REDUCING GLOBAL WARMING AND AIR POLLUTION: THE ROLE OF GREEN DEVELOPMENT IN CALIFORNIA

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EXECUTIVE SUMMARY

The Indirect Source Rule (ISR) was adopted by the San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD) in December 2005 and took effect in March 2006. The Indirect Source Rule requires development projects that exceed size thresholds to mitigate oxides of nitrogen (NOx) and particulate matter (PM) during construction (20 percent of NOx and 45 percent of PM10 from construction equipment exhaust) and after occupancy (33 percent of NOx and 50 percent of PM over 10 years of operation). Mitigation measures may include low-emissions construction equipment, buildings designed with energy efficiency measures, building and site design measures, and a mitigation fee. This paper focuses on a literature review of the building and site design measures and their connection to air pollution, including greenhouse gas emissions, and vehicle travel.

Four questions are addressed in this report: 1) Is there a link between land use decisions developers make and indirect source pollution? 2) Are there things developers can do to mitigate indirect source pollution? 3) Is the objective of the Indirect Source Rule as adopted by the San Joaquin Valley Unified Air Pollution Control District consistent with the available evidence to date? 4) How can an ISR be applied to greenhouse gas emissions? Existing research cited in this report supports the following responses to these questions:

1. **There is a measurable link between new development and vehicle-based (indirect source) air pollution.** Vehicle miles traveled (VMT) and vehicle hours of travel (VHT) are direct predictors of per capita vehicle emissions. All else being equal, significantly higher per capita VMT and VHT is consistently associated with single-use, low-density development, especially when development is located in outlying areas. Conversely, compact development with a mixture of land uses on-site and near by, and set within an interconnected street grid providing direct pathways to destinations, is associated with significantly less per capita VMT and VHT. These factors comprise what is known as "walkability," which is associated with less per capita generation of criteria air pollutants. Researchers have estimated vehicle-generated emissions and correlated it with land use patterns and levels of walkability in a variety of regional contexts. Results from this work are based on assessments at the site, neighborhood, and metropolitan scale. More recently, evidence shows that relationships between walkability and travel demand remain significant after adjusting for travel and neighborhood preference (Bagley and Mohktarian 2002; Handy and Cao 2006; Frank et al 2007). Other recent research documents the presence of a latent demand for more walkable environments (Levine and Frank 2006). Taken collectively, this evidence shows that accommodating more of the demand for walkable development would reduce vehicle travel demand and associated emissions.

2. **Because of the link between land use decisions and travel behavior, developers can play a role in reducing indirect source pollution from vehicle travel.** The evidence shows that there are several ways in which developers can design and develop their projects that will result in lower per capita vehicle

emissions. Project designs that allow for and encourage greater ability to walk or use transit to destinations are linked to significantly lower per capita VMT- and VHT- associated emissions. These strategies include on-site design features, land use composition and presence of a variety of uses, direct connections to adjacent destinations, pedestrian and bike amenities, and reduced parking supply and locating parking to the rear of sites. There are also other quantifiable actions developers can take to reduce emissions, such as implementing transit service, Transportation Demand Management Programs, or parking pricing, among others. However, the evidence shows that development location will likely have the largest impact on emissions – development that is located in already developed areas, close-in areas, or near high quality transit service will not only induce mode shift, but reduce trip distance as well – particularly important for CO2 reduction. For this reason, compact, walkable development in exurban or remote locations may only have marginal benefits.

3. **The Indirect Source Rule is an appropriate mechanism to reduce pollution created by new development projects.** The ISR is an appropriate mechanism to incorporate into the development decision-making process those costs that are arguably externalized with auto-oriented development – PM and NOx emissions. Findings in the research support the mitigation strategies pertaining to land use, and the approach for modeling emissions and mitigation used by the SJVUAPCD (the URBEMIS model). However, both the ISR and URBEMIS can be strengthened to better encourage close-in, infill development and discourage fringe or exurban development. Travel demand models and other modeling tools may be used in conjunction with, or in place of, URBEMIS to increase the precision of its estimates and better account for regional location. Where applicable, policy level criteria could be incorporated into the ISR in order to give credit for development that is consistent with regional plans.

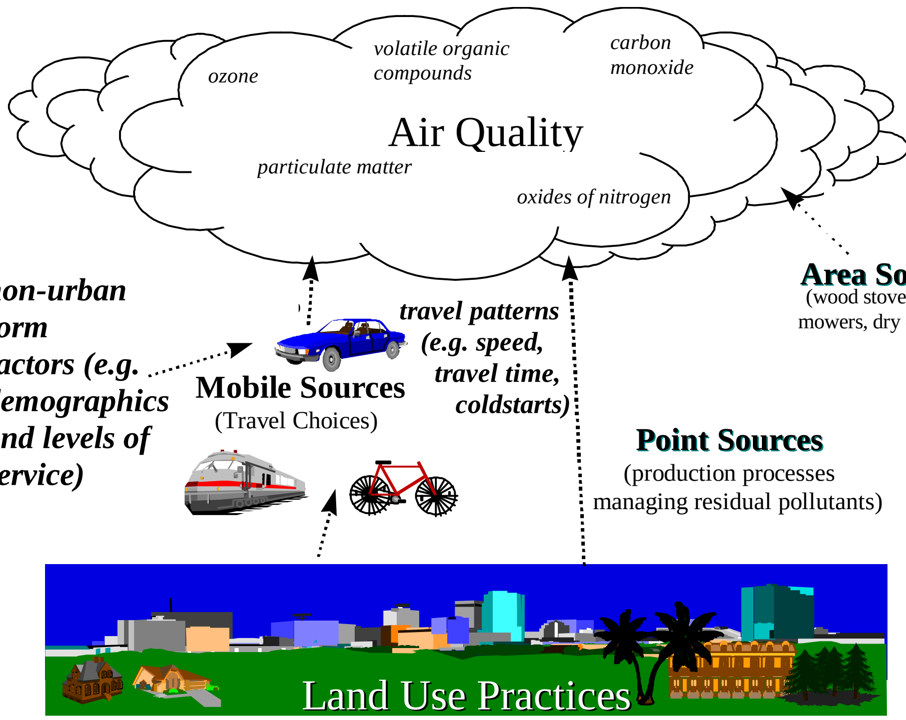
4. **An Indirect Source Rule can effectively be applied to reduce greenhouse gas emissions such as carbon dioxide (CO2).** This research supports the use of the same land use, site design, and bicycle / pedestrian / transit infrastructure factors for mitigation as those currently used in the ISR. Although there is little research *directly* on the urban form factors that influence CO2, the strong connection between CO2 and VMT coupled with the results of early research allows us to draw this conclusion. Because URBEMIS is currently used to measure PM and NOx for the existing ISR, this tool could ease the addition of CO2 into an ISR in the San Joaquin Valley region and other regions around the state. The close connection between VMT and CO2, and between land use patterns and VMT, emphasizes the key importance of regional location. URBEMIS measures a project's emissions using a regional average per trip VMT and number of trips a development generates. A more precise accounting of VMT will best support an ISR that is focused on CO2 emissions, and encourage developers to consider location in their proposals.

About This Report

This report is structured to follow the conceptual diagram of the relationship between land use, travel behavior, and air pollution depicted below in Figure 1. Per capita generation of air pollutants (PM and NOx in particular) and greenhouse gases (largely CO2) are influenced by a number of factors; an important one is the distance and numbers of trips made in vehicles. Travel behavior is also influenced by a number of factors, including land use patterns – the primary focus of this report. These land use patterns result from development regulations and practices.

- Section I consists of a short background on air pollution in general and air pollution and vehicle travel, emphasizing PM and NOx.
- Section II summarizes the literature on the relationship between land use, travel behavior and air pollution in order to demonstrate that there is a clear nexus between development design, location, and air pollution.
- Section III provides a more in-depth discussion of the specific land use factors used by URBEMIS in applying the ISR, documenting the connection in the research to each of those individual factors, and demonstrating that there are actions developers can take to reduce or mitigate air pollution.
- Section IV is a more in-depth discussion of the research on the relationship between urban form and CO2, including an estimate of the CO2 reductions that could result if CO2 impacts were included in the San Joaquin Valley Air District ISR.
- Section V is a conclusion.

Figure 1. From Air Pollution to Travel Behavior to Land Use



Commonly Used Acronyms

CARB: California Air Resources Board
CO2: Carbon Dioxide
FAR: Floor Area Ratio (the ratio of building square footage to the square footage of the lot)
GHG: Greenhouse gas
ISR: Indirect Source Rule
LFC: Lawrence Frank and Company
LUTAQH: The Seattle Area Land Use, Transportation, Air Quality and Health study
LUTRAQ: The Portland Area Land Use, Transportation, and Air Quality study
NOx: Oxides of Nitrogen
PM: Particulate Matter
SMARTRAQ: The Atlanta Region Strategies for Metropolitan Atlanta's Transportation & Air Quality study
SJVUAPCD: San Joaquin Valley Unified Air Pollution Control District
URBEMIS: Urban Emissions Model
VMT: Vehicle Miles Traveled
VHT: Vehicle Hours Traveled

SECTION I.
Background on Criteria Pollutants Regulated by the San Joaquin Valley's Indirect Source Rule

Oxides of nitrogen (NOx) and fine particulate matter (PM) are the two pollutants that are regulated by the San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD) through the ISR, and are the focus of this report. NOx and PM are two of a number of air pollutants regulated by the Clean Air Act and other legislation. Among the different pollutants, each has different patterns of source generation, geographic dispersion, and health impacts. Both NOx and PM have been shown to have harmful effects on health and are regulated under the Federal Clean Air Act and the California Clean Air Act largely because of their health impacts. Certain populations--elderly, people with pre-existing respiratory and/or cardiovascular disease, and children--have been found to be more vulnerable to the effects of exposure to NOx and PM (Gauderman et al. 2000, 2002, Frumkin et al. 2004).

Vehicles are a well-established source of emissions (Heywood 1988). Many factors play a role in the amount of pollutants generated by vehicle travel, including the individual vehicle characteristics, trip characteristics, type of pollutant, and weather conditions. Therefore, each pollutant is impacted differently by land use and transportation factors (Guensler 1993). These factors are summarized in Table 1 below.

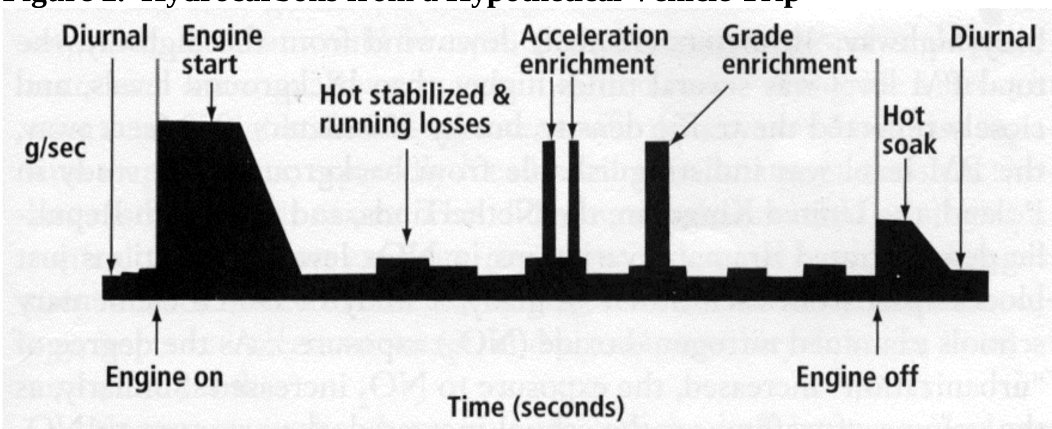
Table 1. Emission-Producing Vehicle Activities and Emissions Produced. Source: Adapted from Guensler (1993).

Emission-Producing Vehicle Activity	**Type of Emissions Produced**
Vehicle Miles Traveled (VMT)	Running Exhaust Emissions (CO, VOCs, NOx, PM, SOx) Running Evaporative Emissions (VOCs)
Cold Engine Starts	Elevated Running Exhaust Emissions (CO, VOCs, NOx, PM, SOx)
Warm or Hot Engine Starts	Running Exhaust Emissions (CO, VOCs, NOx, PM, SOx)
Engine "Hot Soaks"	Evaporative Emissions (VOCs)
Engine Idling	Running Exhaust Emissions (CO, VOCs, NOx, PM, SOx) Elevated Evaporative Emissions (VOCs)
Exposure to Diurnal and Multi-Day Diurnal Temperature Fluctuation	Evaporative Emissions (VOCs)
Vehicle Refueling	Evaporative Emissions (VOCs)
Modal Behavior (e.g. high power demands, heavy engine loads, or engine motoring)	Elevated Running Exhaust Emissions (CO, VOCs, NOx, PM, SOx)

Note on emissions abbreviations: CO: Carbon Monoxide; VOCs: Volatile Organic Compounds; SOx: Oxides of Sulfur.

Emissions from vehicles vary based on vehicle speed and starts. Automobiles pollute most when cold, as their catalytic converters do not operate at peak efficiency until they reach ordinary operating temperature ('stabilized') (Bielaczyc and Merkisz, 1998). 'Cold starts,' therefore, are more highly polluting. As an example, Figure 2 illustrates the hydrocarbon emissions from a hypothetical trip.

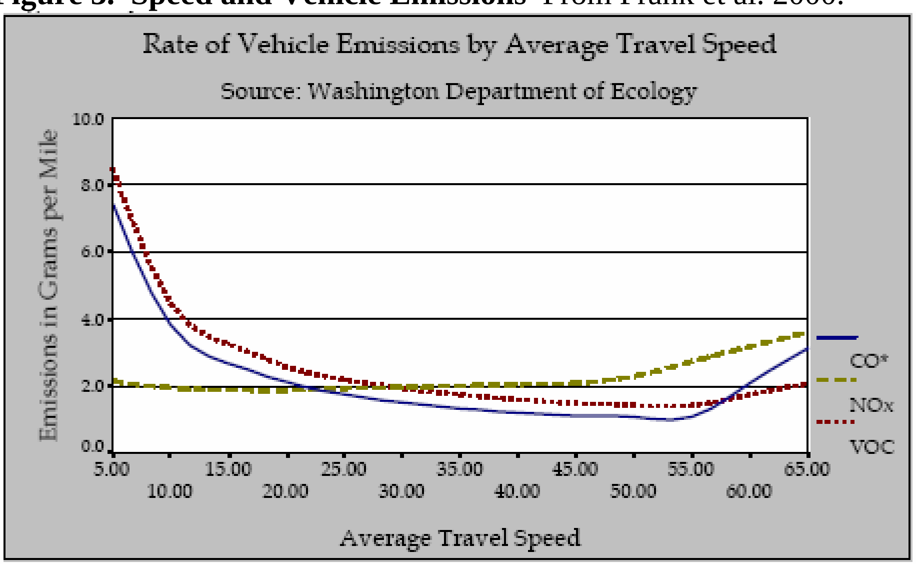
Figure 2. Hydrocarbons from a Hypothetical Vehicle Trip



Source: Bachman et al. 1998 as excerpted from Frumkin et al. 2004.

Emissions vary based on speed as shown in Figure 3 below. The amount and nature of the variation depends on the pollutant as well. NOx emissions increase slightly with speed, and at an increasing rate at speeds over 50 mph (Frank et al. 2000).

Figure 3. Speed and Vehicle Emissions From Frank et al. 2000.



Emissions profiles for stabilized mode (CO was reduced by a factor of 10 in order to present on common y-axis with NOx and VOC. Please note that emission rates are presented in grams per mile for display purposes. Rates in grams per second were used in the emissions modeling).

Oxides of Nitrogen (NOx)

Characteristics. NOx is a broad category of pollutants that contain some combination of Oxygen (O) and Nitrogen (N), primarily Nitrogen Dioxide (NO2). NOx is formed any time fuel is burned at high temperatures. Of the man-made sources of NOx, vehicles (diesel and gasoline), power generation, and industry are the primary contributors. In the San Joaquin Valley, on-road motor vehicles make up 58 percent of total NOx emissions (California Air Resources Board Emissions Inventory 2006). NOx is highly reactive and forms a number of secondary pollutants. In combination with Volatile Organic Compounds (VOCs) in the presence of heat and sunlight, NOx will result in ground-level ozone (smog) (Boubel et al. 1994; Frank & Engelke, 2005; Frumkin et al., 2004). Ozone tends to form at the regional scale, often some distance from the source of where it is generated (Brunekreef and Holgate, 2002).

