedded energy. More to the point, it means that reducing demand for cars through better community design brings with it a substantial “bonus” of avoided embedded energy, on top of the avoided operating energy use.

For buildings, the ratio of embedded to operating energy is relatively low, partly because buildings are operated for several decades. Improving the operating efficiency of buildings is therefore of greater importance than reducing the embedded energy. To the extent that energy-intensive materials such as steel, silicon and high-performance glass are necessary to achieve these operational improvements, they are very likely worth it from a building life-cycle perspective. Also, the longer the building stands, the more important operational efficiency is relative to embedded energy. Choosing the most durable and adaptable materials and designs is therefore also critical to life-cycle optimization.

In addition, some energy-intensive structural materials, such as steel, allow construction at higher densities, which will likely lead to reduced transportation energy demand for the reasons described in chapters 2 and 3. Given the long-lasting effects of building siting, it appears likely that these materials are “worth it” from a community-scale energy consumption point of view. The carbon footprint of these materials can also be reduced by substitution of renewable for fossil energy in the supply chain.

2. More research is needed on the embedded energy of urban infrastructure.

There is much less research on the embedded energy of urban infrastructure. Indeed, as Horvath (2004) has said, “the environmental impacts of [urban] infrastructure (for example, roads and bridges), especially construction materials and processes, and nonuse phase impacts (e.g., construction, maintenance, demolition) have thus far garnered unjustifiably limited research attention.” This is an important need for resource efficient communities, especially with respect to roads.

3. Improved water use efficiency offers large opportunities for energy demand reduction.

Especially in southern California, replacing

imported “raw” water with local stormwater, reused water, or recycled water, will save significant amounts of energy through avoided pumping, treatment, and in some cases disposal. Use of these local water resources is a community design issue, since it involves outdoor landscape irrigation and code reforms to permit indoor non-potable uses of stormwater and recycled water. Quantifying the energy savings potentially available through water re-use on a community level is an important research need. The fact that the end-use of water is the most energy-intensive stage of the water cycle also means that resource efficient communities should find alternative means of heating water for household use. Solar hot water heaters are a good solution, but also require that the solar access of building rooftops, facades, or ground locations be preserved. For reasons discussed in chapter 5, this too is an important community design issue.



7. Economic Dimensions of Resource

Planners and public finance experts have long recognized that investments in the public realm and infrastructure have important benefits for private property values. At the most basic level, public roads, sewers, and power lines make individual parcels developable, and therefore impart significant market value that would not otherwise exist. Mass transit stops or high-quality schools can add significant value to properties with access to them. More subtly, the design qualities of the public realm, such as attractive streetscapes or walkable shopping districts, can also increase the value of nearby properties. On the flip side, nuisance-generating infrastructure such as airports and sewage plants harm nearby property values.

Building resource efficient communities will require re-designing the public environment, especially the streetscape, which is primarily a matter of public investment. But such investments tend to distribute costs and benefits unevenly throughout the community. Understanding these differentials is therefore critical to creating fiscally and politically viable resource efficiency strategies.

Research findings

Resource efficient community design has the potential to have a positive effect on nearby property values. Access to destinations, abundant street trees, street design, and slower traffic are all typically valued by real estate consumers, both residential and commercial. Estimating and capturing these values may be critical to creating

financing structures for the necessary public realm improvements.

1. Nearby access to commercial destinations and transit stops increases residential property values.

Several studies have investigated the relationship between nonresidential uses and residential property values at the neighborhood or sub-regional level. Researchers have found that neighborhood-scale commercial uses have the most beneficial effects on property values (Grether and Mieszkowski 1980, Song and Knaap 2004), and that the positive price effects of increasing access to neighborhood-scale commercial zones are greater than negative effects due to additional noise and congestion (Li and Brown 1980). The benefits of mixed-use development appear to be most pronounced either in single-family neighborhoods with low current levels of commercial development (Geoghegan et al 1997, Cao and Cory 1981) or in urban areas that are more likely to already contain a mix of uses (Geoghegan et al 1997).

Cortright (2009) and Pivo and Fisher (2009) have found that a one-point increase in WalkScore¹² is associated with a \$700-3000 increase on residential values (Cortright 2009) and a 0.5-0.8% increase in commercial, retail, apartment and industrial market values (Pivo and Fisher 2009). The higher increases in property values associated with mixed-use development that Geoghegan et al (1997) and Cortright (2009) have found in high-density urban areas imply that combining commercial-scale retail, higher densities and walkable neighborhood design may produce the largest benefits.

¹² WalkScore ranks neighborhoods based on the average distance from homes to thirteen types of destinations.

Efficient Communities

Several studies (Bowes and Ihlandfelt 2001 and Hess and Almeida 2007; see Cervero and Duncan 2002 for a review) have concluded that proximity to transit stations increases property values. Notably, Kahn (2007) found that the walk-and-ride transit stations in fourteen U.S. metropolitan areas increase property values by almost three times as much as the park-and-rides over a ten-year period.

2. Pedestrian-friendly neighborhood designs generally can increase property values, but certain design features may have negative price impacts.

Another set of studies has used hedonic analysis to explore the effects of pedestrian-friendly neighborhood designs. Tu and Eppli (1999 and 2001), Plaut and Poarnet (2003), and Song and Knaap (2003) all found that buyers pay premiums ranging from four to eighteen percent to live in “New Urbanist” neighborhoods¹³ as compared with nearby control neighborhoods. Song and Knaap (2003) compared home sales in Orenco Station, a New Urbanist development in Portland, OR, to county-wide sales, and found that the increase in values associated with increased internal and external connectivity outweighed the negative impacts of higher densities and greater distances between housing and parking.

Other researchers have found mixed or negative price impacts due to certain New Urbanist design elements. Guttery (2002) found negative price impacts in Dallas due to rear-entry alleyways, a design element commonly promoted by New Urbanists. Asabere (1990) found that homes on

cul-de-sacs in Halifax, Nova Scotia are associated with a 22% price premium over homes on a grid pattern. Matthews and Turnbull (2007) compared values in Seattle neighborhoods with grid layouts to those with cul-de-sacs and found conflicting results depending upon the measure of connectivity they used.

Overall, these studies suggest that smart growth designs can increase property values, but the degree of benefits depend upon context. Researchers have found that the largest benefits are associated with New Urbanist neighborhoods in regions known for comprehensive planning and good transit systems, such as Portland (Song and Knaap 2003) and Washington, DC (Tu and Eppli 2001). Lower or negative benefits exist in smaller cities or in areas where conventional suburban development is the prevailing pattern.

3. Street trees and urban forests increase both residential and commercial property values.

A variety of studies have shown that trees have a positive effect on property values. One set of studies (Campbell and Munroe 2007, Nicholls and Crompton 2005, Riddell 2001, Bolitzer and Netusil 2000) has generally found that regional open spaces have positive price effects on adjacent homes. Another body of work has examined the effects of privately owned trees and landscaping (e.g. Peters 1971, Morales 1980, Anderson and Cordell 1988, Henry 1994) on property values, again finding generally positive effects.

Wolf (2007) summarizes several studies with

¹³ “New Urbanist” (a.k.a. neo-traditional) developments have greater residential density, greater mixture of uses, shorter blocks (often in grid patterns), and better-designed pedestrian environments than traditional developments.

the conclusion that “good tree cover” in a neighborhood increases residential property values by about seven percent, with greater tree-related value increases in lower-income neighborhoods. She also reports a nine to twelve percent increase in consumer spending in “forested business districts” (which would have significant effects on commercial property values) and a 23% increase in the value of homes within ¼ mile of an “excellent” commercial corridor with trees. Payton et al (2009) found that households are willing to pay \$15-92 annually for a one percent countywide increase in vegetative cover. In a ten-month study in Portland, Donovan and Butry (2009) found that a single street tree brings a \$7,130 premium for the house that it fronts, and that public trees have a positive impact on all homes within a 100-foot radius, adding almost \$13,000 in aggregate value to neighboring houses. Overall, the authors estimate that street trees have a twelve-to-one benefit-cost ratio.

Studies in California have supported these general conclusions. Relying on findings from Anderson and Cordell (1988) that found a 0.88% increase in residential sale price for *each* large tree in front of a house (including yard trees), McPherson et al (1999) estimated that each street tree in Modesto added approximately \$508 (in 1999 dollars) to the resale value of the adjacent residential property. In a later study, McPherson and Simpson (2002) refined this estimate to as much as \$900 in Modesto and as much as \$3,969 in Santa Monica, depending on the precise location of the trees relative to the house.

4. Slowing traffic increases residential property values substantially.

There is widespread agreement among researchers that residential property values are lower on high-traffic and high-speed-limit streets (Hughes and Sirmans 1992; Kawamura and Mahajan

2005; Nelson 1982; Kim, Park, and Kweon 2007). Analyses focusing on traffic and noise (Bagby 1980; Litman 1999; Nelson 1982; Kim, Park, and Kweon 2007) find that residents are sensitive to subtle changes in traffic, but detailed data on traffic volumes is often not available for residential streets (Hughes and Sirmans 1992).

Fewer studies have examined the effect on property values of traffic calming measures and street design elements. Cervero et al (2009) examined sale prices along two San Francisco corridors where freeways were replaced with pedestrian-friendly boulevards and found that prices increased by \$116,000 - 118,000. Bagby (1980) compared sales prices in two neighborhoods in Grand Rapids, MI, one of which installed diagonal diverters to prevent through traffic from using neighborhood streets. Traffic volumes dropped by several hundred vehicles per day, and sale prices rose by eighteen percent. Based on Bagby’s work, Litman (1999) calculated that each reduction of average daily vehicle trips by 100 (below a threshold of 2000) along a given street yields a one percent increase in property values. More recently, Bretherton et al (2000) found that speed tables produced mixed and statistically insignificant impacts on property values in Atlanta. A hedonic analysis by Krizek (2006) of three different types of bicycle paths in Minneapolis-St. Paul concluded that on-road bike lanes have no significant effects on home prices.

Conclusions and research needs

Rather few studies have examined the effects of street-level design on property values, likely because it is more difficult to collect data and isolate the different variables that affect property values at a finer grain of analysis. However, the increasing number of smart growth developments may make it easier to find viable neighborhood-level case studies, and improved GIS technology may facilitate additional analyses.

1. Building and financing resource efficient communities will require greater understanding of the property value impacts of street design features.

Sidewalks and other pedestrian-friendly street design features are critical components of community-scale resource efficiency. Opponents of such improvements are often well-supplied with information about project costs while comparatively little information about benefits is available to proponents (Krizek 2006). More research and better data, particularly on property values and traffic volumes, are needed in order to inform a balanced analysis of design improvements to the streetscape.

2. Future property value studies of street design improvements should control for traffic volumes.

Street re-designs and bicycle lanes are often built on streets where residents perceive higher traffic volumes or where there is sufficient room in the right-of-way for new design features. The literature agrees that high traffic decreases home values, but many studies of street layouts and traffic calming measures do not fully account for this possible confounding effect, or do so only through a simple “dummy variable” that is not sensitive to varying degrees of traffic intensity. Both benefits and costs that appear to be associated with street re-design or traffic calming measures could actually be a product of changes in traffic volumes, unless a given study explicitly controls for them.

3. Future studies may need to examine community design elements as a package.

Though statistical analysis produces the clearest results when researchers focus on a single dependent variable, many of the studies reviewed

above (e.g. Cortright 2009, Kahn 2007, Tu and Eppli 2001) imply that the success of smart growth developments is due to a combination of factors including the local built environment, accessibility to nearby destinations, and the regional context. A recent literature review by Bartholomew and Ewing (2009, 24) concludes that “design is probably perceived in an integrated way by most consumers.” If this is indeed the case, more research is needed not just on individual design elements, but also on how these elements work in combination with each other.



8. Codes and Standards

Land use regulation in California, as in almost all of the U.S., is a prerogative of local government. The primary legal instruments that guide the development of the built environment are municipal planning and zoning codes. Cities and counties create general plans, which are “constitutional documents” that state the community’s vision for its future and identify desired policies and patterns of land use. Zoning ordinances turn these broad policies into parcel-specific regulatory requirements. California law requires zoning ordinances to be consistent with the general plan.

For any given parcel, the zoning code defines in specific terms the permitted land uses and maximum physical dimensions of buildings relative to the site, as well as imposing other impact- or performance-based requirements that may be relevant. Zoning also defines the placement and orientation of buildings, and their relationship to the street. All of the following critical issues are addressed by zoning:

- The overall development density allowed in a given area
- Whether buildings can be attached or detached
- The overall shape and size of buildings, including their height
- How much setback there must be from the edge of the lot to the building
- How much parking must be provided per unit of development

These parameters strongly affect the energy performance of buildings, the likely transportation choices of their occupants, and the character of the streetscape. Thus, getting the zoning “right” is critical to community resource efficiency.