NOx is more a function of hot stabilized engine operation and distances traveled than of engine starts. This is unlike CO and VOCs, which are more concentrated during the engine warm up period. Therefore, long-distance high-speed travel that is associated with outlying area development can result in considerable increases in NOx on a per capita basis.

Health Impacts. High ozone levels have been linked to chronic acute respiratory conditions, shortness of breath, and asthma (Bell et al. 2004; Friedman et al. 1998, Gauderman et al., 2004, Hoek et al. 2002; Areskoug et al. 2000; Nyberg & Pershagen 2000). Friedman et al. (1998) used the 1996 Summer Olympics in Atlanta as a case study. Concerned about the impact a million visitors (and their vehicles) might have on the health of athletes, residents and those visitors in a region with serious air quality concerns, Atlanta took dramatic measures. These included an integrated 24-hour public transportation system, 1,000 buses for park-and-ride services, closing downtown to vehicles, and altering downtown delivery schedules. An outreach program encouraged local businesses to allow alternative work hours and telecommuting, and warned the public about potential traffic and air quality problems. As a result, morning peak-hour traffic decreased by 22 percent and one-hour peak ozone emissions decreased by 28 percent. Various measures of asthma attacks also decreased between 11 and 44 percent. When controlling for weather variables, researchers found that reductions in peak hour traffic could explain a 13 percent decrease in ozone levels, leading them to conclude that reducing automobile traffic reduces both emissions and asthma attacks.

Particulate Matter

Characteristics. Particulate Matter (PM) is made up of tiny airborne liquid and solid particles which can combine or break apart as they drift through the atmosphere. PM, therefore, varies in size and chemical composition. These particles can come from a large number of sources: dust from unpaved roads, "resuspended" dust from vehicle traffic, construction, wood burning, industry, and vehicle exhaust, diesel vehicle exhaust in particular. PM from fuel combustion can contain carbon, ammonium, sulfates, nitrates, organic chemicals, water vapor, and metals.

Two types of PM are regulated by the Clean Air Act: "coarse" particles (between 2.5 and 10 microns) and "fine" particulates (under 2.5 microns). Particles under 10 microns in diameter (PM_{10}) are small enough to bypass the body's defenses at the nose and throat. "Fine" and "ultrafine" particles, under 2.5 and 0.1 micron respectively, penetrate deep into the lungs (Frumkin et al. 2004).

The geographic distribution of particulates is impacted largely by particle size and wind conditions. Large particles, such as those from diesel exhaust, tend to settle in closer proximity to where they are generated, and will decrease in concentration sharply from that point. Smaller particles, or those formed as secondary pollutants, tend to drift further from where they are generated and stay suspended for longer periods.

In the San Joaquin Valley, on-road motor vehicles make up 5.7 percent of PM10 and 13.1 percent of PM2.5, not including natural sources of PM[1] (California Air Resources Board Emissions Inventory 2006). Motor vehicle emissions are estimated to make up an even greater percentage of ultrafine particles (Shi et al., 1999, Shi et al., 2001).

Health Impacts. Particulate matter has been linked to increases in mortality rates, respiratory infections, asthma attacks, and hospitalization (Dockery et al. 1993; Katsouyanni et al. 2000; Samet et al. 1999; Samet et al. 2000). A few studies have found PM to be associated with lung cancer and reduced life spans (Pope et al. 2002; Shprentz et al. 1996). One study found that increased exposure to PM 2.5 can trigger heart attacks in at-risk populations (Pope et al. 2000).

There is some evidence suggesting that PM from motor vehicles contributes more greatly to health impacts than other sources of PM. In a study that examined death rates and air pollution in six U.S. cities, investigators separated out the impacts of different PM sources on mortality. They concluded that PM from mobile sources contributed three times more to mortality than did PM from coal combustion. PM from "crustal sources" such as road dust was not found to contribute to mortality (Laden et al. 2000). If this is indeed the case and the contribution of vehicle (indirect) sources to PM and public health is of greater importance to public health than other PM emissions, the impact and relevance of the Indirect Source Rule (ISR) is potentially also stronger than originally assumed.

[1] Natural sources add about 35 tons/day of PM10 and 29 tons/day of PM2.5 to the total in the San Joaquin Air District, from wildfires (2005 California Air Resources Board Emissions Inventory data).

SECTION II.
The Land Use / Travel Behavior Relationship

The Conceptual Relationship between Land Use, Travel Behavior, and Air Pollution

The conceptual link between air pollution, travel behavior, and land use patterns is depicted in Figure 1 on page iv. Land use patterns are influenced by policies such as zoning designations and economic signals, including incentives and disincentives imposed by the government, such as regulations and impact fees. This combination of fees and regulations with real estate market trends is a key factor in determining where new development is located and how it is built.

The resulting urban form patterns influence travel behavior by making certain modes of travel more or less convenient or 'costly' than the others (Boarnet & Crane 2001a; Cervero & Kockelman 1997; Handy 1996; Frank et al. 2007b).

Travel behavior, and vehicle travel in particular, is directly related to air pollution. In the research, a number of outcomes can be tied to emissions, including vehicle miles and hours of travel, and number of vehicle trips. Estimating emissions off of travel patterns allows a more precise understanding of the potential change in different pollutants emissions that might be associated with urban form strategies. A few studies have estimated vehicle emissions, including Frank et al. 2000, Frank et al. 2006, Frank & Chapman 2004, and LFC. et al. 2005a.[2]

Definitions of the three key travel-related concepts used in the literature are provided below along with a basic definition of how they have been found to relate with land use and air quality.

- **VMT / VHT:** Per capita vehicle miles of travel (VMT) and vehicle hours of travel (VHT) describe how much people drive, and are therefore closely linked to vehicle emissions. In their literature review of over 50 studies, Ewing and Cervero (2001) found that the built environment had the most impact on trip length, VMT and VHT. VMT has been positively associated with per capita NOx and VOC emissions (Frank et al. 2000). Neither VMT nor VHT captures speed or cold starts/number of trips, which is necessary to accurately predict emissions. However, a study for the Washington State Department of Transportation showed the additional driving necessitated by longer distances between destinations

[2] In several of the studies cited above (LFC et al. 2005a, Frank et al. 2006, and Frank & Chapman 2004), the approach used to measure emissions outcomes is highly detailed and deserves mention, as it strengthens the defensibility of results presented from these sources. Rather than using a standard methodology, which applies a simple average speed for each trip, the emissions estimates included speed and cold start information for each link of each vehicle trip. Speed was calculated for each link of each auto trip based on the road type (local, collector, arterial, freeway, etc.) and time of day.

overwhelmed any increase in trips / cold starts found in more urban areas (Frank et al. 2005a; Frank et al. 2006).

- **Vehicle Trip Generation:** Trip generation rates are an important aspect of assessing air pollution. Increased trip generation can be associated with more highly-polluting cold starts.

- **Mode Choice:** The relative shares of autos, transit, walking, and bicycling relates to the amount of driving in an area, and by extension, other pollutants. However, although there is some substitution between driving and other modes, it is not a 1:1 relationship – more walking trips do not necessarily translate into less driving trips and emissions. That is because more walkable environments and close-in neighborhoods can also encourage short vehicle trips.

Overview of the Literature

There is a growing body of evidence documenting urban form relationships with travel behavior. The connection between land use and transportation extends back decades and noted as a fundamental aspect of transportation planning (Meyer, Kain, and Wohl 1962). Land use density was used as primary criteria to determine transit ridership and justification of new starts for rail investments in the 1970s Pushkarev and Zupan (1977). Newman and Kenworthy (1989) in Gasoline Consumption and Cities provide an aggregate comparison of 32 cities worldwide and show that more compact cities were more sustainable based on less fuel use and more transit ridership.

A number of empirical studies and reviews argue that the connections between land use and transportation are inconsistent or lacking (Crane & Crepeau 1998, Boarnet and Sarmiento 1998, Ewing et al. 1996, Boarnet and Crane 1998, Guiliano 1991). These articles have helped to highlight the sensitivity of land use - transportation research to methodological differences, and to inform the methodology in subsequent research. Some inconsistencies in results across studies can be at least partially attributed to considerable differences in geographic scale, data quality and methods used to measure built environment predictors of travel (Frank 2000b). For example, the use of larger geographic scales can "wash out" differences in urban form, and also fail to capture the scale at which decisions about mode choice may happen – generally walking distance from a particular origin or destination point (Moudon et al. 2006). While some studies measure land use patterns within walking distance of households, (Frank et al. 2004 2005, 2006; Moudon et al. 2006), others rely on larger scales, such as census tracts (Crane & Crepeau 1998). In some cases, whole counties have been used to develop national level results (Ewing et al. 2002, 2003). Earlier research also relied more heavily on auto trip generation as an outcome (Ewing et al. 1996, Boarnet and Sarmiento 1998), while urban form tends to correlate less well with auto trip generation and better with VMT (Frank et al. 2000, 2006). When examining air pollution, this stronger relationship to VMT will matter more for some pollutants – particularly NOx and CO2.

The science has evolved considerably in recent years through the advent of GIS and computing capabilities. There has been a veritable explosion of research on this topic, and several literature reviews and meta-analyses that have been used to summarize this literature and the findings. Such reviews have been published by Ewing and Cervero (2001), Frank (2000); Boarnet and Crane (2001), USEPA (2001), Kuzmyak and Pratt (2003), Bento et al. (2003); TRB/IOM (2005); and most recently Ewing et al. (2007) making the link with greenhouse gases. Each of these reviews has concluded that there is a measurable connection between land use and travel behavior. While they note limitations in the current evidence including differences in methods and data used to measure specific relationships, the overall message is that residents in relatively more compact, mixed use neighborhoods with an interconnected street network tend to drive *less* and walk *more* than residents of sprawling, single-use, auto-oriented neighborhoods when adjusting for demographic factors. The most recent meta-analysis published by Ewing et al. (2007) concludes that close-in, compact and walkable development "…has the potential to reduce VMT per capita by anywhere from 20 to 40 percent relative to sprawl."

There has been a considerable debate in the scholarly literature over the extent to which the relationship between land use and travel is causal in nature. Some argue that land use patterns may be merely masking the effect of underlying preferences for neighborhood type and/or travel choice (TRB/IOM 2005) - claiming that, for example, some people may prefer driving to walking and may therefore be less likely to walk, even if they are living in a walkable neighborhood. More recently, researchers have been testing the relationships between neighborhood design while taking into account people's preferences for neighborhood designs and/or travel mode. Over the past three years several new studies have been released that confirm the importance of land use on travel behavior, even when adjusting for those preferences. Overall, research results suggest that both preferences and the actual features of the neighborhood in which we reside impact our travel behavior (Handy et al. 2006; Frank et al. 2007a).

It is also necessary to point out that increases in density is likely to increase congestion levels, as discussed by Boarnet and Crane (1998). While this is often the case, because congestion is a function of the increase efficiency gained in concentrating population and/or employment over space and time for the transaction of goods and services, reducing congestion is unlikely - particularly in larger urban areas and cities with strong economies. Nor will the public tolerate or fund highway expansions to the point that peak period congestion is reduced. Tolling, taxes and other user fees can help – central business district or cordon pricing schemes such as those used in London may have particular utility - but generally these solutions are limited in comparison to the fundamental need to concentrate activities (in urban and suburban centers). The Texas Transportation Institute even adds "realistic expectations" to its list of solutions for congestion discussed in the 2005 Urban Mobility Report (Schrank and Lomax 2005, p. 5).

Additionally, mode choice is driven most strongly by time-competitiveness of each travel mode, across all modes available (Ben-Akiva and Lerman 1985, Train 1986, McFadden 1978). Consistent with this body of evidence, one recent study found that for home-based work travel, a 10 percent increase in auto travel time was associated with a 3.1

percent increase in transit mode share, a 2.8 percent increase for bicycling, and a 0.5 percent increase for walking. For home based, non-work travel, this same 10 percent increase in auto travel time resulted in a 2.3 percent increase in transit, a 2.8 percent increase in bicycling, and a 0.7 percent increase in walking. This phenomenon also works in reverse – when travel times (congestion) are reduced, the likelihood of taking transit, biking and walking decreases. Costs of fuel, parking and transit also played a significant role in mode choice decisions. Increasing the cost of fuel and parking costs by 10 percent for the solo commuter was associated with an increased transit demand of 3.71 percent, bike demand by 2.7 percent and walk demand by 0.9 percent. However, transit mode choice was much more sensitive to travel time than to fare costs – a 10 percent increase in transit travel time was associated with a 3.9 percent decrease in travel demand for work trips and a 2.3 percent decrease for non-work trips. This is over three times the decrease in transit demand found with a 10 percent increase in fares – a 1.1 percent reduction for work trips, and a 0.8 percent reduction for non-work trips. This seems to be a function of a low level of transit service (high transit travel times relative to auto travel times) in the Puget Sound Region, where the study was conducted (Frank et al. 2007b).

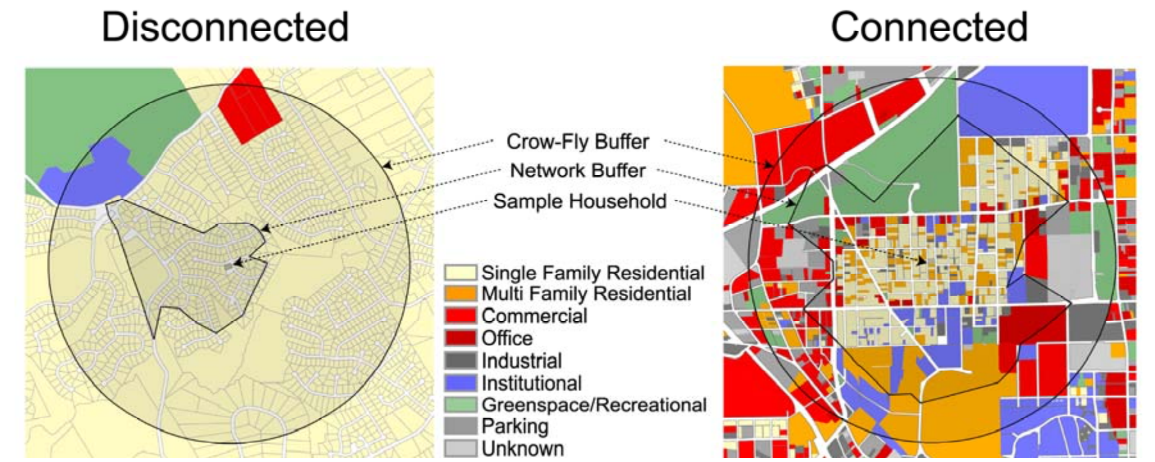
For this reason, changes in travel time for each mode should not be seen in isolation from the other modes – particularly in the case of a reduction in auto travel time, VMT (and the associated air pollution and CO2) could increase as a result of increased vehicle demand and long term impacts from induced travel and land use change (Noland 2001) - possibly to a level beyond any expected short term emissions benefits from congestion reduction.

Neighborhood Design, Travel, and Emissions

Neighborhood-scale walkability relates to travel primarily by impacting proximity between destinations and directness of travel between these destinations. Proximity is a function of the density or compactness of activities and the level of land use mix (the spatial distribution of different land use types, such as residential, office, and retail). Both density and land use mix help to determine how many routine tasks—going to work, grocery shopping, visiting friends, etc.—are within a convenient distance (Frank 2000; Sallis et al. 2004; Frank and Engelke 2001). Street network connectivity—whether the street network is an interconnected 'grid' design or a disconnected system dominated by cul-de-sacs—determines how directly one can travel between activities. Figure 4 illustrates how street network design, in conjunction with the presence of adjacent land uses, determines what is accessible within a given distance from where someone lives. Collectively, these factors impact distances to destinations shown to impact travel choice and emissions.

As proximity and directness between destinations increases, distance between those destinations decreases. As the distance between destinations decreases, so does vehicle miles traveled (Boarnet & Crane, 2001b; Ewing & Cervero, 2001; Holtzclaw, Clear, Dittmar, Goldstein, & Hass, 2002). These results are consistent with the URBEMIS modeling platform. Where distances between destinations are sufficiently short (between ¼ - ½ mile) walking trips will substitute for some driving trips (Sallis et al., 2004, Handy and Clifton 2001, Bagley & Mokhtarian 2002).

Figure 4. How Proximity and Connectivity Impact Travel Patterns



This diagram contrasts a household located in a typical low-density, disconnected suburban neighborhood with separated uses on the left with a household located in a more compact, connected, mixed use neighborhood on the right. The circle represents a 1-kilometer radius (the 'crow-fly' distance) from each household, while the asymmetrical 'network' buffer inside the circle captures the 1-km area actually walkable on the street network. This diagram shows not only how a disconnected street network pattern can impact walking accessibility ***(directness)****, but how a low-density, single use land use pattern restricts the number of accessible destinations within walking distance* ***(proximity)****.* From Frank et al., 2004.

The LUTAQH (Land Use, Transportation, Air Quality, and Health) study in Seattle integrated several basic neighborhood urban form measures—residential and retail **density**, street **connectivity**, and **land use mix**—into a walkability index. The index was found to be a statistically significant predictor of vehicle miles traveled and NOx emissions. A 5 percent increase in walkability was associated with 6.5 percent fewer vehicle miles traveled and 5.6 percent fewer grams of NOx emitted (Frank et al. 2006).

The Atlanta-based SMARTRAQ study used a similar walkability index that included residential density, street connectivity and land use mix to measure land use, travel behavior and air quality relationships. People who live in the most auto-oriented neighborhoods drive an average of 39 miles per person each weekday—30 percent more than those who live in the most walkable neighborhoods. Each step up a quintiled five-part walkability scale was associated with a 6 percent reduction in NOx and a 3.7 percent reduction in VOCs (Frank & Chapman 2004).

In both of the above studies, researchers controlled for demographic factors that are known to influence travel patterns such as income, gender, education, household size and vehicle ownership.

In an analysis based in the Puget Sound region, Frank et al. (2000) looked at the relationship between land use, travel patterns, and air pollution (NOx, VOCs, and CO). Five variables were tested in a multivariate model: household density, home location employment density (a proxy for land use mix), census block density (a proxy for street connectivity), work tract employment density, and distance to work. These variables were all found to be statistically significant in explaining VMT, VHT, and NOx. The incorporation of the five land use factors into the model along with demographic variables nearly doubled the model's ability to explain household-level NOx emissions. The model for NOx had a higher explanatory power than similar models constructed for CO and VOCs—approximately 38 percent of the variation in household NOx emissions. When considering the large number of variables that potentially influence travel behavior and emissions, a model that explains 38 percent of emissions is rather noteworthy.

Neighborhood-scale walkability also factors in the decision to take transit for longer regional trips (such as work trips) because it facilitates access to transit as well as non-driving access to auxiliary destinations, such as the bank or dry cleaner. Research has documented a link between walkable employment centers and travel mode to work. In numerous studies of employment centers in California, Robert Cervero found that increasing the mix of land uses at employment centers was associated with higher shares of employees taking transit and ridesharing to work, and fewer vehicle trips to work (Cervero 1991, 1988a, 1988b). Frank and Pivo (1995) found a threshold of about 75 employees/acre at which driving to work began to drop off in a measurable way. Frank et al. (2000) also found household-level NOx, CO, and VOC emissions followed a similar pattern, with a sharp drop off when employment densities reached medium-high levels.

The 'Ds' of Travel Behavior

A number of individual land use factors have also been shown to be associated with travel behavior. These factors have been evaluated individually in the research.

Although there can be some overlap in the way the different characteristics of land use patterns are categorized, they can be thought of as the "Three Ds" of the land-use-and-travel-behavior relationship, as first presented by Cervero and Kockelman (1997): Density, Diversity (land use mix), and Design (street connectivity, building placement and streetscape). Later authors (Moore et al. 2007), inspired by Cervero and Kockelman, have added two more Ds: Destinations and Distance. The fourth D, 'destinations' refers to the effect of regional location on travel. 'Distance' is an overarching category that frames how the other 4 Ds affect each other, functioning like the term "proximity" discussed on page 13 and in Figure 4. This document focuses on the first four Ds, as those are the individual land use factors that developers have the best opportunity to address.

Each of these factors is defined below, in addition to a description of how they influence travel behavior and a summary of the relevant literature findings. These specific factors are available as mitigation measures under the SJVUAPCD's Indirect Source Rule. Section III of this report provides a thorough discussion of the research on each of these factors and a discussion of how they support the mitigation factors in the ISR.

Density. An area's density, or compactness, provides the critical mass necessary to support shops, services, and transit and determines how close people are to destinations. As the compactness of an area increases, the per capita amount and share of car travel decreases. Residential density is by far the most commonly measured urban form factor, and has been consistently associated with transportation outcomes at a number of geographic scales. Researchers have also studied retail and employment density (LFC 2005a; Frank and Pivo 1995; Cervero 1991).

All else being equal, as a community's residential density increases, decreases can be seen in per capita VMT and VHT (Ewing and Cervero 2001; Holtzclaw 1994; Holtzclaw et al. 2002; Dunphy and Fisher 1996; Cervero and Kockelman 1997; Frank and Pivo 1995; Frank et al. 2000; Frank et al. 2006), the number of vehicle trips (Frank et al. 2000), and the share of auto travel (PBQD 1996, Ross and Dunning 1996, Kitamura et al. 1997, Cervero and Gorham 1995, Cervero and Kockelman 1997). Because density is strongly co-linear with other land use measures such as intersection density, land use mix, presence of retail and high quality transit services (particularly in older cities with strong central cores), it can be a useful aggregate scale indicator and consistently emerges as a significant predictor of travel behavior in aggregate studies (Holtzclaw et al. 2002, Ewing et al. 2002, Newman & Kenworthy 1989).

In a study on Chicago, Los Angeles, and San Francisco, Holtzclaw et al. (2002) found strong relationships between VMT and net residential density and transit accessibility, weaker relationships to bicycle-pedestrian friendliness, and no relationship to local shopping access, taking into account household size and income. In all three cities, net residential density had the single strongest relationship to VMT. Each doubling of residential density reduced VMT 32% in Chicago, 35% in Los Angeles, and 43% in San Francisco.

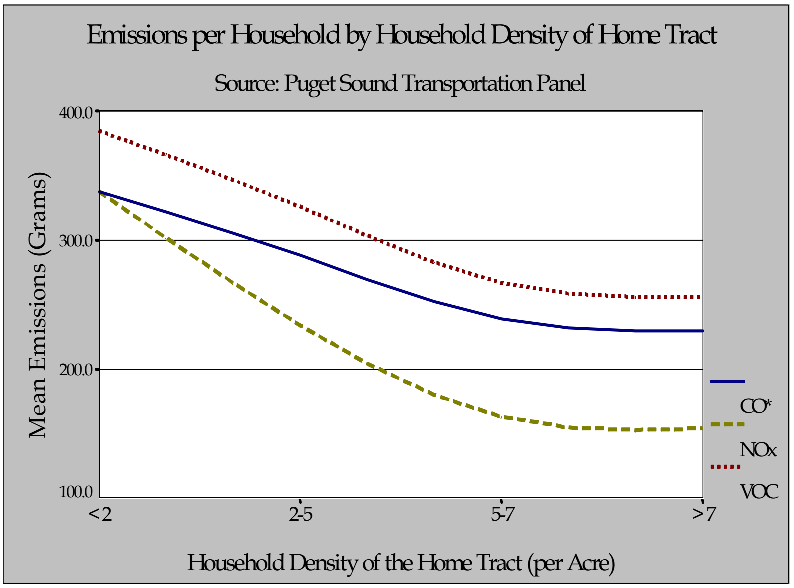
Another aggregate-level study, which examined four sprawl factors (density, centeredness, land use mix, and network connectivity) in 83 U.S. metro areas found that, of the four factors, density had the strongest relationship to travel outcomes overall. Density was the only urban form variable that maintained a significant relationship to VMT when sociodemographic and the other three urban form variables were controlled for (Ewing et al. 2002). Ewing (2007) elaborates on those findings:

> "…a 50-unit increase in the density factor (from one standard deviation below average to one standard deviation above average) is associated with a drop of 10.75 daily VMT per capita (50 x –0.215). That is, controlling for metropolitan population, per capita income, and other factors, the difference between low- and high-density metropolitan areas is more than 10 VMT per capita per day, or 40 percent. Fifty units is roughly the difference in density between San Francisco (denser) and Washington, D.C. (less dense), or between Chicago (denser) and St. Louis (less dense)."

Ewing and Cervero (2001) synthesized the results of 14 studies to derive travel elasticities for neighborhood density, mix, and design, resulting in a density elasticity of 0.05 with respect to vehicle trips and VMT where a 1 percent change in density (as measured by jobs + residents / land area) results in a 0.05 percent reduction in VMT and vehicle trips. These elasticities control for the other built environment variables, making their estimated effects cumulative.

Increases in density have also been correlated with lower per capita levels of air pollutants, including NOx, when controlling for income, age, vehicle ownership, and household size (Frank & Engelke 2005; Frank et al. 2000; Frumkin et al. 2004), as Figure 5 below illustrates. The results depicted in Figure 5 measured density at the census tract level.

Figure 5. Co-Variation in Emissions and Census Tract Level Household Density. From Frank et al. 2000.



Another study known as the SMARTRAQ project in Atlanta, found that per person NOx, hydrocarbon (HC), and carbon monoxide (CO) emissions vary by residential density as well. Once residential density exceeds four dwelling units/acre, emissions for these pollutants are 16-22 percent lower than in places with density levels below four units/acre (Frank and Chapman 2004). These results were achieved using detailed parcel level land use data, aggregated to 200-meter grid cells.

One of the reasons density has been so consistently associated with travel behavior, especially at larger scales, is because it is co-linear with so many other variables that are also connected to travel. It can be difficult to separate the impacts of, for example, transit accessibility, parking costs and availability, the pedestrian environment, land use mix and street connectivity.

Two recent studies in the Seattle area (LFC2005a; LFC 2005b) found that land use mix and street connectivity were better predictors of travel behavior than density, leading the researchers to conclude that density may be over-emphasized as an influence on travel behavior. The researchers note that this finding recognizes the need to take a "more nuanced appreciation of the influence of density and land use on travel behavior" (LFC 2005b, p. 154).

In light of these findings, density's role may best be described as a necessary but not sufficient condition for changing travel behavior. Higher residential densities are needed to create the market for shops and services and to make transit a viable option. However, in the absence of destinations within walking distance and direct connections to those destinations, residential density will have much less of an impact on travel patterns. Moudon and Hess (2000) documented the existence of 'suburban clusters' in the Seattle suburbs, areas of medium density multi-family housing, frequently adjacent to retail and office development, that house nearly 20 percent of the region's suburban population. However, the urban form in these areas could be only described as disconnected and auto-oriented, with little or difficult pedestrian access. When the clusters were compared to urban neighborhoods (with similar levels of density, mix, and income but with fine-grained street networks), Hess and Moudon et al. (1999) found they generated an average of one-third the pedestrian activity.

Diversity (Land Use Mix). Areas with a mixed land use pattern have a less homogeneous distribution of land use types (such as residential, office, retail, entertainment/recreation, educational uses and institutions), placing people in proximity to more everyday destinations. Researchers have measured land use mix primarily using measures of entropy/dissimilarity or using measures of jobs/housing balance.

Land use mix has been measured in a variety of different ways and seems to be especially sensitive to issues of measurement and scale. Ewing and Cervero (2001) divide land use mix measures into three types: measures of accessibility to jobs or shopping; entropy (land use diversity) measures; and jobs-housing/population balance measures.

Although a number of studies have documented decreased levels of driving in mixed-use places (Cervero and Kockelman 1997; McCormack et al. 1996; Frank and Pivo 1995; Frank et al. 2006), a national study did not find their land use mix factor (which included six measures of mix) significant in explaining VMT (Ewing et al, 2002). The researchers note that this may be due to difficulties in measuring land use mix. In addition to problems with the underlying data, mix may have been measured at a scale too large to capture its true impact. Holtzclaw et al (2002) found similar results; a measure of local shopping did not add to the model's predictive power after density and transit accessibility were accounted for.

In a detailed analysis of destinations and walking behavior, Moudon (2006) states that "the walkable neighborhood seems geographically contained within a 1-km circle, an area smaller than 500 acres (2 km^2)." Other studies which have examined land use mix at a fine-grained level such as this have found mix consistently significant in explaining VMT (Frank and Chapman 2004; LFC 2005a; LFC 2005b; Kockelman 1997).

In a Seattle-area study (LFC 2005b), researchers applied regression coefficients to estimate changes in VMT based on changes in mix, and found that changing the mixed use of a location from a single use (mixed use index =0), to an even distribution of floor area across residential, entertainment, retail, and office uses (mixed use index =1), was associated with a 19.70 percent decrease in VMT and 23.51 percent decrease in VHT. In the synthesis by Ewing and Cervero (2001) the elasticity for land use mix (as expressed by jobs-population ratio) was found to be -0.03 with respect to vehicle trips and -0.05 for VMT. These elasticities controlled for the other built environment variables, making their estimated effects cumulative.

A mixed land use pattern is correlated with increased walking and reduced automobile travel, all else being equal. A number of studies have documented decreased levels of driving in mixed-use places (Cervero and Kockelman 1997; Frank and Pivo 1995; McCormack et al. 1996, Frank et al. 2006).

With increasingly sophisticated GIS, land use and aerial photography data, researchers' ability to calculate and test measures of urban form has improved a great deal in the past ten years. This has lead to the emergence of retail development and land use mix as highly significant predictive factors for transport and air quality outcomes. Several recent studies have used detailed land use data to objectively measure distances between different types of activities such as residential, office, retail, entertainment, parks, and other uses (Lee and Moudon 2004; Moudon and Lee 2003; Hess 2001; LFC et al. 2005a; Frank et al. 2005, Frank et al. 2006).

One of these studies, the LUTAQH study (Land Use, Transportation, Air Quality and Health, LFC et al. 2005b) examined the impact of individual land uses on VMT in a multivariate linear regression model. Despite the fact that these trip purposes account for only a small share of the number of trips generated by a household, the following land uses all accounted for small but significant decreases in VMT:

- The Number of Educational Facilities
- The Number of Grocery Stores
- The Floor Space of Civic Uses
- The Rentable Floor Space of Doctor and Dentist Offices
- The Rentable Floor Space of Neighborhood Retail Attractions
- The Number of Large Retail Attractions
- The Number of Convenience Stores
- The Number of Fast Food Restaurants

When the same study looked at level of land use mix as a whole, significant differences in VMT were observed across levels of mix, as seen in Figure 6 below (LFC et al. 2005b). [3] Although the differences in VMT in the table below are statistically significant, they are also conservative; the use of quartiled data masks larger differences in VMT and land use mix. The land use mix variable measured the evenness of distribution of several

[3] ANOVA, or ANalysis Of VAriance, is used to determine if differences found between groups of data, such as the quartiles used here, are statistically significant. ANOVA compares variation around the mean values of groups of measurements – for example, household VMT at different levels of land use mix near households. In the ANOVA analyses presented in Tables 6, 8 and 9, the difference in at least one pair of mean values for each VMT is statistically significant.

different land use types: retail, office, single family residential, multifamily residential, education, and entertainment. In addition to the land use mix measure, retail availability (number of retail parcels) and retail density (retail Floor Area Ratio) also emerged in that study as significant predictors of VMT, NOx, and other emissions (LFC et al. 2005b; Frank et al. 2006).

Figure 6. **Differences in VMT across Land Use Mix** (LFC et al. 2005b).

LUTAQH ANOVA ANALYSIS **Land Use Mix** (controlling for gender, income, age, education, total number of household vehicles, distance to nearest bus stop)	**Quartiles of Land Use Mix** (1km road-network-based household buffer)							
	1 (LOW)		**2 (MED-LOW)**		**3 (MED-HIGH)**		**4 (HIGH)**	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Land Use Mix (scale from 0-1)	-3.25	0.20	0.20	0.28	0.28	0.36	0.36	0.84
VMT	32.26		30.38		27.94		27.15	

A study in the same region also found land use mix to be highly significant in predicting VMT, VHT, and emissions. In applying the modeled findings, researchers found that increasing a similar index of land use mix (which included entertainment, residential, retail and office uses) from 0 (the lowest value) to 1 (its highest value) was associated with a 19.7 percent decrease in VMT, a 23.5 percent decrease in VHT, and a 10.3 percent decrease in NOx (LFC 2005a).