General plans and zoning are not the only drivers of community design outcomes, however. The actual physical form of California’s communities is also shaped by a confusing tangle of other plans, codes and standards, ranging from transportation plans to fire codes. Understanding the barriers and opportunities presented by these codes and standards is critical to assessing the prospects for resource efficient designs.

Research findings

A review of relevant plans, codes and standards in California yields the following findings.

1. Prevailing zoning practices enforce automobile dependency and inefficient community design.

The predominant trend in zoning since its inception in the 1920s has been to create single-use zones that separate residential, commercial, and industrial districts. Cities built prior to the advent of zoning had mixed-use neighborhoods, many of which are still active today. As zoning took hold, the segregation of land uses led to increased travel times between homes, jobs, retail, and other destinations, creating a development pattern best-suited to navigation by automobile (Duany, Plater-Zybeck, and Speck 2000).

Even when local governments have policies that explicitly encourage compact growth, most zoning codes and municipal regulations predominantly focus on avoiding the perceived negative impacts of growth. These include codes such as lot size and setback requirements meant to preserve property values, and parking requirements intended to reduce congestion. As Talen (2009, 146) has said, conventional zoning “produces urban form as a

byproduct of regulating something else, such as separation, property value, traffic flow, or perceived harmful effects.” Municipal codes do not arise from, or advance, any physical vision for urban form (Duany, Plater-Zyberk, and Speck 2000, 19), leading to development projects that are shaped piecemeal via discretionary reviews instead of comprehensively planned (Langdon 2006).

Conventional development is often perceived as the result of market demand, but researchers have found that zoning in fact distorts the market (Pendall 1999, Levine and Inam 2004). Though the demand for large-lot single-family homes is projected to decline due to the diminishing share of married couples with children that are the primary consumers of such housing (Nelson 2006), traditional land use controls may prevent developers from producing alternatives to single-family housing. Levine and Inam (2004) found that almost 80% of developers said that conventional land use regulations acted as a barrier to denser development, and 70% thought that codes prevented mixed-use development.

Though minimum lot size requirements are the most common form of growth control measure (Talen and Knapp 2003), other regulations that require larger-than-necessary minimum setback requirements or pavement widths may also serve to limit the amount of land available for residential development. Taken together, these policies tend to push new housing growth out to the urban fringe (Pendall 1999). Some cities have gone so far as to enact a statutory cap on total residential development, in defiance of state laws that require each city to take on a share of the housing growth necessary to accommodate population growth (California Attorney General’s Office 2009).

2. Design standards for streets are generally based upon standardized rules that restrict design flexibility in important ways.

Policies governing the public right-of-way typically originate as recommendations from national engineering organizations, or from standards embedded in federal transportation policies and funding mechanisms. State governments may promulgate model ordinances based on these standards, and regional metropolitan planning organizations (MPOs) may make transportation project funding conditional upon adherence to them. Ultimately, however, it is ordinances passed by local municipalities that turn these recommended standards into codes with the force of law. Fear of liability, lack of funding to develop locally appropriate standards, and fear of losing project funding often deter local governments from deviating from the recommended standards in their codes (Southworth and Ben-Joseph 2003).

The American Association of State Highway and Transportation Officials’ (AASHTO) “Green Book” provides the recommended standards for public rights-of-way. The Green Book defines the street network primarily as a hierarchy of movement corridors designed to maintain steady flow for motor vehicles (AASHTO 2004). The Transportation Research Board’s Highway Capacity Manual (2000) provides guidance for calculating levels of service for traffic, pedestrians, and other modes. In both of these critically important sets of standards, the role of streets as public spaces, infrastructure corridors, or sites for microclimate and ecosystem management is not generally recognized or emphasized. Instead, street standards are overwhelmingly devoted to improving automobile level of service, to the

detriment (or even the exclusion) of almost all other uses of streets.

The AASHTO definitions of the “right-of-way” set the standard for all related codes and policies governing streets and sidewalks. Trees and vegetation, sidewalks, bicycle lanes, parking lanes, and travel lanes are right-of-way elements that are controlled by various agencies and their codes. Each element has a set of codes and policies, many of which create barriers to pedestrian and bicycle activity. These codes and barriers are discussed below.

Trees

The governance and maintenance of street trees, or trees within the public right-of-way, vary from place to place. Often, no written standards or codes exist for the regulation of street trees, which requires the city to employ discretion on a case-by-case basis (Macdonald et al 2006). Street trees are typically planted in the roadside space of the right-of-way. This means they have to compete for space with sidewalk pavement, driveways, overhead power lines, utility poles, parking meters, transit stops, fire hydrants and subsurface utilities. These physical conflicts often make the establishment of a continuous tree canopy difficult. AASHTO standards also prohibit planting trees anywhere in the roadway, which includes the parking lane, and restrict street trees within certain distances of intersections based on driver visibility.

Caltrans requires a 20-foot wide “clear zone,” free of any immobile object, on arterial highways with speed limits above 40mph (Macdonald et al. 2008, 24). For the built environment of California, this means trees cannot be planted within 20 feet of the roadway on the arterial highways that connect

most suburban residential developments with nearby commercial and employment centers. In hot climates, the lack of shade on these rights-of-way creates an important barrier to comfortable walking and biking.

The rationale for these restrictions is that driver safety could be endangered by the presence of trees, due to collision potential and view obstruction. But Macdonald et al (2008, 27) have found that “numerous research studies support the idea that physical elements along highway roadsides, such as parking lanes, trees, and closely-spaced buildings, can serve as environmental references that reinforce lower design speeds and are therefore important mechanisms for influencing drivers to travel at a desired speed.” The safety benefits of these “environmental references” may outweigh any potential collision hazards. Macdonald et al (2006) demonstrated in another study that well-maintained street trees contribute only the same level of visual obstruction as the traffic signal utility poles located at intersection corners. Since pedestrians and cyclists are frequently stationary at intersections while they wait for the lights to change, this may be a particularly important finding with respect to thermal comfort.

Sidewalks

The governance and maintenance policies of sidewalks vary from place to place. Public sidewalk governance belongs to the local municipality, but in some cases the maintenance responsibility may belong to the adjacent property owner, or be divided between the property owner and the municipality. The sidewalk represents the most flexible use zone within the right-of-way. Dozens of activities and objects, from jogging to café seating to newspaper boxes, routinely appear within them. Despite this diversity, AASHTO and

TRB define a high pedestrian level-of-service primarily by the existence of a “clear path” for pedestrian travel and a low density of users. As discussed in Chapter 4, this approach to calculating pedestrian level-of-service equates the mobility of a pedestrian to that of an automobile, without considering any social, psychological or aesthetic factors whatsoever.

More legitimately, the Americans with Disabilities Act (ADA) also requires a continuous clear path of 48 inches on sidewalks for wheelchair clearance. In particularly constrained rights-of-way in some older neighborhoods, this clearance requirement can sometimes conflict with other potential uses of the sidewalk. Tree roots and subsurface utility access points can also sometimes cause sidewalk unevenness that is hazardous or obstructive to the disabled.

Bicycle lanes

AASHTO designates bicycle lanes as part of the roadway, which means that bicycle lanes cannot be located between the parking lane and the sidewalk, which is much safer for the cyclist and is a common practice in Europe and Canada. More generally, cyclists may not feel safe without designated space, particularly on arterials where traffic is greater. These same urban arterials often provide the most direct routes, so bicyclists often wish to use them just as drivers do. Providing adequate space on arterials, or defining alternative bicycling networks that achieve equally good connectivity, is perhaps the largest barrier to creating bikable communities, especially in suburban contexts.

A review of ten different California cities’ Bicycle Master Plans showed very little deviation from the standards set forth in the Caltrans Highway Design Manual, which is derived

from the AASHTO standards. As of 2009, sixty-six municipalities or counties included a bicycle master plan element in their general plan documents (OPR 2009). Of the ten plans reviewed, only San Francisco departed significantly from the standard design details, and as a result has undergone a significantly longer CEQA review.

Travel lanes

AASHTO recommends standard lane widths for roads based on the functional classification system, including a standard lane width of twelve feet for motor vehicles which is intended to protect driver safety. However, Macdonald et al (2009, 20-1) found that lanes of this width on urban arterials are “more likely to be associated with higher driver speeds than narrow lane widths (ten feet)” and that “higher highway driving speeds are more associated with vehicle crashes and fatalities than are slower speeds.” The faster driving speeds are also correlated with reduced safety perceptions for pedestrians and cyclists. Therefore, increased lane widths and associated increased driving speeds act as barriers to bikability and walkability. The increased travel lane width also increases the crossing distance for pedestrians, and therefore also increases their safety risk for crossing the street.

Emergency vehicle access

The lane width demands for emergency response vehicles often conflict with efforts to reduce street widths in new and existing developments. The National Uniform Fire Code and the International Fire Code recommend a clear street width for moving traffic of 20 feet (Ewing, Stevens and Brown 2007). If a street has seven-foot parking lanes on both sides, this would represent a 34-foot roadway surface, at minimum. A 34-foot roadway

in a residential neighborhood creates barriers to walkability and bikability through increased cut-through traffic and faster driving speeds.

In new developments, the emergency response vehicle lane width requirement represents the primary barrier to designing smaller, less auto-centric streets. In existing neighborhoods, the width requirement often stalls traffic calming efforts that are aimed at improving pedestrian and bicycle safety. There have been cases where reduced widths were negotiated with local fire marshals (Burden and Zykosfsky 2001).

3. Parking requirements strongly disadvantage new development proposals in destination-rich urban infill locations.

Parking requirements reduce densities, create environments that are difficult to navigate by foot, and push development away from infill areas. Cities require that new developments provide parking spaces based on an independent variable – such as the number of dwelling units in a residential area, or the square footage of a retail store – rather than site-specific studies. Instead, planners either rely upon data from national surveys, typically those conducted by the Institute of Transportation Engineers (ITE), or copy regulations from other cities that are in turn based on ITE data (Shoup 2005).

In order to examine the relationship between land uses and automobile travel, ITE typically studies suburban sites with a large supply of on-site parking that are seldom well-served by transit instead of more urban locations that may not have dedicated parking lots (Shoup 2005, Arrington and Cervero 2008). Without any method for adjusting trip generation estimates based on design characteristics that may mitigate vehicle travel, the ITE estimates assume that all

developments will produce the same travel patterns as these suburban locations. Researchers have shown that this “suburban bias” causes the ITE to “understate the traffic benefits of mixed use developments” (Langdon 2008, 1), overestimating the amount of trips generated by these developments by an average of 44% (Arrington and Cervero 2008). Others have questioned the ITE’s methodology more extensively, arguing that sample sizes are too small to draw conclusions, and that the dependent variables used often have little or no correlation with the number of trips generated (Shoup 2005). Planners often further inflate ITE overestimates by requiring that developments provide enough parking not just for average daily use, but for annual peak demand.

These parking requirements restrict the amount of money and space available for design improvements, and raise the overall price tag on new development. Surface parking lots consume space that could be devoted to other land uses, thereby reducing net density and discouraging non-automobile travel (Wilson 1995, Manville and Shoup 2005, Shoup 2005). In infill locations, which are less likely to have space for a surface lot, but more likely to be accessible by transit or non-motorized modes, developers must construct parking structures, which raises development costs substantially compared to suburban locations. In infill locations, parking structures add roughly \$20,000 to the cost of each housing unit. In areas where land values are especially high, parking can account for up to 20% of unit costs, making it particularly hard to build affordable housing (Millard-Ball 2002). Furthermore, large parking garages conflict with small blocks that lend variety to the streetscape and encourage walking (Tumlin and Millard-Ball, 2003)



4. Infrastructure costs and land assembly are often larger barriers in infill locations than in previously undeveloped locations.

Higher-density developments often necessitate infrastructure improvements in the immediate neighborhood. Though studies (Burchell et al 2000, Burchell 1999, California Energy Commission 1996) have concluded that smart growth policies would reduce total infrastructure costs in the long term, increasing densities or creating mixed use developments in urban centers carries high marginal costs associated with improvements to the sewer system, fire and seismic safety upgrades for larger buildings, government services, and new schools (U.S. Conference of Mayors 1999, Cervero et al 2004, Tarnay 2004). Infill sites are also more likely to be located on brownfields that may require cleanup, create liability issues, and require additional environmental assessment, all of which require additional money, time, and effort (U.S. Conference of Mayors 1999).

Larger projects in infill neighborhoods often require planners and developers to acquire parcels from multiple owners, and to involve stakeholders who may be reluctant to see densities increase. This makes it especially difficult to implement higher density projects in existing single-family neighborhoods. Thirteen of California's eighteen MPOs have created long term, consensus-based "blueprint" land use plans aimed at encouraging smart growth and reducing auto travel. However, these plans largely assume no change in existing single-family areas due to the cost and political difficulty of projects in these areas (Sacramento Area Council of Governments 2007, San Diego Association of Governments 2004, Southern California Association of Governments 2004, San Joaquin Valley Regional Policy Council 2009).