In a regional household travel survey as part of the SMARTRAQ project in Atlanta, 60 percent of respondents indicated that at least one type of destination located near public transportation would encourage them to use public transportation. Over 30 percent of people indicated a grocery or retail store, bank/credit union, doctor/health clinic, or sports facility would be important to have near transit (Frank and Chapman 2004).

Design (Street Connectivity, Building Placement, and Streetscape).

Street Network Connectivity

Whether a street network is interconnected (a gridded street system, as is found in older and in-city areas) or disconnected (a system dominated by cul-de-sac/dead end streets) will determine the directness of travel between destinations, as Figure 4 on page 9 illustrates. Researchers have used a number of measures to calculate street connectivity, such as block face length, block size, or intersection density (number of intersections per acre or mile).

Route directness is especially important for walking trips, as walking is such a slower mode of travel. Two early studies on this topic by Kitamura et al. (1997) and Greenwald and Boarnet (2001) found significant relationships between connectivity variables and walking. Moudon and Hess (2000) also found indications that connectivity may be a necessary element (in addition to compact and mixed-use development) to increase walking and decrease driving. They found that almost 20 percent of residents in suburban areas of the Central Puget Sound Region live in “suburban clusters”—medium-density neighborhoods in close proximity to neighborhood retail. These suburban neighborhoods, however, are lacking in connectivity. When the suburban clusters were compared to urban neighborhoods with similar levels of density and mix of uses but higher levels of connectivity, the suburban clusters generated an average of one-third the pedestrian traffic than their urban counterparts.

Although early research on this topic was less conclusive, with a number of studies finding insignificant results (Cervero 1994; Boarnet and Sarmiento 1998; Messenger and Ewing 1996) consensus in the research has grown with better quality data and improved measurement. More recent studies have been able to draw a connection not only between connectivity and walking, but driving as well. Cervero and Kockelman (1997) found VMT to decrease as proportion of 4-way intersections increased. Frank and Pivo (1995) measured connectivity at the census tract level and found that VMT and VHT were significantly lower in areas with smaller blocks.

Some researchers have argued that increasing connectivity also means more vehicle trips, and thus more cold starts, resulting in higher levels of vehicle emissions. These assertions have been challenged by subsequent evidence which take cold start production into account when estimating emissions (LFC et al 2005a, LFC et al. 2005b). These studies demonstrated that overall NOx and VOC emissions rates are lower for residents of more compact, mixed use, connected environments. Researchers believe this was due to the overwhelming impact of travel distance on vehicle emissions rates for those in the most sprawling environments.

In a study which used parcel level land use data in combination with link-level vehicle speed and start data, increases in intersection density were significantly associated with decreases in VMT, VHT, and NOx emissions. When these model results were applied to unit changes in the independent variables, a one-unit increase in intersection density (as measured by the number of intersections per sq km) was associated with a 0.39 percent decrease in VMT and a 0.28 percent decrease in VHT while controlling for vehicle ownership, income, and transit access. A 0.1 percent decrease in NOx was found under these same conditions even *after controlling for VMT*. The additional impact of intersection density on NOx is probably due to speed and start patterns (LFC et al. 2005a). It should be noted that one additional intersection per square kilometer is a very small increase, and much greater variation is common when comparing levels of intersection density across regions.

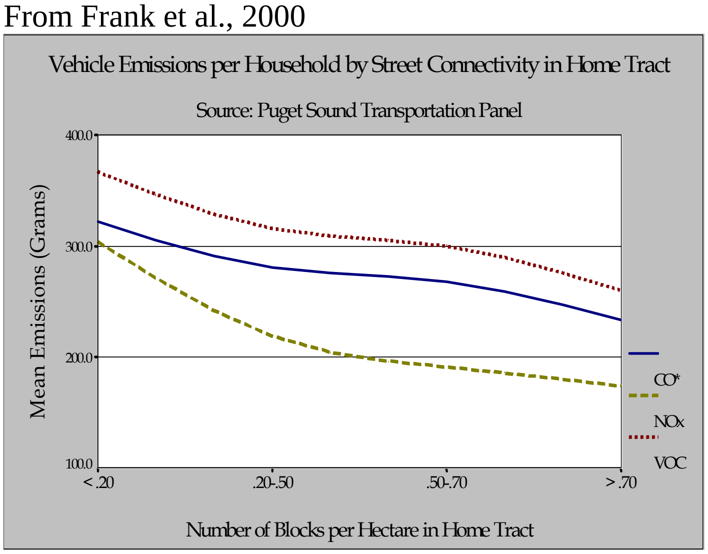
The Seattle-area LUTAQH study (LFC 2005b) looked at the influence of intersection density, land use mix, and residential density on VMT, and found the greatest differences across levels of intersection density, where the mean VMT was 34 miles per person in the least and 25 miles in the most connected environments of King County. This difference is statistically significant and represents 26 percent fewer vehicle miles of travel for residents who live in communities with the most interconnected street networks in the county. It is expected that these results are conservative; the use of quartiled data masks larger differences in VMT and street connectivity found in the area.

A similar study in the Seattle area examined intersection density, residential density and land use mix as continuous variables, rather than breaking them into quartiles as was done in the LUTAQH analysis. Again, intersection density had a stronger relationship to decreases in VMT and VHT than residential density or land use mix (LFC 2005a). When these model results were converted to elasticities and applied to unit changes in the independent variables, a one-unit increase in intersection density (as measured by the number of intersections per sq km) was associated with a 0.39 percent decrease in VMT and a 0.28 percent decrease in VHT while controlling for vehicle ownership, income, and transit access. One additional intersection per square kilometer is a very small increase, and much greater variation is common when comparing levels of intersection density across regions.

In the meta-analysis by Ewing and Cervero (2001) the network design measure was a composite measure of a neighborhood's sidewalk completeness, route directness, and street network density (in this paper, sidewalk completeness is discussed in the following section on site design/pedestrian environment). The elasticity of this measure was estimated to be -0.05 with respect to vehicle trips and -0.03 for VMT. These elasticities controlled for the other built environment variables (density and land use mix), making their estimated effects cumulative.

In an earlier study by Frank et al. (2000), the generation of NOx was found to be more sensitive to street connectivity (block density) than was CO or VOC. This finding, illustrated below in Figure 7, can be attributed to the effect of street network configuration on average travel speed. Lower average travel speeds occur on interconnected street networks (Frank et al. 2000), and as Figure 2 on page 7 illustrates, NOx emissions tend to increase at high travel speeds more than CO or VOCs.

Figure 7. Co-Variation in Emissions by Census Tract Level Street Connectivity.
From Frank et al., 2000



The LUTAQH research found similar results - street connectivity where people live appeared to be the most closely associated with NOx generation. Mean NOx emissions declined from 29 to 23 grams per person per day, a 21 percent reduction, between residents of the least to the most connected environments (LFC et al. 2005c).

In an ANOVA analysis for the LUTAQH study, the greatest differences in VMT were observed across levels of intersection density (as compared to land use mix, retail floor area ratio, and residential density), as seen in Figure 8 below. The average VMT was 34 daily miles per person in neighborhoods with the least connected street networks and 25 miles per day in the most connected neighborhoods—a 26 percent decrease in VMT for residents who live in communities that have the most interconnected street networks in the countywide study area. Again, it is expected that these results are conservative; the use of quartiled data masks larger differences in VMT and street connectivity found in the region. Increases in street connectivity at **household and employment locations** were also associated with reductions in per capita levels of NOx, VOCs, and CO2 when controlling for household income and size (LFC et al. 2005b).

Figure 8. Differences in VMT Across Intersection Density (LFC et al. 2005b).

LUTAQH ANOVA ANALYSIS Intersection Density (controlling for gender, income, age, education, total number of household vehicles, distance to nearest bus stop)	Quartiles of Intersection Density ((1km road-network-based household buffer)							
	1 (LOW)		2 (MED-LOW)		3 (MED-HIGH)		4 (HIGH)	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Intersection Density (# per square kilometer)	0.00	27.56	27.78	43.35	43.37	58.71	58.75	158.93
VMT	34.03		28.83		30.01		25.46	

Site Design & Pedestrian Environment

Building site design (PBQD et al. 1993b, Frank et al. 2000, LFC et al. 2005b) and the quality of the pedestrian environment (PBQD el al. 1993a) have also been shown to influence VMT and other travel patterns. If a building is placed adjacent to the sidewalk, walking distances are shorter and the walking environment more pleasant than if there is a parking lot between the building and the sidewalk. Additionally, the presence of sidewalks, street trees, benches, and other facilities can increase pedestrians' safety, convenience, and comfort and provide an attractive environment for walking.

The LUTRAQ (Land Use, Transportation, and Air Quality) study in Portland, Oregon combined subjective measures of the built environment—ease of street crossing, sidewalk continuity, street connectivity, and topography—into a Pedestrian Environment Factor (PEF). These factors were quantified on a scale, and used in the development of statistical models. From this the researchers found that "a 10% reduction in vehicle miles traveled (VMT) can be achieved with a region-wide increase in the quality of the pedestrian environment" comparable to Portland's most pedestrian-friendly areas (PBQD el al. 1993a).

The Portland (LUTRAQ) study also performed an analysis using age of buildings as a proxy for building placement, and found that VMT drops significantly where more buildings are oriented towards the sidewalk rather than towards a parking lot (PBQD et al. 1993b), as was found in pre-WWII development. In another study in the Seattle region, the mean age of development was significantly correlated with household non-auto trip generation – the newer the development, the lower the non-auto share of trips.

This suggests that at the time of this study the age of residential development was a proxy that captured the overall quality of the pedestrian environment, including sidewalk provision and building setbacks (Frank et al. 2000).

The King County (Seattle area) based LUTAQH (Land Use, Transportation, Air Quality & Health) study examined retail Floor Area Ratio (FAR) as a predictor of VMT and air pollution. FAR is a standard measure of commercial development and is frequently used in zoning regulations. This real-world applicability makes it a useful measure.
FAR approximates the portion of the lot that is covered by a building by dividing the total square footage of a building by the lot area. For example, a building with a FAR of 2 could be a 4-story building on 50 percent of the lot, or a 2-story building on 100 percent of the lot (or something else entirely). Therefore, FAR measures retail density but also serves as a proxy for building orientation (as the portion of the lot not covered by the building is frequently parking)

FAR was found to be a significant predictor of VMT in the ANOVA analysis shown below in Figure 9. In this analysis, the divisions between quartiles reflect what is still a relatively auto-dependent area (the Puget Sound region) with lots of land devoted to parking in retail areas. Although the difference in VMT between each quartile is statistically significant, there is very little difference in VMT between the lowest three quartiles. Again, the use of quartiled data masks larger differences in VMT and retail FAR, making these results conservative. Retail floor area ratio was subsequently incorporated into the LUTAQH study's Walkability Index along with residential density, intersection density and land use mix. The Walkability Index, as discussed previously, was found to be a significant predictor of not only VMT, but vehicle emissions as well (LFC et al. 2005b).

Figure 9. Differences in VMT across Retail Floor Area (FAR) (LFC et al. 2005b).

LUTAQH ANOVA ANALYSIS Retail Floor Area Ratio (controlling for gender, income, age, education, total number of household vehicles, distance to nearest bus stop)	**Quartiles of Retail Floor Area Ratio** (1km road-network-based household buffer)							
	1 (LOW)		**2 (MED-LOW)**		**3 (MED-HIGH)**		**4 (HIGH)**	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Retail F.A.R (building square footage / lot square footage)	0.00	0.00	0.00	0.14	0.15	0.33	0.33	3.53
VMT	**30.16**		**30.48**		**30.50**		**25.57**	

Destinations (Regional Location). The regional location of a given site as measured by distances and travel times to major centers for employment, recreation, shopping, or specialized services have also been shown to be strongly and significantly correlated with travel (Holtzclaw et al. 2002, Ewing and Cervero 2001, Frank et al. 2000, Ewing et al. 2002). Centered regional development patterns will create a large "bang for the buck" when seeking to reduce emissions.

In a study of land use patterns and emissions in the Puget Sound region, researchers found that distance to work, which serves as a proxy for the region's "centeredness", was significantly related to VMT. A different study compared the relative impact of land use mix and jobs-housing balance, a measure that is more closely related to regional level travel patterns. Researchers found that the longer work trip travel distances overwhelmed the larger share of auto trips devoted to shopping travel by a substantial margin - improving jobs-housing balance was estimated to reduce VMT 72.5 percent more than land use mix (Cervero and Duncan 2006).

A number of other studies have confirmed the relationship between regional location and travel outcomes (Kockelman 1997; Holtzclaw et al. 2002; Frank et al. 2000; Ewing and Cervero 2001; Ewing et al. 2002). In a recent national analysis of metropolitan areas, the degree of sprawl was the strongest influence on vehicle-miles traveled per person, more than metropolitan population and per capita income (Ewing et al. 2002). In a literature review and meta-analysis (Ewing and Cervero 2001), the authors computed urban form/travel elasticities based on the results of 14 published studies. Regional accessibility had an elasticity value of -0.20 on VMT, higher than all three neighborhood-level urban form measures of density, mix/balance, and design put together.

SECTION III.
The San Joaquin Valley Indirect Source Rule as an Application of Effective Indirect Source Pollution Reduction Tools

As discussed in the previous section, individual land use factors such as density, diversity (land use mix), street connectivity (grids versus cul-de-sacs), site design/pedestrian environment, and access to transit all influence travel behavior and vehicle miles traveled individually and in combination. Travel behavior and vehicle miles traveled, in turn, influence pollution emissions levels. Each of the above factors can be applied in the URBEMIS model as a mitigation strategy under the SJVUAPCD's Indirect Source Rule. In this section, we briefly describe the research for each factor and discuss its application to the ISR and in URBEMIS. The research supports the ISR's assumptions that by employing these factors in the design of their developments, developers can reduce indirect source pollution.

The URBEMIS model is used by the Air District to determine ISR mitigation requirements for proposed developments. Although other models can be used to estimate emissions, their use must be approved by the Air District. URBEMIS relies on trip generation numbers from the Institute of Transportation Engineers' (ITE) Trip Generation Manual. URBEMIS uses the most recent (7th) edition of Trip Generation, published in 2003. The trip generation numbers for this edition are developed based on surveys of development types across the country—more than 4,250 individual case studies. The Trip Generation Manual is considered a standard in the planning and land development field and is commonly used in traffic studies associated with new development. However, because it does not take into account variables such as transit access and pedestrian environment, and because in some cases results rely on only a few case studies or reflect extremely wide variation between those case studies, URBEMIS users may input additional information and assumptions in order to further reduce (mitigate) predicted vehicle demand (URBEMIS 2002 users' manual, p. D-5).

The URBEMIS modeling approach adopted by the San Joaquin Air District takes into account both on-site land uses and design features, as well as the surroundings of a given project. Consistent with current evidence, increased connectivity on-site and to adjacent destinations, increased density, the presence of complementary uses on-site or nearby, and the presence of a supportive pedestrian / cycling environment results in lower estimated levels of vehicle use and emissions. The elasticities[4] used in URBEMIS to adjust projected trip generation are documented in the 2002 URBEMIS users' manual[5] and derived from a variety of peer-reviewed research papers and government reports (URBEMIS 2002 users' manual, Appendix D). The evidence-based elasticities URBEMIS uses and the resulting reductions in trip generation are presented in Table 2.

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[4] An elasticity describes how much of a change in the dependent variable (the outcome; in this case VMT, VHT or vehicle trips) is associated with an increment of change in the independent variable (in this case, the land use measure such as density, land use mix, or intersection density).
[5] A more recent version of URBEMIS (URBEMIS 2007, version 9.2) has recenlty been released; however, the 2002 URBEMIS users' manual provides a more thorough discussion of the background research that underpins the land use module. The land use calculations have not been altered in the updated version.

Table 2. Summary of Recommended Trip Reductions available in URBEMIS (adapted from URBEMIS users' manual, Table D-3)

	Residential	Non-Residential
Physical Measures		
Net Residential Density[6]	Up to 55%	N/A
Mix of Uses	Up to 9%	Up to 9%
Local-Serving Retail	2%	2%
Transit Service	Up to 15%	Up to 15%
Pedestrian/Bicycle Friendliness	Up to 9%	Up to 9%
Physical Measures sub-total	*Up to 90%*	*Up to 35%*

Density

Density relates with travel behavior by decreasing distances between destinations and increasing the number of destinations that can be reached by walking and cycling. A concentration of jobs and households also makes transit service more viable and provides the critical mass needed to support retail services and employment. A relationship between higher residential and employment density and decreased vehicle travel has been found at many different scales of analysis – from aggregate urban area level comparisons to studies at the household level. Increases in density have also been correlated to lower per capita levels of air pollutants, including NOx, hydrocarbon (HC) and Carbon Monoxide (CO).

The research indicates that increased density is associated with less indirect source pollution from development.

Residential Density in the ISR. Residential density is available for mixed-use/commercial and residential projects under the ISR as a mitigation measure. Developers may mitigate up to 55 percent of their emissions, the highest allowable trip reduction of any of the land use or transit mitigation measures. As the research has shown, compact development has a strong relationship with travel patterns, and from a practical standpoint, a certain amount of compactness is often a precondition for a number of other supportive land use factors, such as adjacent commercial development and transit service. Without a critical mass of customers, these additional services will be less viable.

Residential Density Trip Reduction Formula for URBEMIS:
$=0.6*(1-(19749*((4.814+\text{ households per residential acre})/ (4.814+7.14))^{-0.639})5914)$

[6] The maximum density reduction was reduced by 40% from the elasticity on which it was based (Holtzclaw et al. 2002) to account for the effects of transit service and pedestrian facilities. See discussion of the residential density trip reduction formula used in URBEMIS.

> "An apartment development of 16 units per residential acre, for example, would be estimated to generate 27.9 percent fewer trips than a three unit per acre project. The maximum allowable reduction recommended is 55 percent (equivalent to a 380 unit per acre development)…This is equivalent to the elasticity generated by Holtzclaw et al. (2002), reduced by 40% to take into account effects of transit service and pedestrian facilities, which were not controlled in the Holtzclaw study." (URBEMIS users' manual, p. D-20).

The formula used to estimate trip reduction in URBEMIS is taken from a peer-reviewed study by Holtzclaw et al. (2002) of density and vehicle use in three cities, two of which are in California. Because of the co-linearity between density and other built environment and parking variables. the approach used in URBEMIS – where density's effect is limited to a 15% reduction in VMT – is appropriate.

Land Use Mix

A mixed land use pattern is one that places different land uses (i.e. residential, retail, office, recreational, or educational uses) in close proximity to each other. With a mixed land use pattern, everyday destinations are easier to access on foot or bicycle from work or home. Mixed land use patterns can also encourage the use of transit – a person can use transit to get to a central destination and then complete individual errands on foot. All else equal, a mixed land use pattern is correlated with increased walking and reduced automobile travel (including VMT) and per capita emissions.

The research indicates that incorporating mixed use in a development is associated with less indirect source emissions.

Land Use Mix in the ISR. The inclusion of residential development in commercial projects, and the inclusion of commercial development in residential projects, counts as a mitigation measure in the ISR. A maximum of 9 percent of vehicle trips may be reduced with land use mix as a mitigation strategy, and an additional 2 percent of trips may be reduced with the incorporation of local serving retail into a project.

Land Use Mix Trip Reduction Formula in URBEMIS:

Trip reduction = (1- (ABS (1.5 * h – e) / (1.5 * h + e)) – 0.25) / 0.25 * 0.03

Where: h = study area households (or housing units)

e = study area employment

In addition to the above formula, the presence of local serving *retail* further reduces trip generation by 2 percent. The URBEMIS users' manual states that the 2 percent is a conservative amount in order to avoid double counting. (URBEMIS users' manual, p D-21).

The above formula takes into account the ratio jobs and households outside the actual development itself, recognizing that the most significant trip reductions may result from placing a complementary use in the midst of a single-use project (for example, retail in a residential area). The formula used by URBEMIS is from Criteron and Fehr & Peers (2001), who have used the results of over 50 studies to develop formulas that can be used to estimate the impacts of land use changes on transportation behavior. Formulas developed by Fehr & Peers have been incorporated into a number of different modeling structures, URBEMIS being one.

Street Connectivity

As with land use mix, measuring street network connectivity has become much more reliable in recent years with the increased availability of detailed spatial road network data in a Geographic Information System. The ability to measure street connectivity allows researchers to disentangle its effects from the effects of other land use measures such as mixed use and density. Because its connection to travel behavior can now be precisely measured, consensus has grown in the research around its importance. Connectivity measures the degree of route directness between destinations.

The research indicates that developers can increase walkability and reduce VMT and vehicle emissions by creating a connected street network onsite and to the adjacent environs. Because road and walkway connectivity is generally determined when communities are first planned, new development presents a clear opportunity to build interconnected street networks. Therefore, using connectivity as a mitigation option for the ISR is especially appropriate, since large developments will generally require building new street networks.

Street Connectivity in the ISR. The ISR allows the use of interconnected street network designs as a mitigation measure, including grid designs, alleys, small block networks, and pedestrian connections through dead end streets or cul-de-sacs.

In URBEMIS, network connectivity is taken into account as part of URBEMIS's assessment of a development's pedestrian environment. This assessment is therefore discussed in the following section.

Site Design / Pedestrian Environment

As summarized in the previous chapter, research on the pedestrian environment has consistently found that as the quality of the pedestrian environment increases, vehicle travel decreases and walking, bicycling, and transit increase, all else being equal.

Thus, the research suggests that developments can reduce indirect source emissions by improving the pedestrian environment.

Pedestrian Environment in the ISR. The ISR allows up to a 9 percent reduction in vehicle trips based on the inclusion of measures that create a supportive environment for pedestrians and bicycles, such as sidewalks, crosswalks and bike lanes, lighting, signalization, traffic calming measures, and building entrances that are built adjacent to the sidewalk.

No trip reduction is allowed under this category of mitigation in the ISR if the entire area within a half-mile walking distance of the project center consists of a single land use. The distance from the project center is measured using an actual walking distance, rather than using a straight line distance. This takes two factors into account: 1) barriers such as freeways which are not traversable on foot; and 2) the actual street and pathway network available for walking. Figure 10 shows the impact that street network design can have on destinations to actual uses. Although the distances between points A and B in the two photos are about the same, the figure on the left has a much longer actual walking distance than the more connected network on the right.

Figure 10. Travel Distances and Street Networks

Pedestrian / Bicycle Environment Formula in URBEMIS:
URBEMIS calculates trip reduction based on the following factor, which incorporates street network density (connectivity) and the completeness of sidewalk and bike lane networks.

Trip reduction = 9% * ped/bike factor
Ped/bike factor = (network density + sidewalk completeness + bike lane completeness)/ 3
Where:

- Network density = intersections per square mile / 1300 (or 1.0, whichever is less)
- Sidewalk completeness = % streets with sidewalks on both sides + 0.5 * % streets with sidewalk on one side
- Bike lane completeness = % arterials and collectors with bicycle lanes, or where suitable, direct parallel routes exist

(URBEMIS users' manual p. D-27-28).

These factors are based on peer-reviewed papers; one is a meta-analysis (Ewing and Cervero 2001) that developed elasticities based on the results of over 50 studies.

Access to Transit and Transit Service
Transit service has a long and well-documented association with travel behavior, especially in conjunction with compact, walkable land use patterns.

Research shows that developments that ensure close access to transit for end users (home owners, employees, etc.) and with frequent service to major destinations are associated with lower per capita vehicle use and related emissions.

A study of rail transit in California found that people living near rail stations were over five times more likely to commute by rail than the average resident of the same city: 33 percent of work trips were by rail in communities near rail compared to 5 percent for the regional average. With every 100 feet distance from a rail stop, the mode share for rail trips decreased by about 0.85 percent. Similar relationships were found for employment locations – employment sites located near rail stations had 17 percent of work trips by rail - levels over three times the regional average of 5 percent (Cervero 1993).

The LUTAQH study in Seattle found that for every ¼ mile increase in distance from a transit stop to home, the odds of taking a transit trip to work decreased by 16 percent, and for every ¼ mile increase in distance from transit to work reduced the likelihood of taking transit to work by 32 percent (LFC et al. 2005b). Another study in the same region also linked distance to transit to VMT and VHT – as household distance to transit increases, so does VMT and VHT (LFC et al. 2005a).

The LUTRAQ study in Portland, Oregon used the metropolitan planning authority's travel model to evaluate three alternative land use and transportation scenarios: a base case, a "freeway" alternative including a highway bypass and minimal increases in transit, and a land use / transit (LUTRAQ) alternative with new light rail lines, additional bus service, concentrated development around rail lines, demand management strategies and pedestrian infrastructure. The LUTRAQ alternative was projected to reduce NOx emissions from vehicles by 8.7 percent, use 7.9 percent less fuel, and double the number of work trips by transit compared to the freeway alternative (PBQD 1997a; 1997b).

Transit Service & Accessibility in the ISR. Transit service within ¼ - ½ mile of a proposed project can be used as a mitigation measure, and can reduce projected vehicle trips by up to 15 percent. This concept is supported in the research cited above, as well as in a number of other studies on the topic.

Transit Service Trip Reduction Formula in URBEMIS: URBEMIS uses a Transit Service Index which emphasizes frequency of service and gives a greater weighting to rail services and dedicated shuttle services that serve the development:

Transit Service Index =
Number of average daily weekday buses stopping within 1/4 mile of the site; plus
• *Twice* the number of daily rail or bus rapid transit trips stopping within ½ mile of the site
• *Twice* the number of dedicated daily shuttle trips
• Divided by 900, the point at which the maximum benefits are assumed
(Equal to a BART station on a single line, plus four bus lines at 15-minute headways.)
URBEMIS 2002 users' manual, p. D-35)

This formula draws from a number of peer-reviewed journal articles and government reports, among them Holtzclaw (2002) and Kuzmyak & Pratt (2003), which address changes in transit ridership based on transit mode and service frequency, as well as accessibility and proximity to transit.

The Influence of Preferences and Attitudes

To date, the vast majority of the research on urban form and travel behavior relationships is cross-sectional, meaning that it draws conclusions based on a statistical comparison of groups of individuals at a single point in time. Although associations between built environment and travel variables are documented, cross-sectional studies cannot prove changing one variable causes changes in another. This is important because a person's travel behavior and physical activity levels is likely to partially reflect their attitudes and preferences.

People who prefer not to drive are more likely to live in walkable environments, and people who enjoy driving (or are willing to tolerate the extra driving for a cheaper house, a better school, or a backyard) tend to choose more automobile-oriented locations. This is not always the case however, and many people are "mismatched" and would prefer to be in a different type of environment than they are currently located. As a result, it is possible to evaluate the relative contribution of preferences and actual neighborhood walkability in explaining travel choices. It would logically follow that at least some of the observed differences in travel behavior between walkable and automobile-oriented locations may reflect *self-selection* rather than the pure effects of land use.

Overall, research suggests that both preferences and physical environment affect travel behavior (Bagley & Mokhtarian 2002; Khattak & Rodriguez 2005; Kitamura et al. 1997; Schwanen & Mokhtarian 2004, 2005a, 2005b). In these studies, in addition to measuring physical neighborhood characteristics, the researchers incorporated attitudinal factors, including attitudes about transportation and lifestyle preferences.

However, evidence is mounting that the relationship between the built environment, travel behavior, and pollution is still significant, even after adjusting for travel and neighborhood preference. Using a different (quasi-longitudinal) research design, Handy et al. (2006) concluded that the built environment influences walking behavior after taking neighborhood preferences and attitudes into account.

Another study in the Atlanta region analyzed results of a detailed survey of the travel patterns and neighborhood preferences for about 1500 households (Frank et al. 2007a). The study also compared households that were "matched" (e.g. survey respondents preferred walkability and were located in a walkable neighborhood) and "mismatched" (e.g. respondents preferred an auto-oriented neighborhood and were located in a walkable one). A summary of results is depicted in Table 3. Overall, it appears that distances driven (a strong predictor of emissions) is more of a function of walkability than preferences. Those who prefer and live in a walkable environment drove just under 26 miles per day compared with those who prefer but do not live in a walkable environment averaged 36.6 miles per day. Average daily VMT was nearly the same for those that live in walkable neighborhoods, regardless of their preference. Walking appears to be more related to neighborhood preferences. In models generated for this analysis that control for demographic factors, a combined index of urban form factors (density, diversity, design, destinations) or "walkability" remained a statistically significant predictor of VMT after adjusting for neighborhood preferences. Each quartile increase in an index of walkability was associated with a 5.5 mile/day/person reduction in VMT, after adjusting for demographics and neighborhood preference (Frank et al. 2007a).

Table 3. Walking and Driving by Walkability of Current Neighborhood and Neighborhood Preferences

	Walkability & Preference Groups		**Percent Taking a Walk Trip (n)**	**Average Daily Vehicle Miles Traveled (n)**
	Preference for Neighborhood Type	Walkability of Current Neighborhood		
I	**High**	**Low**	16.0% (188)	36.6 (188)
II	**High**	**High**	33.9% (446)	25.8 (446)
III	**Low**	**Low**	3.3% (246)	43.0 (246)
IV	**Low**	**High**	7.0% (43)	25.7 (43)

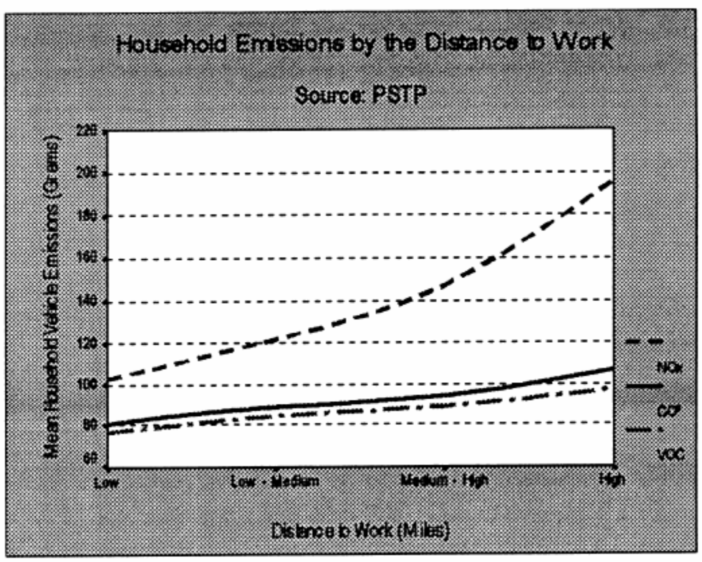
Further, there is recent evidence of latent demand for more walkable neighborhoods. Some research has documented that a significant proportion of residents in sprawl would prefer to be in more walkable environments but trade it off for reasons including spousal preferences, work location, schools, and cost (Belden Russenello & Stewart 2004). Another study documented a significant undersupply of walkable environments relative to the demand for such places. In a forced-tradeoff survey, 24 percent of survey respondents expressed a strong preference for mixed use neighborhoods, 23 percent strongly preferred neighborhoods where they could walk, bike or take transit even if homes were smaller, and 28 percent strongly preferred neighborhoods that are in close proximity to important destinations, even if lot size were smaller (Levine & Frank 2007). Taken together, these studies suggests that simply accommodating the existing demand would allow those who are currently located in auto-oriented environments to choose a more walkable one, thus lowering rates of vehicle travel and emissions.

Regional Location

The location of development in relation to major population and employment centers also impacts household level transportation patterns. Although it does not explicitly give credit for infill development, URBEMIS allows emissions reductions for development that is located within a 1/2 mile of high density residential development, commercial or retail development or a transit stop. Regional location, in combination with transit service and neighborhood level walkability, helps to determine the transportation options people have for their home to work/school trips. A number of U.S. studies have found a strong link between regional scale development patterns and VMT (Holtzclaw et al. 2002, Ewing and Cervero 2001) and emissions (Frank et al. 2000).

A 'sprawl index' developed by Ewing et al. (2002) to measure degree of sprawl at the metropolitan area level was found to exert a greater influence on VMT per person than metropolitan population or per capita income. Using distance to work as a proxy for regional location, Frank et al. (2000) found significant variation in NOx, CO, and VOCs by work trip distance, shown in Figure 11 below.

Figure 11. Co-Variation in Household Emissions by Work Trip Distance, a Proxy for Regional Location. From Frank et al., 2000**.**



A study conducted in Atlanta, GA and Seattle, WA investigated the variation in household travel patterns across both regions and concluded that, on average, people located in more central or infill locations drive and pollute less. More specifically, the findings from this study suggest that the less central a household's location, the more vehicular travel and emissions it will generate when controlling for the level of transit service, vehicle ownership, household size, and income (Frank and Stone, 1997). This finding is based on the usage of census tract size as a proxy for regional location. Census tract size is based upon an ideal sample size of approximately 4000-5000 households (U.S. Census Bureau). Therefore, households located in areas with larger census tracts are at the edge of a region where development densities are sufficiently low and accordingly require more land to be traversed to capture the desired number of households. This concept is visually conveyed in Figure 12 below.