5. New models for codes, standards and planning processes offer important building blocks for resource efficient communities.

While current codes and standards present obstacles to resource efficient communities, there are a variety of innovative efforts underway to develop new codes, standards, and planning processes to reverse this.

Form-based codes

In recent years, a new kind of code has arisen to supplement, or in limited circumstances replace, the traditional zoning code. Known as "form-based codes," these codes seek to ensure that development of individual parcels contributes to the gradual creation of a desired physical form and character for the study area. Traditional zoning codes usually prescribe conditions for the individual parcel with little sense of how those parcels will add up to a larger neighborhood. Form-based codes begin by identifying the desirable physical character for the entire area, then define what is acceptable for the individual parcel in that context. As the name implies, a form-based code is a visual as much as a verbal document.

Form-based codes have large potential to advance community resource efficiency. Because they plan for a neighborhood or street as an integrated whole, they are inherently more concerned with the overall character of the public realm (including walkability and bikeability), the interplay of different land uses, and the physical and environmental context of buildings. They also offer opportunities to gain important efficiencies in public utility investments, and may make it easier to create financing structures that support neighborhood- or community-scale investments in resource efficiency.

Regional blueprint plans

The regional blueprint process has become a successful model of regional planning in California. Their explicit goal is to produce more efficient land use patterns that reduce automobile dependency, accommodate “fair share” regional housing goals, protect habitats, and increase resource use efficiency. Importantly, regional blueprints are supported by federal and state transportation planning funds. A total of eighteen MPOs have participated in the grant program since its inception, with nine in 2009 alone.

The regional blueprints are not binding land use plans. But because they are produced with a large amount of stakeholder input, they have in some cases garnered a high level of political credibility within certain regions, notably Sacramento. In addition, they can provide important guidance – including spatially explicit land use visions – to transportation agencies and local planning departments who are making binding decisions about the region’s future. Even if not binding themselves, the blueprints form a common “sheet of music” from which the many municipal planning agencies in a region can play.

The blueprints may also prove to be an important basis for the Sustainable Communities Plans that must be created under SB 375. As described earlier, these plans will be responsible for identifying ways that California’s metropolitan regions must achieve specified greenhouse gas reductions defined by the Air Resources Board. Though blueprints are created under a different set of rules and goals, they may prove to be a valuable “dry run” for the regional planning that will be needed to meet CO2 reduction goals.

Context-sensitive streets and “complete streets”

The Institute for Transportation Engineering (ITE) has recently promulgated guidelines for the design of “context-sensitive streets”. These are primarily directed to the design of urban arterials and major collector roadways, as opposed to local streets. The standards focus on walkability and allocation of horizontal space within the right-of-way to accommodate multiple modes. These standards go beyond the general mandate of California’s Complete Streets Act, which requires that all uses be accommodated, to offer actual design guidance.



The standards are non-binding, but could be incorporated by reference into local development codes. Because they come from ITE, they carry additional professional credibility within the transportation planning arena, and therefore may be easier to implement on a local basis.

The Complete Streets Act was signed into law in California in September 2008, following the lead of several other states that had established Complete Streets policies (Cal Bicycle Coalition 2008). The Act went into force on January 1, 2009 and “requires the legislative body of a city or county, upon revision of the circulation element of their general plan, to identify how the jurisdiction will provide for the routine accommodation of all users of the roadway, including motorists, pedestrians, bicyclists, individuals with disabilities, seniors, and users of public transportation” (Leno 2007).

LEED

The Leadership in Energy and Environmental Design (LEED) program, run by the U.S. Green Building Council, has become the best-known

rating system for environmentally sensitive design. Though originally focused on buildings, LEED has now expanded to create a rating system for neighborhood design (LEED-ND). The system considers factors within the major categories of “smart location and linkage,” “neighborhood pattern and design,” and “green infrastructure and buildings.” As with other LEED systems, achieving certification means fulfilling certain mandatory prerequisites, as well as accumulating a certain number of points from a large menu of design measures.

The use of points allows the system designers to weigh certain design moves more heavily than others. The current version of LEED-ND most strongly rewards projects that reduce car dependence, create walkable streets, and are compact. Indeed, a project theoretically could achieve 38 points – nearly enough for basic certification – just within the five categories of “preferred locations,” “locations with reduced automobile dependence,” “housing and jobs proximity,” “walkable streets,” and “compact development.” As we have seen, that is



probably justified given the crucial importance of transportation energy to community resource efficiency.

LEED, or other independent rating systems such as Green Point Rated, can be incorporated into local codes, and a number of communities within California have already done so for LEED's building standards. Rated projects can also be incentivized by local governments through regulatory relief or privileged access to financing. Such requirements and incentives for LEED-ND would contribute to a piecemeal evolution of more resource efficient communities on a project-by-project basis.

WalkScore

WalkScore is a computer algorithm that scores the walkability of any given address by calculating its proximity to amenities and destinations such as stores, restaurants, and libraries. Amenities within one-quarter mile are most strongly weighted, then weighting gradually diminishes for amenities up to one mile away from the reference address. Crucially, WalkScore does not incorporate any information about design quality, street width, block length, safety, topography, or the possibility of discontinuous walking paths. Nonetheless, it is a useful summation of the destination accessibility inherent in any given location, and as such can be used as both a planning standard and a research tool. WalkScore has already achieved widespread adoption within the real estate industry, as brokers and agents often tout a high WalkScore as a selling point. Continued refinement of WalkScore through inclusion of additional factors such as design quality could serve as a useful impetus to more pedestrian oriented development.

GreenTRIP

GreenTRIP is a rating system undergoing

development by the non-profit transit advocacy group TransForm that certifies proposed developments as traffic-reducing, transit-friendly projects. To achieve certification, the development must meet certain thresholds for projected maximum vehicle miles traveled per household (as modeled by the California Air Resources Board's URBEMIS model) and for parking ratio, and must implement certain traffic reduction strategies such as unbundling parking, discounting transit passes, and providing free CarShare membership. The thresholds for certification vary depending upon what type of neighborhood the development is in; projects in "regional centers" must meet stricter standards than those in "transit neighborhoods," for example. GreenTRIP focuses primarily on substituting transit use for car use, and does not consider the quality of the pedestrian or bicycling environment. As with WalkScore, it may eventually be possible to expand GreenTRIP by including additional factors, or by changing the certification thresholds for locations that already possess pedestrian- or bicycle-friendly characteristics.