These maps document the fact that census tract size increases with distance from the central cities, as depicted with lighter shades on the map. The four groupings of regional location - urban center, urban periphery, suburban, and exurban - are based upon approximate quartiles of census tract area. Due to decreasing levels of proximity and connectivity with distance from urban centers, it is hypothesized that vehicle travel is minimized in the smallest, most centralized tracts. Figure 12 conveys that VMT also increases with distance from primary regional centers (as measured by census tract area).

Figure 12. Regional Location Based on Census Tract Size in Atlanta and Seattle. From Frank 1998.

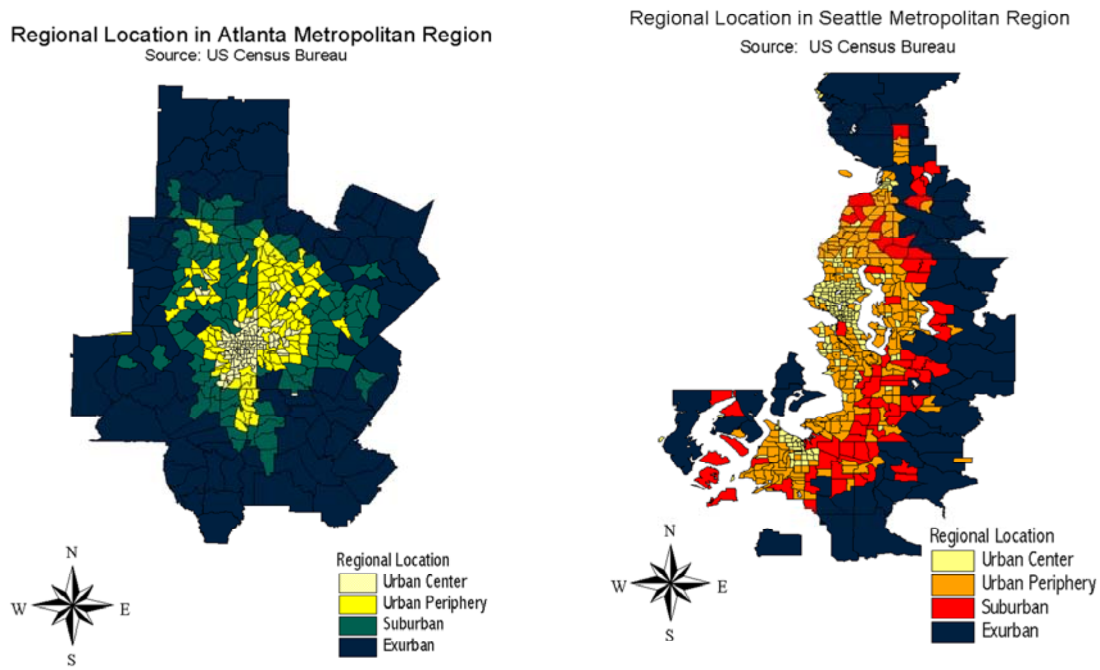


Figure 13. Daily Household Vehicle Miles Traveled by Regional Location. From Frank 1998.

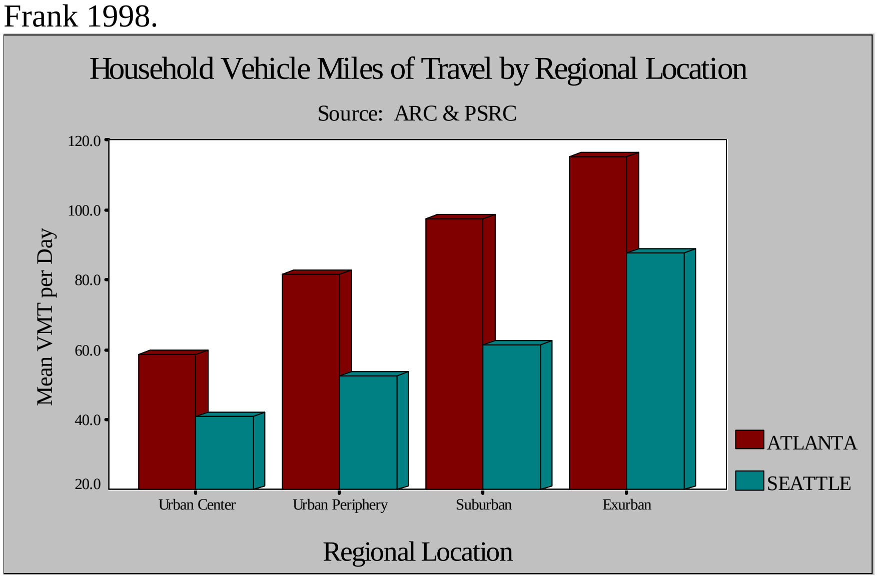
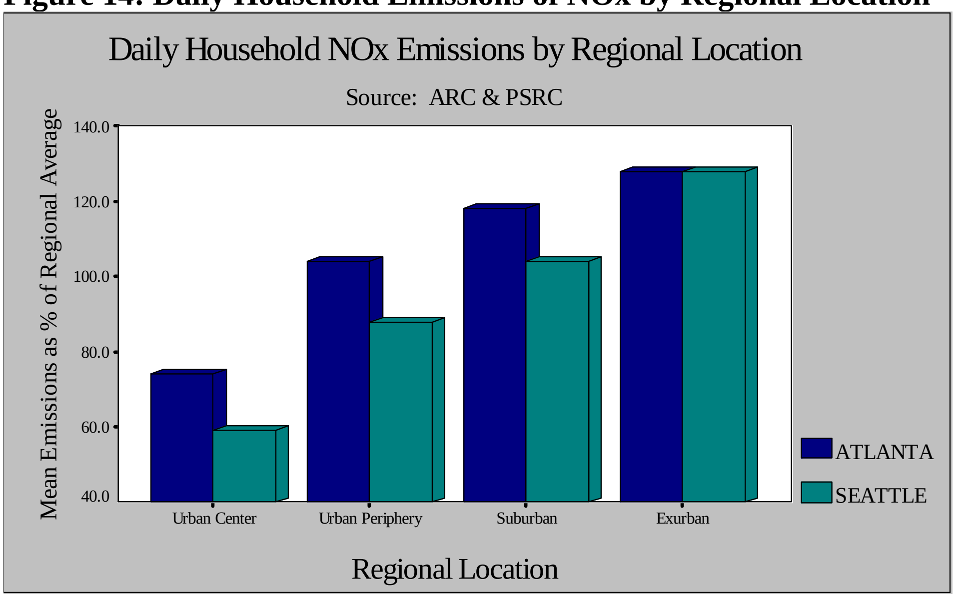


Figure 13 conveys that households in Atlanta uniformly drive more than their Seattle counterparts. This information reaffirms the findings from the 1995 wave of the National Personal Travel Survey (NPTS) which documented that Atlanta leads the nation in the amount of vehicle miles of travel per capita.

Figure 14 reports on the mean level of vehicle emissions that occurs in each of the four regional location groupings for both Atlanta and Seattle. This data was generated through the usage of EPA's endorsed "MOBILE" emissions model. A comparison between Seattle and Atlanta is provided using the same methodology to assess household emissions based upon travel survey data. Each household's vehicle emissions were estimated based upon the individual trips taken by that household and accounting for travel distance, time, speed, and cold start cycles.

The data presented in Figure 14 demonstrates the potential of reduced emissions associated with infill versus greenfield development and overall superior performance in terms of regional air quality. Through a combination of density, land use mix, and high levels of connection between trip ends, travel by transit and pedestrian modes grows increasingly feasible for residents and employees in urban center regions.

Figure 14: Daily Household Emissions of NOx by Regional Location



CASE STUDY: ISR MITIGATION (SITE LEVEL) AT GOSFORD & MING RESIDENTIAL DEVELOPMENT

This project, 217 units of single family housing in Bakersfield, mitigated 17 percent of estimated NOx emissions and 17 percent of estimated PM10 emissions from their proposed development. Urban design mitigation measures included the development of local serving retail in a residential area, street design characteristics, improved jobs to housing balance, bike lanes, and sidewalks. Non-urban design mitigation measures included not building fireplaces or woodstoves and including energy efficiency measures in home design. The developer also got credit for the project's regional location – an infill project in a residential area close to CSU Bakersfield.

IV. The Applicability of an ISR to Greenhouse Gas Reduction

Introduction

With the passage of AB 32, the California Global Warming Solutions Act in 2006, California became the first state in the U.S. to mandate a reduction in greenhouse gas emissions. AB 32 committed the state to reducing its global warming emissions to 2000 levels by 2010, to 1990 levels by 2020, and 80% below 1990 levels by 2050. An enforceable statewide cap on global warming emissions will be phased in starting in 2012.

The California Air Resources Board (CARB) is charged with implementing AB 32. In conjunction with the Climate Action Team, which represents several state agencies, CARB is developing a scoping plan in order to identify the primary actions necessary to meet the goals of AB 32, to be completed by January 1, 2009. CARB is also developing a GHG emissions inventory and reporting program.

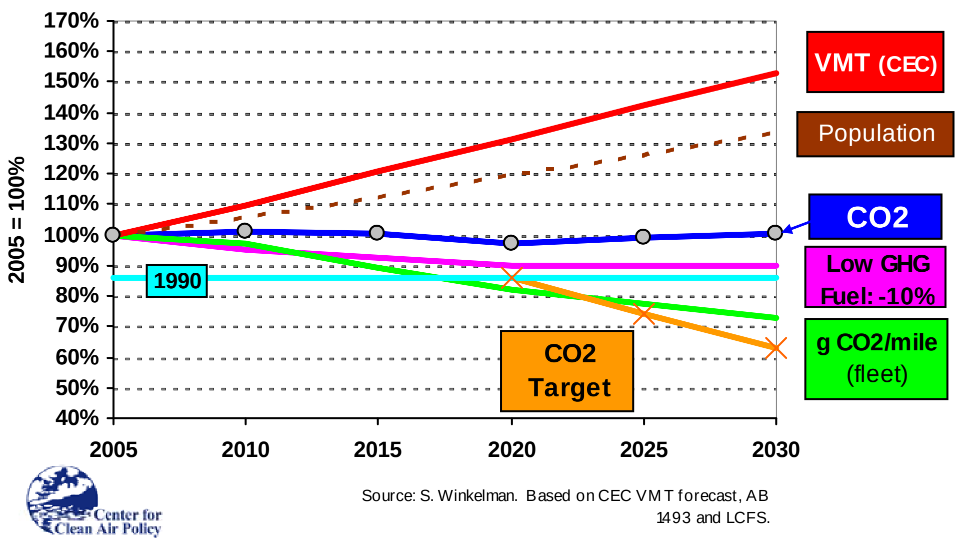
In California, transportation is the largest source of GHG emissions. CARB GHG inventory figures estimate about 38 percent of GHGs were from transportation-related emissions in 2004. Passenger cars and light trucks make up nearly three-quarters of transportation-related emissions, and nearly 30 percent of the state's total GHGs (CARB, 2008). Any effort to reduce GHGs will therefore need to reduce transportation emissions, particularly those used for personal travel.

Figure 15. The Global Warming Gamble: Options for Policymakers

When considering policies to reduce vehicle-related GHGs there are three basic choices: 1) increase vehicle efficiency; 2) shift to less carbon-intensive alternative fuels, such as biofuels; 3) reduce the demand for vehicle travel. For policymakers, deciding which of these levers to pull, and how hard to pull them, is the 'global warming gamble' shown in Figure 15. To date, policies have focused to a large degree on technology – more efficient vehicles and alternative fuel sources - although awareness is growing that changes in vehicle demand are needed. Walkable, transit-oriented land use patterns can reduce vehicle demand by addressing the root cause of transport emissions: land use patterns that practically require driving, often over long distances, for common destinations such as jobs and shopping.

As analysis by the Center for Clean Air Policy has demonstrated, although improvements in vehicle emission rates and low-GHG fuels are critical, they are newly regarded as inadequate given the dramatic reduction in C02 emissions needed to stabilize greenhouse gases. As Figure 16 shows, growth in VMT is projected to counteract the benefits of vehicle and fuel GHG standards in California, leaving CO_2 emissions from light duty vehicles at current levels: 17 percent <u>above</u> 1990 levels in 2030, as opposed to the 27 percent below 1990 levels by 2030, required to be on path to the long-term climate target of 80 percent below 1990 levels by 2050.

Figure 16. The Gap Between Improvements in Vehicles and Fuels Economy and Growing Travel Demand



Biofuels, the topic of much recent discussion, have also been the subject of criticism. Recent research calculating the impact of biofuels on GHGs has found that in many cases, the growth and manufacture of biofuels generate much more greenhouse gases than they save. This is largely due to land clearance inherent to meeting increased demand, although the precise GHG impacts vary widely depending on type of crop, location, and whether the land is already in agricultural use (Fargione et al. 2008; Searchinger et al. 2008).

Research Overview

To date, there has been little research on the connection between land use, transportation, and CO2. Most of what exists has been aggregate in nature, with only a few studies examining the specific land use characteristics that might have an impact on greenhouse gases, or using trip-level information to estimate CO2 emissions. Therefore, in addition to the studies below that address the CO2/built environment relationship, research that looks at the connection between VMT and the built environment can also be instructive. Refer to Section II of this document for discussions about VMT / built environment research.

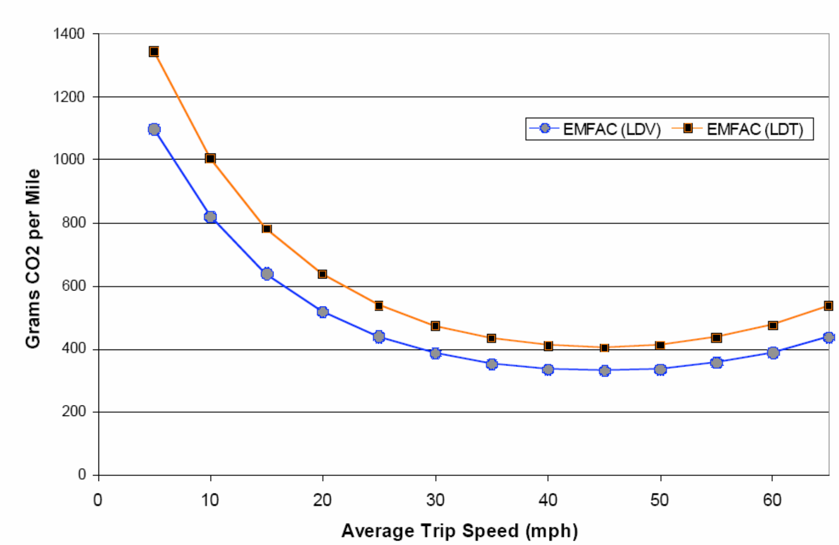
VMT is probably the best overall indicator of CO2; not only is VMT the measure that most closely tracks with CO2, it has been consistently associated with land use patterns in research (Frank et al. 2000; Ewing and Cervero 2001; Holtzclaw et al. 2002). In a recent literature review of over 50 published studies, the authors found that VMT was the outcome with the strongest link to land use variables. Land use variables had even more of an impact on VMT than sociodemographic variables (Ewing and Cervero 2001). A recent literature review and meta-analysis on land use and CO2 used VMT as a proxy, concluding that "compact development has the potential to reduce VMT per capita by anywhere from 20 to 40 percent relative to sprawl" (Ewing et al. 2007; p. 57).

The close relationship between VMT and urban form, and CO2 and VMT, makes VMT a useful proxy for how changes in urban form might impact CO2. Each gallon of gasoline generates nearly 20 pounds of CO2 (US Department of Energy 2008). Because the average passenger vehicle in the U.S. has an actual (as opposed to labeled) fuel economy of about 20 MPG (Oak Ridge National Laboratory 2007) a one-mile decrease in VMT will result in a reduction of approximately 1 pound of CO2. A recent literature synthesis and review on the urban form and CO2 relationship stated that "All else being equal, [including speed and start patterns] there is a one-to-one relationship between VMT and CO2 emissions; a 30 percent reduction in VMT will result in a 30 percent reduction in CO_2 emissions." When considering slower speeds found in compact, walkable areas, the authors estimate the ratio of CO2 to VMT reduction to be approximately 0.93 (Ewing et al 2007).

Unlike conventional air pollutants, CO_2 emissions are not time-of-day or weather-dependent. However, CO2 emissions are impacted by vehicle speed, vehicle type, and cold starts. The precise impact of these factors is just now being documented, but seems to be relatively small compared with VMT. The speed impact is shown in Figure 17 below, and is much less than that of other pollutants such as VOCs and CO (see Figure 3 on p. 2. Recent work by the California Air Resources Board showed that starts only make up about 3 percent of CO2 emissions (Ewing et al. 2007, p. 45).[7]

[7] The number used here was calculated based on data from EMFAC 2007, V2.3 Nov. 1, 2006, provided by CARB.

Figure 17: Effect of Vehicle Speed on CO2 Emissions (source: Ewing et al. 2007, p. 45)[8]



Urban Form and CO2 Emissions / Energy Consumption

Aggregate level studies

At this point, few studies have examined the land use – transport – CO2/GHG relationship, and most of those that have done so have been aggregate level analyses. Rajan (2006) found that demand reduction, including changes in land use, demand management and pricing, and social marketing measures, could bring the U.S. halfway to a target of 75% below current levels by 2050. However, this study did not detail the effects of particular land use characteristics on GHG emissions, or break out the relative impact of land use compared to other demand reduction strategies.

Muñiz and Galindo (2005) looked at the relationship between urban form and the ecological footprint of transport in the Barcelona Metropolitan Region. Transport by the region's residents, land necessary for infrastructure, and energy used in manufacture of transport and construction of infrastructure were all part of the footprint calculation. Urban form measures (net population density, jobs-housing balance and accessibility to a region's center) were more strongly related to ecological footprint than average household income (the only sociodemographic variable used in the study). This lead the authors to conclude that "urban form exercises a clear effect on the ecological footprint of transport." CO2 emissions were not expressly calculated as an outcome, but this research highlights and quantifies the broader impacts of the urban form-transport relationship.

In a spatial analysis of CO2 emissions in the Toronto region, VanDenWeghe and Kennedy (2007) looked at CO2 emissions related to buildings and transport at the census tract level. As distance from the city center increased, per capita transport-related

[8] Data used by Ewing et al. (2007) is from EMFAC 2007, V2.3 Nov. 1, 2006, provided by CARB.

emissions (from transit and private vehicles) also increased. Once outside the region's central core, per capita transport-related CO2 emissions overwhelmed per capita emissions from building operations. Although this analysis did not test for statistical significance, the authors note that out of all the census tracts in the analysis, "the top ten in terms of GHG emission are located in the lower-density suburbs, and their high emissions were largely due to private auto use."

In one of the best-known aggregate level land use and transportation analyses, Newman and Kenworthy (1989) examine gasoline consumption in 32 metropolitan areas worldwide. This analysis uses a number of aggregate-level measures to capture the varying dimensions of the land use and transport relationship: population and jobs density, the number and proportion of jobs within the city center, proportion of residents in the inner city, and average work trip length. Gasoline consumption ranged greatly, from a low of 3 gallons/year/capita (Moscow) to a high of 567 gallons/year/capita (Houston). Population density was found to have a significant and exponential relationship with energy use, with a "strong increase in gasoline consumption where population density is under 12 people per acre." (ibid, p. 29) Assuming an average household size of 2.5 persons per household, this translates into a density of close to 5 households/acre, a threshold which may prove instructive. With the exception of number of jobs in the city center, all of the other land use measures were significantly correlated to gasoline consumption. Average work trip length, a proxy for an area's compactness, had the strongest relationship to gasoline consumption.

Disaggregate Analyses

The LUTAQH (Land Use, Transportation, Air Quality and Health) study in King County (Seattle) Washington used parcel level land use data and trip level travel data (including VMT, travel speed, and CO2 emissions for non-vehicle travel modes) to specifically examine CO2 as an outcome of the land use and travel behavior relationship.

The LUTAQH study found a significant relationship between a number of urban form measures and per capita transport-related CO2 emissions. After controlling for demographic factors (gender, age, income, education and drivers' license availability), households in areas with higher levels of land use mix, residential density, retail availability and street connectivity generated lower per capita CO2 emissions. Figures 18-21 illustrate these relationships.

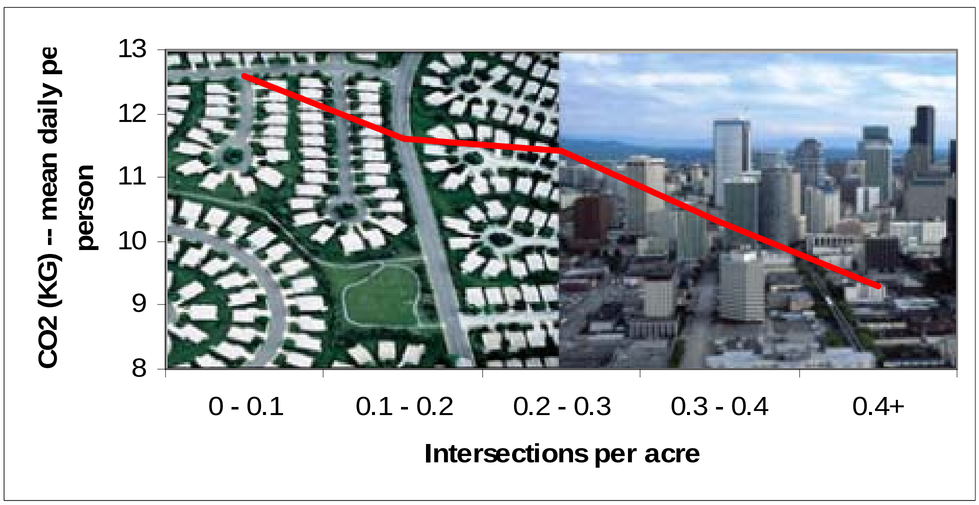
Figure 18. Net residential density and per capita CO2 from transport

Retail availability, as measured by the number of retail parcels within a 1 kilometer walking distance from home, was found to be the strongest land use predictor of carbon dioxide emissions. This particular measure, and its relationship to transportation, has not often been studied in the past – however, its ease of measurement and transferability to policy goals makes it an excellent way to operationalize neighborhood retail accessibility. In this case, mean daily transport-related carbon dioxide emissions declined slowly until a household had at least 10 retail parcels within a 1 kilometer walking distance; then emissions dropped off sharply. This threshold is probably a function of increased transit service and other supportive land use/pedestrian conditions found in these places, which were not controlled in this analysis. In addition, it does not account for the underlying effect of residential preferences and self-selection. More research is needed to fully gauge the presence or not of this "threshold" condition. At the employment trip end, housing density, number of commercial buildings, and number of restaurants were all inversely related to CO2 emissions.

Figure 19. Retail availability and per capita CO2 from transport

Figure 20. Land use mix and per capita CO2 from transport

Figure 21. Street connectivity and per capita CO2 from transport



Estimating Change in VMT/CO2 from Compact Urban Form

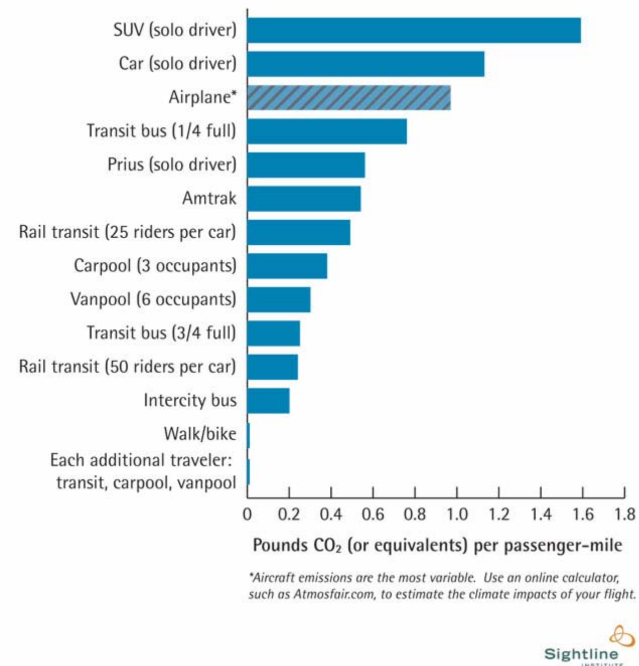
Only a few sources have attempted to estimate the total, collective impacts of a more compact, walkable urban form on VMT. According to the Ewing & Cervero meta-analysis (2001), the total elasticity of urban form on VMT is equal to -0.33: a sum of local density (-0.05), local land use mix (-0.05), local street network design (-0.03) and regional location (-0.20).

The recent literature review and meta-analysis by Ewing et al. (2007), *Growing Cooler*, projected the net impact of compact and walkable development in the U.S. on transport-related CO2 in 2050. The authors found that, compared to continuing sprawl, compact development could reduce transport-related CO2 emissions by 7 to 10 percent in 2050. The authors note that although these reductions may seem small, gas prices would have to double to achieve equivalent reductions in VMT, and that CO2 reductions from land use change are relatively permanent and compoundable over time, as opposed to other types of demand reduction measures (Ewing 2007, p. 46). Given recent gas price increases, accommodating more people in transit-accessible, walkable areas makes even more and more sense. As of May 2008, U.S. Department of Energy and the FHWA reported that total nationwide VMT has been dropping since November 2007. Data for March 2008, the most recent time period for which data is available, shows a 4.3% decrease in VMT compared to March 2007 – the largest single year-to-year decrease in FHWA's history (FHWA, 2008). At the same time, public transit ridership has soared to their highest levels in 50 years (American Public Transit Association, 2008).

Transit Service and Accessibility

High-quality transit service, especially transit that is close to walkable population and employment centers, can have large impacts on travel and CO2 emissions. By inducing mode shift, transit can reduce the average daily VMT. Because transit is particularly useful for work trips, which are typically longer than other trip types, it can be a high-payoff investment for CO2 reduction. However, transit is not emissions free. Although transit is more efficient than driving solo in most cases, the net CO2 benefits of transit will depend a great deal on type of transit and occupancy, as shown in Figure 22.

Figure 22. Variation in CO2 emissions by mode (from Sightline Institute, 2008: http://www.sightline.org/maps/charts/climate-CO2byMode)



In a recent analysis of mode choice, the relative travel time between modes was found to be an extremely important predictor of mode choice. Transit riders were found to be more sensitive to changes in travel time than to transit fares. Transit use was found to be nearly three times as sensitive to in-vehicle travel time as to fare cost increases for non-work travel. Increasing transit in-vehicle travel times for non-work travel by 10% was associated with a 2.3% decrease in transit demand, compared to a 0.8% reduction for a 10% fare increase (Frank et al. 2007). Increasing transit in-vehicle travel times for home-based work travel by 10% was associated with a 3.9% decrease in transit travel, while a 10% fare increase was associated with only a 1.1% decrease. The same analysis found that each mile increase in the distance to the nearest bus stop was associated with a 5 percent increase in per capita VMT (LFC 2005a).

Coupled with changes in land use, transit service that is competitive with the car in terms of travel time could induce a modal shift away from the car, reducing per capita VMT and net CO2 emissions. Express buses, or in congested areas dedicated rights-of-way for transit (Bus Rapid Transit or rail) will be necessary to achieve these goals.

In their research in San Francisco, Los Angeles, and Chicago Holtzclaw et al. (2002) developed and tested a zonal transit accessibility factor in combination with other urban form and sociodemographic variables. For each transit route, the daily average number of buses or trains per hour was calculated and multiplied by the fraction of the zone's land area within 1/4 m. of each bus stop (or 1/2 mi of each rail or ferry stop or station). The sum of all the transit routes in or near the zone resulted in the final transit accessibility factor. This factor was found to have significant predictive value in explaining VMT, along with residential density as shown in Figure 23 below.

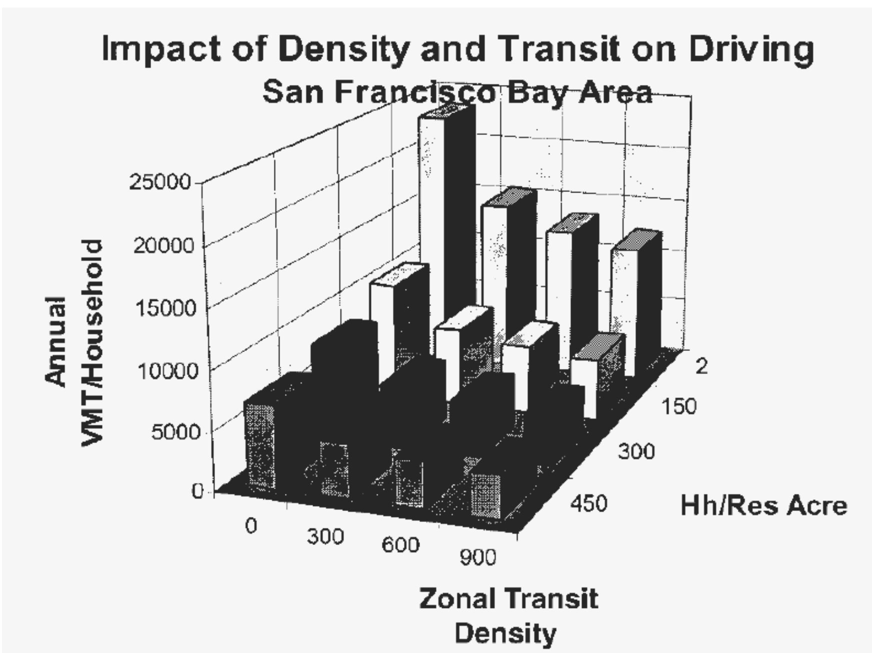


Figure 23. The combined impact of density and transit on household VMT (from Holtzclaw et al., 2002)

Regional scenario modeling, typically used in the context of regional transportation and land use planning, has yielded similar results. A review of over 40 long-range scenario planning exercises by Johnston (2006) found that, in a 20 year time frame, VMT reductions ranged from 20-40 percent less than the trend scenarios. The author goes on to add that "In most studies, the highway levels-of-service are the same as, or better than, the trend scenario" - concluding that compact development scenarios "generally produce higher transportation system productivity, positive net user economic benefits, greater equity in the distribution of transportation system benefits, reduced congestion delays, and a reduction in other adverse environmental impacts." Similar results were found by Bartholemew, who evaluated 23 different regional studies and found that compact scenarios had VMT levels that were, on average, 8 percent less than the trend scenarios (Bartholemew 2007, as cited in Ewing et al. (2007).

The Sacramento Council of Governments (SACOG) recently examined the CO2 impacts of the proposed Placer Vinceyards development in Placer County, and found that the development as proposed would generate more CO2 as opposed to if that project was developed in a way that was consistent with the regional blueprint. This study is a particularly salient example of how regional location can have an impact on CO2. SACOG's analysis also serves as an effective prototype for how regional transportation and land use modeling can support project-specific evaluation. Particularly for large projects, a more robust modeling effort may be necessary to fully and more precisely understand a project's total CO2 impacts (SACOG 2007).

Estimating Impacts of an ISR on CO2

During the period leading up to the implementation of the Indirect Source Rule, San Joaquin Air District staff prepared estimates of potential emissions reductions from the ISR.[9] At a conceptual level, it is possible to develop a rough estimate of the potential CO2 reductions from an ISR, using these staff estimates of the rule's pollution reduction impact as a base. We used the findings from the Frank et al. (2006) Journal of American Planning Association article discussed in this section to estimate the reduction in VMT due to compact development and to calculate the amount of CO2 based on VMT.

We found that, based on these assumptions, an ISR that is implemented beginning in 2010 to include CO2 could potentially reduce 2.1% of the total CO2 in 2015. Again, as pointed out in the discussion of the national estimate by Ewing et al. (2007), although this may seem like a small number it is relatively permanent and grows over time. Further, in comparison to other policy efforts to reduce CO2, an ISR, or a similar type of land use regulation, could offer a significant payoff for a comparatively small investment.

The estimate was developed as follows. Table 4 summarizes these assumptions and the calculations derived from them.

Baseline Numbers (VMT, population & VMT per capita from new development). Attachment 1 (page B-15) of the San Joaquin Air District staff report provides the regional population and daily total VMT for years 2010-2015. To net out incremental growth in VMT, Air District staff subtracted the current year ("no growth") population /VMT from the projected totals ("growth") . This difference is assumed to be due to new development. For all years, per capita daily VMT for new development remains at roughly 40 miles / day / capita.