Conclusions and research needs

Existing codes, standards and planning processes are a major barrier to resource efficient communities. Standards promulgated by engineering associations become codified at various levels of government, too often reducing design flexibility for streets and other public infrastructure. There are several major research needs for resource-efficient codes.

1. The legal origins and evolution of codes and standards, including case law on local government liability for deviation from prevailing professional standards, should be reviewed.

Fear of liability is a major reason why local governments adhere strictly to otherwise non-



binding engineering standards. Research should be conducted to examine case law to assess the degree of liability that local governments actually face. This is a critical first step to developing flexible codes and standards that local governments can implement with confidence on a routine basis – not merely as an occasional “special case.” A key part of this work will also involve establishing greater dialogue with fire marshals, police departments, and public works agencies to ensure that legitimate public safety needs continue to be met by new street configurations. There is no inherent barrier to protecting public safety in a context of smaller, slower-traffic streets – indeed, on a global level, that is more the rule than the exception. Research on this experience should be conducted and shared with public safety officials.

2. Innovation of codes and standards that allow design flexibility for resource-efficient streetscapes, including ways to expand the use of form-based codes.

The codes that regulate the physical design of streets are often physically prescriptive, allowing little flexibility to respond to local conditions. Because resource efficient design usually demands such flexibility, standard codes are a major barrier to achieving community-scale efficiency. Research should be conducted to identify statutory or regulatory means of institutionalizing design flexibility in the creation of public street environments. Community-scale resource efficiency involves paying attention to fine-grained spatial relationships that are too detailed for conventional planning and zoning codes. Form-based codes, though to date often used primarily for aesthetic purposes, hold great promise as a tool for resource efficient development because they integrate streetscape planning with architectural guidelines, building setbacks, tree planting, and other critical physical features of the public realm.

Accumulated experience in using form-based codes should be reviewed, and major barriers to more widespread acceptance identified. The prevailing models of form-based codes may themselves require adjustment to emphasize resource-efficient design more strongly.

3. Best practices in adoption of LEED and other green standards should be further studied.

Adoption of LEED standards into building codes has become widespread enough in California to begin to attract research attention. As LEED and other green codes grow in importance, it will be critical to continuing this effort to understand how such standards can most successfully be incorporated into local codes in a streamlined manner. New standards such as GreenTRIP and LEED-ND, which apply to entire developments or neighborhoods, will likely soon become important tools in shaping resource efficient communities, so learning how to incorporate them properly is critical.

4. Models for better institutional coordination in the construction, maintenance, and retrofit of urban infrastructure should be identified.

Finally, the fragmentation of authority in street rights-of-way is a significant impediment to creating more resource efficient designs. The physical infrastructure of cities, most of which runs within the public rights-of-way, is controlled by numerous different public agencies and utilities, ranging from Public Works departments to electric companies. Changing street designs often requires extensive coordination among these entities, each of which has their own planning, investment and maintenance schedules. Effective models of institutional coordination for street re-designs should be studied, and applicable lessons universalized, so that such changes can occur on a more routine basis elsewhere.

9. Research Opportunities

Deep reductions in carbon emissions are justified by science and called for by California law and executive order. These reductions must be achieved in every sector of the economy, including transportation, building energy use, and industry. Community design is absolutely central to transportation and building emissions, and also has a significant role to play in reducing industrial emissions by reducing demand for materials.

The transition to a low-carbon economy will certainly involve developing and deploying carbon-free energy sources, such as wind and solar, that can directly replace fossil fuels in many current applications. Perhaps even more importantly, however, the transition will also involve reducing demand for mechanically generated energy of any kind with efficiency improvements. For appliances and light bulbs, this is mainly a matter of building (and selling) a better widget. But for transportation and buildings, these improvements will require several fundamental changes in the way that we build cities.

First, demand for transportation and building use energy is inescapably tied to spatial relationships in the local environment. Merely improving the efficiency of each individual car or house is not likely to be adequate; the spatial pattern in which they relate to each other needs to be changed as well. Housing, jobs, and retail need to be brought much closer together, or closer to transit lines that connect them. Buildings may need to be clustered or oriented differently to save on heating, cooling and lighting energy. And streets need to be designed to take advantage of sun, wind, and shade to create comfortable conditions for carbon-free transportation. Though general principles apply, the precise means of achieving these goals in any given community will be a product of local conditions. Traditional general planning

and zoning are not flexible and specific enough to consider these conditions in detail.

Second, transportation modeling has for decades concerned itself almost exclusively with facilitating automobile use. These models, and environmental impact assessments based on them, are arguably more influential even than general plans in determining the shape of California's communities. Pedestrianism and bicycling will never achieve sufficient mode shares unless these models are revised to assess them on an equal footing with automobiles and transit. Third, actual city-making is a complex tangle of codes, regulations, incentives, and political stakeholders. As innovative designers and developers have discovered, there are numerous financial and procedural hurdles to actually creating resource-efficient cities. Devising effective and equitable means of incentivizing and streamlining resource efficient development is critically important to making tangible improvements in California's communities. Finally, even if new development practices were to take hold immediately, California will still be living with our existing roads and buildings for a long time to come. As new developments are created, they should to interface with the existing urban fabric in a manner that achieves community-scale efficiencies.

For all of these reasons, creating resource-efficient communities is a complex, long-term task. Research must focus on both technical issues, such as thermal comfort analyses, and socio-economic issues, such as permitting and financing processes. Research findings in both areas must be disseminated widely in the planning, design, development, and construction professions.

Within this context, the CREC intends to embark on research organized within three program areas.

Program Area 1: Street Design and Travel Behavior

Transportation is the single largest use of energy and cause of greenhouse gas emissions in California. Any resource efficient community must therefore devote significant effort to improving the energy and carbon efficiency of its transportation systems. This includes not only modifying automobile and mass transit systems to reduce per-capita vehicle miles traveled, but also promoting greater use of the most energy efficient transportation modes of all: walking and bicycling.

Numerous interviews with professional experts and extensive secondary research have led the CREC to conclude that there is a significant need for research into the street design conditions that support widespread walking and bicycling, particularly that which can substitute for short-distance car trips. While certain relationships are widely assumed, there is little direct evidence to substantiate these conclusions or to provide quantitative inputs into the models that shape transportation investments.