[9] These are documented in Appendix B of the Rule 9510 staff report.

Baseline CO2 totals.
To convert VMT to CO2, VMT is multiplied by the pounds of CO2 generated per mile. This number decreases slightly each year due to slight increases in fuel economy over time.[10] A ratio of 0.93 based on Ewing, et al. (2007) is also used to account for slower speeds found in compact, walkable areas. The resulting baseline daily CO2 totals for the baseline and for each scenario is rolled up to a yearly and cumulative totals for years 2010-2015.

ISR Applicability (Amount of new population growth impacted by an ISR).

1) **Subtract population exempt from ISR mitigation requirements.** In their estimates Air District staff assumed 85 percent of NOx emissions would be impacted by an ISR based on their experience with CEQA review, as discussed in Appendix B, p. B-14 and Attachment 2, p. B-26. This estimate assumed that the same percentage of population growth and VMT would be subject to an ISR.
2) **Subtract population not subject to on-site mitigation.** Because developers have the option of mitigating emissions under the ISR (on-site) or paying the equivalent fee (off-site), Air District staff estimated the percentage of new development that would choose on-site emissions (see Appendix B, Attachment 2, p. B-26). This estimate increases slightly each year.

[10] The source used to calculate lbs/CO2/mile was EIA, Annual Energy Outlook 2008 Report #: DOE/EIA-0383. Table 7. We used MPG for Light Duty Stock. These numbers are national fleet averages; if California gets approval from the federal government to enact higher standards, the MPG for California could be slightly higher.

Table 4. Estimating an ISR's impact on CO2 - Baseline Assumptions and Calculations

BASELINE NUMBERS	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Total Daily VMT "Growth" scenario	51,952,000	53,253,000	54,544,000	55,835,000	57,127,000	58,427,000
Total population "Growth" Scenario	1,308,670	1,340,690	1,373,190	1,406,290	1,440,000	1,474,400
Total Daily VMT "No Growth" scenario	46,885,000	46,849,000	46,784,000	46,702,000	46,601,000	46,487,000
Total population "No Growth" scenario	1,181,030	1,179,460	1,177,840	1,176,250	1,174,680	1,173,100
Difference b/t "growth" & "no growth" (annual VMT growth due to new development)	5,067,000	6,404,000	7,760,000	9,133,000	10,526,000	11,940,000
Difference b/t "growth" & "no growth" (annual population growth due to new development)	127,640	161,230	195,350	230,040	265,320	301,300
VMT per capita from new development	39.70	39.72	39.72	39.70	40	40
BASELINE CO2 TOTALS						
Light Duty Stock MPG (EIA, Annual Energy Outlook 2008 Report #: DOE/EIA-0383. Table 7)	20.3	20.5	20.7	20.9	21.2	21.5
Lbs/CO2/Mile	0.966	0.958	0.947	0.937	0.925	0.910
Total Daily CO2, baseline without reduction (lbs)	46,657,785	47,427,671	48,042,507	48,644,827	49,119,677	49,446,078
Total Yearly CO2, baseline without reduction (lbs)	17,030,091,344	17,311,100,080	17,535,515,087	17,755,361,829	17,928,682,085	18,047,818,443
Total Cumulative CO2, baseline without reduction (lbs)	**17,030,091,344**	**34,341,191,424**	**51,876,706,510**	**69,632,068,340**	**87,560,750,425**	**105,608,568,868**
ISR APPLICABILITY						
Rule Penetration - % of population from new development subject to ISR (1) (0.85)	108,494	137,046	166,048	195,534	225,522	256,105
Estimated % of sources to perform on-site reductions	60%	65%	70%	70%	70%	70%
Total population subject to on-site reductions	**65,096**	**89,080**	**116,233**	**136,874**	**157,865**	**179,274**

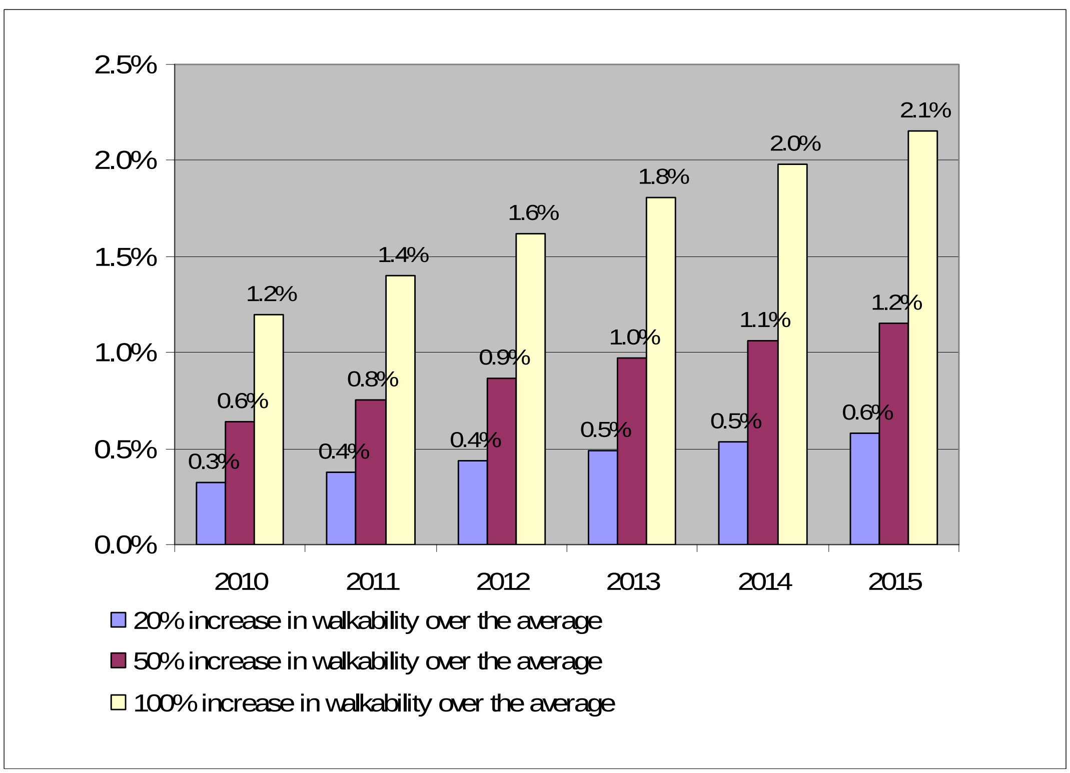
VMT impacts from increased local walkability.
Three scenarios are used here to represent the range of potential increase in local walkability due to an ISR (20%, 50% and 100%), based on results presented in Frank et al (2006).

The increase in walkability was calculated by applying the percentage increase to the countywide average for the following four measures of walkability:

- Net residential density
- Intersection density
- Land use mix
- Retail Floor Area Ratio

Each of the four components was then used to re-calculate the walkability index and apply its estimated percentage change in VMT (its elasticity at that particular point on the index score). The resulting percentage decreases in VMT per capita (6.5%, 12.9%, and 24.1%, respectively) were applied to generate an adjusted VMT per capita for each scenario. The VMT per capita for each scenario were then used to adjust the total projected VMT from new development, the total projected regional VMT, and the amount of regional VMT reduced. VMT amounts were converted to CO2 (lbs), resulting in a daily total CO2 reduction. This amount is then rolled up to a yearly total, and a cumulative total for years 2010-2015. This results in 0.8%, 1.6%, and 2.1% reductions from the baseline total CO2, respectively in year 2015. Figure 23, below details estimated reductions for years 2010-2015:

Figure 23. Estimated CO2 Reductions in the San Joaquin Air District with an ISR, 2010-2015



CAVEATS

In interpreting this analysis, readers should keep in mind that it is *exploratory* in nature. When interpreting any research, especially with an emerging research topic such as this one, one should keep certain caveats in mind.

- This analysis is based on a study in King County, WA. For the analysis, we assumed a 20/50/100% increase in the King County average of four walkability elements (residential density, intersection density, land use mix and retail FAR) for new development. The King County study also controlled for sociodemographic variables known to influence transportation choice, as well as distance to transit. The distance to transit variable serves as a proxy for regional accessibility, although more sophisticated measures could be developed in the future.

  It is quite possible that the average for each of these walkability elements is different in the San Joaquin Air District region, particularly for new development (as opposed to the average for all development, which was used in the King County analysis). It is also possible that the nature and degree of relationship between VMT and walkability is different in the San Joaquin region, although the existence of a relationship and the urban design elements that comprise it is well-documented in the literature review and underpin the base validity of this analysis. Adjusting this estimate using local data to calculate the walkability components would be the next logical step in creating a more refined estimate. Local transportation survey and land use data may allow the development of factors that describe the specific relationship between walkability and VMT/CO2 in the San Joaquin region. Although such analyses are beyond the scope of the current effort, data resources do exist to extend future work in this direction.

- All measures of change in VMT and CO2 with respect to changes in walkability are subject to diminishing marginal returns. One should not assume a straight line relationship between improving walkability from 50% to 100%, or from 20% to 50%, and reductions in VMT and CO2; further improvements will become progressively harder to achieve as areas attain a higher level of walkability. This concept is reflected in the amount of change in VMT generated at each level of walkability in the analysis – with a 20% increase in walkability, we get a 6.5% reduction in VMT per capita from the baseline; a 50% increase in walkability (a 30 percentage point increase) increases the VMT reduction by only 6.4 percentage points. The next increment of increase - 50 percentage points - in walkability yields only an 11.2 percentage point decrease in VMT. In addition, the further away the increase is from the baseline, the more difficult it becomes to accurately predict a result.

  This analysis does not include all the aspects of new development that could be associated with VMT and CO2, such as traffic calming measures, increased transit service, and attractiveness and vibrancy of the streetscape for pedestrians as discussed in the literature review. In particular, the specific amount, type, and location of transit service, roadways, and other transportation infrastructure can play a large role in the amount of per capita VMT, and the potential to reduce CO2 with urban design interventions. Incorporation of these attributes may be possible in more detailed investigations in future.

- It is important to note that this estimate only deals with the operational energy used by vehicles. It does not include ‘embodied energy’ – the energy used in the manufacture of vehicles or other transport systems.

In addition, the following assumptions are inherent in this analysis:

- Under an ISR, developers would choose urban design mitigations. There are a number of mitigation strategies, and even those developers choosing to mitigate may in actuality elect to, for example, incorporate green building elements or to use low-emissions construction equipment rather than using urban design mitigation. However, a more compact design (multi-family or multi-use buildings) would also decrease energy use from building operation. These benefits are not accounted for in these calculations.

- An ISR would only influence local walkability (urban design), and not the location of development. Although by increasing the cost of development on the fringe an ISR could indirectly influence a development’s location, there is no way to anticipate situations where this may occur in the abstract. This analysis assumes that regional location of a development will remain constant. It may be necessary to strengthen regional growth policy in order to discourage fringe development, rather than attempting to regulate it on a project by project basis.

- A segment of the adjusted VMT total includes people in developments that are subject to an ISR, but for where the developer chooses to mitigate “off-site” – i.e., pay an impact fee. Because this impact fee would be dedicated to CO2 reduction programs, there may in fact be CO2 and/or VMT reductions for this segment of the population through such a program. However, there is no way to know what those reductions might be, so in the analysis they are treated conservatively – using the same daily VMT rate as the existing population and new development not affected by the ISR.

SECTION V. CONCLUSION

There is a measurable link between new development and vehicle-based (indirect source) air pollution. Therefore, the current literature supports the San Joaquin Valley Air Pollution Control District's Indirect Source Rule. Evidence also supports the following broad principles:

- Land use and transportation are connected.
- Walkable neighborhoods with interconnected streets, a mix of land use, and compact development are associated with lower levels of vehicle travel and emissions, all else being equal. This relationship holds true at different scales, in different locations, and when taking into account neighborhood and travel preferences (self-selection).
- Centrally located locations are also associated with lower levels of vehicle travel.

Therefore, a development strategy that encourages more compact, walkable, and infill development and makes investments in regional transit service to connect population and employment centers will be effective at reducing vehicle travel and emissions, and will also increase neighborhood scale walkability. It also increases the ability of transit to efficiently serve a region.

Because of this link between the built environment and travel behavior, actions developers take can play a role in reducing indirect source pollution from vehicle travel. The evidence supports the use of the following specific site design mitigation measures used in the ISR:

- Residential Density
- Mixed Use Development/Amount of Retail
- Interconnected Street Networks
- Pedestrian-Oriented Street and Site Design
- Transit Service
- Regional Location of Developments

The Indirect Source Rule therefore applies appropriate site design mitigation mechanisms to reduce pollution created by new development projects. Not only are each of the above air pollution mitigation measures reasonable and appropriate for developers to apply as they build new development, they have consistently been associated (individually and in combination) with lower levels of vehicle travel and emissions. Their use as mitigation measures in the ISR, and the use of the URBEMIS model to estimate the effectiveness of these actions, is based on sound conclusions drawn from empirical research and are supported by a number of modeling applications.

The current literature also supports the use of Indirect Source Rules to regulate CO_2 emissions. Regional and local development patterns have a clear impact on VMT in particular. Because VMT is so closely related to CO_2, the use of an ISR to reduce CO_2 emissions is particularly appropriate. Decisions made by developers can play a key role in reducing CO_2 emissions from vehicle travel.

The same factors listed above, currently used as mitigation measures for the San Joaquin ISR, are shown by the evidence to support CO2 reduction. Although there is little research directly on the urban form factors that influence CO2, the strong connection between CO2 and VMT coupled with the results of early research allows us to draw this conclusion.

The URBEMIS model that is used in the San Joaquin Valley Air District Indirect Source Rule takes into account both on-site land uses and design features, as well as land uses around a project. Consistent with current evidence, increased connectivity on-site and to adjacent destinations, increased density, the presence of complementary uses or transit service on-site or nearby, and the presence of a supportive pedestrian / cycling environment results in lower estimated levels of vehicle use and emissions. The most recent version of URBEMIS (9.2.4) can calculate CO2 impacts from transportation. Because URBEMIS is currently used to measure PM and NOx for the existing ISR, this could ease the addition of CO2 into an ISR in the San Joaquin Valley region and other regions around the state. However, URBEMIS does not currently calculate GHGs other than CO2, or take into account CO2 efficiencies in building operation or embodied energy used to manufacture autos and transit vehicles.

Mitigation requirements under the current San Joaquin ISR are based on URBEMIS calculations which multiply the number of vehicle trips reduced by the average trip length for the travel zone in question (average trip length is generated from the regional travel model). Because of the close connection between VMT and CO2, and between land use patterns and VMT, the URBEMIS model is appropriate as a tool by which to estimate mitigation, although it should be refined to more finely differentiate VMT (by trip or location). Such a system would result in increased fees/requirements for areas that require longer distances of travel between daily activities. This would encourage infill, contiguous and close-in development due to the strong connection between regional location, VMT and therefore CO2. Although local density, diversity (land use mix), and design (street connectivity and pedestrian environment) are important and can have real impacts on CO2 emissions, the clear payoff will be with close-in development. As summarized by Ewing and Cervero (2001, p. 100), "dense, mixed use developments in the middle of nowhere may offer only modest regional travel benefits." The cumulative amount of CO2 generated from a less centrally located development, even if it is well-designed, could even be far greater due to increased vehicle miles or hours of travel.

Several refinements could be made to in an ISR and with URBEMIS to better encourage infill or close-in development. A factor could be incorporated into the ISR that would give additional emissions reductions for infill development projects, or projects that are consistent with regional plans or blueprints. Ideally, bonuses of this nature should be substantial enough to tip the scale in terms of costs, encouraging developers to develop in close-in locations. A measure of regional accessibility generated by the travel model could be used to refine the ISR review and encourage closer-in projects. Accessibility could be measured, for example, as the number of employees/households in each travel zone within 20 minutes by car to every other travel zone, plus the number of employees/households within 40 minutes by transit. These measures could be generated periodically (every few years), rather than having to run the travel model for every ISR evaluation. In many cases, these measures can be derived from the output tables saved from the last model runs used in the regional transportation planning process.

In order to generate more precise estimates of per capita VMT at a proposed development location, a regional travel model could be used to supplement URBEMIS analysis. By using the travel model to generate a sample of evaluations of commuter and customer VMT per employee for a few standard projects (large / small projects in various locations around the region), these results could be applied to any project by size and location.

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