It is widely understood that certain prerequisites must exist for walking to take place, such as having relevant destinations close enough to the walkers' origin, and having an uninterrupted sidewalk or path route to those destinations. These factors have been researched to a reasonable extent, and are recognized in transportation mode choice models and neighborhood rating systems such as WalkScore. However, the actual conditions of the pedestrian environment, including the thermal conditions and the architectural quality (among other things) are largely neglected in transportation-related research.

The research activities CREC is proposing to fill this gap are described in the CREC Research Plan 2010-2013.\

Program Area 2: Cool Communities

Cool communities strategies are a critical aspect of a resource efficient California for three reasons. First, much of the growth expected for California in the coming decades will take place in the hotter portions of the state – the Central Valley and Inland Empire, particularly. For the state to meet its energy efficiency and climate change goals, these locations will need to take aggressive steps to reduce ambient and surface temperatures to reduce cooling loads on buildings and improve outdoor comfort for pedestrians and bicyclists.

Second, managing the urban microclimate in these locations is a dress rehearsal for conditions that will likely become widespread as climate change takes hold. As global temperatures rise, management of urban microclimates will become a routine necessity across many parts of California and the United States. Finally, cool roofs and cool pavements have a role in counteracting climate change by directly changing the albedo of urban surfaces. If implemented globally, this could be a significant – and highly cost-effective – tool in the fight against climate change. For all these reasons, California should continue innovating the development and implementation of cool communities strategies.

The research activities CREC is proposing to fill this gap are described in the CREC Research Plan 2010-2013.

Program Area 3: Codes and visualization

The third major program area for the CREC involves research into how resource efficient communities can most effectively be brought into being. This involves examining the codes, standards and regulations that shape the creation of the built environment in California and elsewhere. Zoning and development

codes, often derived from standards promulgated by engineering associations, have nearly dispositive effects on the physical form of cities, and therefore on their performance with respect to resource efficiency. Creating new codes and standards that incorporate resource efficiency criteria and allow appropriate design flexibility to meet local conditions will be an indispensable step toward more resource efficient communities. Equally important is creating compelling visions of what those communities could look like, in order to motivate necessary changes in design, policy and management.

The research activities CREC is proposing to fill this gap are described in the CREC Research Plan 2010-2013.

The task of creating a resource-efficient California is complex, and must be carried out with seemingly implausible speed. Carbon emissions must be reduced 88% per capita in the span of just 40 years, and the need for water conservation in California is nearly as urgent. Even for a state that has led the world in energy efficiency innovation for the last three decades, these are transformational challenges.

Nonetheless, there is a substantial body of knowledge upon which to build. A generation's worth of planning and environmental design research has yielded critical insights about each of the five links between community design and energy efficiency described here. Greater densities, mixture of land uses, walkable and bikeable streets, cool communities measures, and solar access for buildings – all are indispensable aspects of a resource-efficient future. In many cases, basic quantitative parameters, and the physical means by which to achieve them, are already understood. To carry this work forward, the primary tasks

are to refine existing models to incorporate missing information, to identify the flexible codes and standards that will allow resource efficient development to proceed, and to understand the ways in which various resource efficiency measures interact with one another. Indeed, the “layered benefits” of resource efficient community design may prove to be the critical lever toward a better future. Most resource-efficient design strategies – from walkable streets to cool roofs – produce a wide range of benefits, not all of which are easily captured in project-level financing structures or incorporated into conventional cost-benefit analyses. Community design and planning need to fill this gap by establishing development criteria that protect a range of values and ensure resource efficiency for the entire community.

Development patterns tend to be self-reinforcing, either toward an automobile-dependent, energy-consuming landscape, or toward a compact, pedestrian-oriented landscape with high-quality local environments. After decades of building the former, the momentum has to be reversed so that progress toward the latter becomes self-sustaining. Creating an “upward spiral” – in which better street environments lead to more pedestrianism and more community vitality, which then further improves street environments – will hinge upon understanding the full range of benefits that communities will reap over the long term, and then structuring development conditions to achieve them.

Ultimately, resource efficiency in California will be achieved not because planners require it, but because Californians themselves choose it. Resource efficiency does not imply scarcity. Rather, it means crafting communities that derive more of what they need from local landscapes and communities – and that also reward their inhabitants with security, vitality, and joy.

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Appendix A: Common Methods Used to Research the “Five Links”

The “five links” between community design and energy efficiency are researched in a variety of ways. What follows is a short description of prevailing methods, with a brief identification of particular advantages and disadvantages of each.

Land use-transportation connection research methods

In their landmark survey of research on the relationship between VMT and land use patterns, Ewing et al (2007) identify four research approaches used to investigate this issue.

- Comparing travel statistics for regions and neighborhoods with varying degrees of compactness and auto orientation. This typically involves creating a measurement of “compactness” then searching for a statistical relationship between the compactness scores of the areas in question, and the observed travel behavior of the inhabitants. This method has the advantage of being able to assess a wide range of environments collectively and to uncover broad patterns in the transportation – land use relationship. A disadvantage of this method is that defining and measuring “compactness” is an inexact science, and varying methods of doing this have led to varying results in assessing transportation outcomes (Cutsinger and Galster 2006).
- Analyzing the travel behavior of individual households. This involves surveying travelers to collect travel behavior data, then analyzing it in light of neighborhood

characteristics such as density. The advantage of this method is that it allows for a spatially fine-grained view of the question. The disadvantage is that limitations in statistical validity and generalizability can sometimes arise. Nonetheless, this is the most common of the four methods of analysis, with more than 100 studies.

- Regional scenario analysis. This involves running standard trip generation models on spatially specific scenarios for future regional growth, such as regional blueprints. An important advantage of scenario analysis is that different alternatives of the scenarios can be generated, while other contextual factors are held constant. The disadvantage is that such predictions are based on models, not on actual behavior by real people.
- Project-level scenario analysis. Similar to the above, but done at the individual project scale. An additional disadvantage is the degree of uncertainty in transportation and trip generation modeling at such fine scales. Idiosyncracies of particular projects that cannot be captured in models may have a large effect on actual transportation behavior.

Street design – transportation connection research methods

Studies of pedestrianism and bicycling generally seek to associate the total number of trips taken with relevant characteristics of the physical environment, such as path connectivity or aesthetic

quality. To date, this has been done almost entirely through empirical observation, rather than modeling. The specific research methods include:

- **Nationwide cross-sectional studies.** This method uses cross-sectional analyses of planning and census data to determine which factors in the physical environment influence pedestrian or bicycle mode share. The advantage of this method is that census data is national, so numerous cities can be compared relatively easily. A disadvantage of this method is that, for bicycle mode share, census data only counts travelers who regularly commute by bike as cyclists (Dill and Carr 2003), and does not provide data on other trips. Partly because of this, few cross-sectional analyses have focused on the relationship between cycling and the built environment, focusing instead on the effect that socioeconomic or physical variables have on cycling (e.g. Baltes 1996).
- **Surveys.** In general, information on walking and bicycling behavior originates as self-reported survey data. The U.S. Census long form asks questions about transportation choices, and researchers often distribute surveys that inquire about motivations and required conditions for various mode choices. These surveys may be distributed through the mail or, in more advanced studies, used in concert with specified walking courses or field-intercept arrangements. The general advantage of survey methods is that they permit access to information about travelers' decision-making that is not available any other way. The disadvantage of surveys is that all self-reported data is subject to

uncertainty due to question bias and the respondents' capacity for misperceptions about themselves.

Locally-based revealed preference surveys examine the actual variation in mode share, routes, and preferences across a given metropolitan area using aggregate data. Stated preference surveys ask study subjects to evaluate or respond to scenarios or images that they are presented allowing researchers to isolate the importance of a given factor or facility more clearly by exerting experimental control over how the scenarios are presented. However, the validity of responses to hypothetical scenarios is open to question in terms of its ability to predict actual behavior in real environments.

- **Trip diaries.** Essentially an advanced form of a survey, a trip diary methodology requires that study participants record their transportation behavior in detail for a given period of time (often weeks). The advantage of trip diaries is that they usually provide a rich set of fine-grained data. The major disadvantage is that they require sustained motivation and attention to detail on the part of participants, which usually limits the scope of the study that researchers can undertake. Use of mobile phones and handheld devices may remove some of these barriers, however.
- **Behavior observation.** Researchers also observe pedestrians and bicyclists directly in the environment. In its simplest form, this involves straightforward counts of pedestrians/bicyclists passing a given point.

A major advantage of behavior observation is its empiricism. A disadvantage until recently has been the relative expense of collecting and analyzing large amounts of data. However, as wireless sensing, video, and visual data analysis technologies have advanced, it has become possible to observe people's behavior in outdoor environments for less expense.

- Remote sensing. As noted, the goal of most studies of pedestrianism and bicycling is to relate observed human behaviors to dimensions of the physical environment. With respect to the latter, the advent of GIS technologies and ubiquitous aerial and street-level photography (available through Google Earth) has allowed researchers to identify and examine street environments with ease. The fixed physical characteristics of a given street environment, such as sidewalk connectivity, extent of tree canopy, and size dimensions, can often be measured or assessed from such tools. More dynamic characteristics, such as weather, are better captured by in-situ wireless sensing.
- Design simulations. Three-dimensional digital simulations of street environments are becoming more widespread and have important potential for the evaluation of the street design – transportation connection. A major advantage of these methods is that they allow the study of proposed environments that have not yet been built. A major disadvantage is that they only capture visual characteristics of environments, which are not the only

determinants of transportation choices. Weather, social relationships, and shopping preferences are important elements that cannot be effectively simulated.

Heat island research methods

Heat island effects are measured both directly and indirectly through a variety of means. Data drawn from urbanized environments must be compared with data from nearby rural environments to estimate heat island effects (Stone 2007).

- Near-ground measurements. Most major metropolitan regions contain several fixed weather stations, which are often supplemented by additional stations placed by researchers. These networks of sampling points are then used to interpolate isotherms (i.e. lines of equal temperature) to map urban temperatures and estimate atmospheric heat island effects. These fixed stations are often supplemented by mobile traverses that gather additional data on a regional cross-section of interest at specific times.
- Remote sensing. Satellites and other remote sensing devices can measure surface temperatures from the air or space, allowing researchers to create thermal images of urban landscapes. These are often at sufficient resolution to distinguish individual buildings and other small features such as parking lots.
- Modeling. Mesoscale urban meteorological models are used to examine the effects of albedo and vegetation increases on urban climates (Taha et al 1997). Leading models include ENVI-met (Huttner, Bruse and Dostal 2008), uMM5 (Taha 2008), FAST3D-CT (Tunick 2005), and STAR-CD. Photochemical models are also used

to assess the influence of rising temperatures on ozone and smog formation.

Solar access research methods

Methods for assessing the solar access of buildings fall into two main categories.

- **Solar geometry.** For any building or small set of buildings, the solar access of any given surface can be determined by using sunpath diagrams and building dimensions to project light and shadows at chosen points in time (Littlefair 1998). Though the solar access between selected times can be interpolated, it is labor-intensive to calculate total solar access over a season or a year using geometrical methods. Geometry methods remain useful for determining the shape of solar envelopes at the site scale.
- **Modeling.** More recent solar modeling tools, such as TOWNSCOPE (Littlefair 1998) and RADIANCE (Compagnon 2004) can model the passage of sunlight through complex 3-D urban environments and integrate the results over seasonal or annual timescales. This provides better information with which to assess the feasibility of various solar energy gathering techniques.

Embedded energy research methods

Embedded energy is most often researched within one of three comprehensive frameworks for assessing sustainability.

- **Life Cycle Analysis.** Life Cycle Analysis (LCA) is a technique used to empirically assess the potential environmental impacts associated with a product, process, or service by compiling an inventory of relevant energy

and material inputs and environmental releases (EPA 2006). There are five major stages of an LCA: raw material acquisition, materials manufacture, production, use/reuse/maintenance, and waste management. LCA is best suited for the assessment of site-specific considerations or isolated products used in transportation, power generation, or construction. Recent research shows that LCA can be further utilized to assess regional characteristics (Yi et al 2007), and common sustainable development indicators (Cooper 2003). The major disadvantage of LCA is that it is often costly, time consuming, and tends to require significant assumptions.

- **Urban metabolism.** Urban metabolism analysis measures the total “flow” of materials or resources into and out of a region. Urban metabolism has the advantage that it produces a simple overall energy or materials “budget” for a community. A disadvantage of urban metabolism analysis is that it requires data on energy and resource flows that are often accessible only at the municipal scale, making it difficult to perform metabolism calculations at finer scales (Kennedy, Cuddihy and Yan 2007).
- **Ecological footprint analysis.** Ecological footprint analyses attempt to assess the overall environmental impact of a defined region or population, and translate it into the acres of arable land that are hypothetically necessary to sustain that impact. Footprint analyses incorporate embedded energy, but do not provide a means of primary research into the topic (Wackernagel and Rees 1996).



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