

# Measuring the Benefits of Compact Development on Vehicle Miles and Climate Change

Jerry Walters, Reid Ewing

For climate stabilization, the United States (US) will need to cut its transportation carbon dioxide (CO<sub>2</sub>) emissions by 60%–80% by 2050. As we cannot accomplish this reduction through vehicle and fuel technology alone, the environmental and transportation communities are focusing on strategies to reduce growth in vehicle miles traveled (VMT), reversing recent trends. The majority of recent VMT growth is due, not to population growth, but to the effects of urban environment, such as increased auto ownership, longer trips, and driving alone. The US Department of Energy forecasts that driving will continue to increase at almost threefold the growth in population. Even under the most stringent vehicle and fuel standards, transportation-related CO<sub>2</sub> emissions will be 40% above the target level. In response, climate-change legislation has been passed in California and is pending in other states and in the US Congress that places strict new requirements on mandated environmental impact documentation. One limitation on compliance has been the lack of a unified set of scientific information on the underlying relationships between development form and VMT generation. This article distills and reconciles various forms of prior research on the subject, producing a unified quantitative understanding of the mechanisms that relate urban development forms with VMT and CO<sub>2</sub>. The findings will help improve the insightfulness and accuracy of the next generation of environmental documents. The article provides results of research and planning studies from throughout the US that indicate the degree to which developments with higher densities, mix of uses,

accessible destinations, and interconnected streets reduce vehicle trips and VMT. Sources include regional blueprint studies, as well as project-specific studies such as Atlanta's Atlantic Station development, whose predicted trip reduction was found to be so compelling that the development was deemed a transportation control measure and air quality benefit by the Environmental Protection Agency and Federal Highway Administration. The article identifies the emerging practices in transportation impact analysis for assessing the degree to which the characteristics of development can reduce VMT and carbon impacts. It presents the empirical evidence of how vehicle travel is affected by density, diversity, walkability, regional accessibility, and distance from transit. It also reviews tools that transportation planners and analysts have available to capture these effects, including simple elasticities and new trip generation rates under consideration by the Institute of Transportation Engineers.

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Scientific consensus now exists that greenhouse gas (GHG) accumulations due to human activities are contributing to global warming. International and domestic climate policy discussions have gravitated toward the goal of limiting the temperature increase to 2°–3°C by cutting greenhouse gas emissions by 60%–80% below 1990 levels by the year 2050. The primary GHG is carbon dioxide (CO<sub>2</sub>), and every gallon of gasoline burned produces about 20 pounds of CO<sub>2</sub> emissions. The United States (US) is the largest per-capita emitter worldwide of the greenhouse gases that cause global warming. Transportation accounts for a full third of CO<sub>2</sub> emissions in the US (Ewing et al., 2008).

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Transportation CO<sub>2</sub> reduction strategies will need to combine three major objectives: improve vehicle fuel efficiency, reduce the carbon content of the fuel itself, and reduce the amount of driving or vehicle miles traveled (VMT). Technological improvement in vehicles and fuels is likely to be offset by continuing, robust growth in VMT. Since 1980, the number of miles Americans drive has grown three times faster than the US population and almost twice as fast as vehicle registrations (Winkelman, Hargrave, and Vanderlan, 2000). Average automobile commute times in metropolitan areas have risen steadily over the decades.

The growth in driving is due in large part to trends in urban development: homes that are located farther from workplaces, larger suburban schools that are inaccessible except by motor vehicle, and shopping destinations that are segregated from homes and workplaces. As a larger and larger share of our built environment has become automobile dependent, car trips and distances have increased as walking and public transit use have declined. Population growth has been responsible for only a quarter of the increase in VMT in recent decades. More of the increase has been due to trends related to the development pattern of the urban environment, such as longer trips and people driving alone.

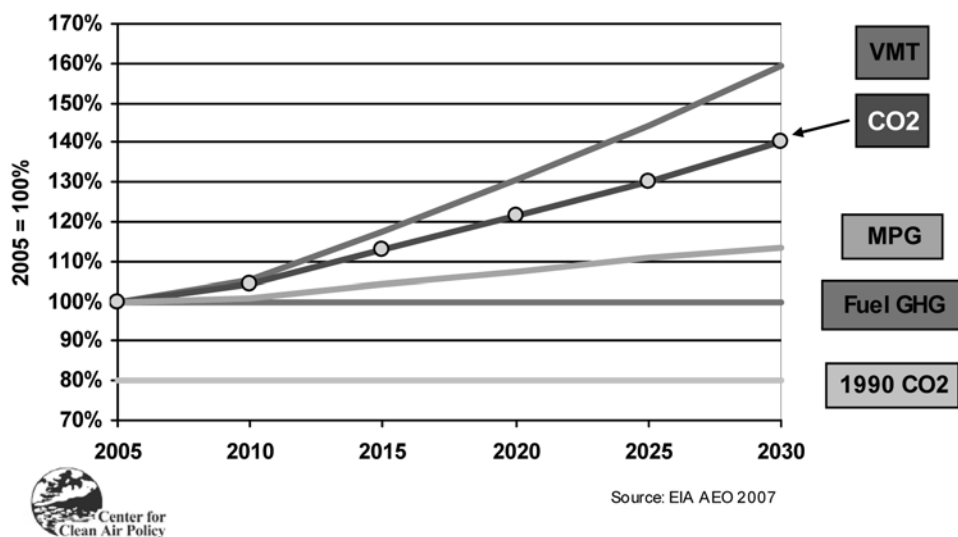
This article provides a unique and essential synthesis of scientific research that will enable future environmental analysis to address the underlying relationships between

different forms of urban development and the generation of VMT and CO<sub>2</sub> and climate-change impacts.

## How Growth in Driving Offsets Improved Vehicle Fuel Economy

CO<sub>2</sub> is more difficult to control through vehicle technology than are conventional air pollutants. Conventional pollutants can be reduced in automobile exhaust with sophisticated emission control systems (catalytic converters, onboard computers, and oxygen sensors). CO<sub>2</sub>, meanwhile, is a direct outcome of burning fossil fuels; there is no practical way to remove or capture it from moving vehicles. At this time, the only way to reduce CO<sub>2</sub> emissions from vehicles is to burn less gasoline and diesel fuel (Ewing et al., 2008).

CO<sub>2</sub> emissions will continue to rise, despite technological advances, as the growth in driving overwhelms planned improvements in vehicle efficiency and fuel carbon content, as shown in Figure 1. The Energy Information Administration (EIA) of the US Department of Energy forecasts that driving will increase 59% between 2005 and 2030 (red line), outpacing the projected 23% increase in population. The EIA also forecasts a fleetwide fuel economy improvement of 12% within this time frame, primarily as a result of new federal fuel economy standards for light trucks (green line). Despite this improvement in efficiency, CO<sub>2</sub> emissions would grow by 41% (dark blue line) (Ewing et al., 2008).



**Figure 1.** Projected growth in greenhouse gas (GHG) carbon dioxide (CO<sub>2</sub>) emissions from cars and light trucks. MPG, miles per gallon; VMT, vehicle miles traveled. Source: EIA, 2007.

US fuel economy has been flat for almost 15 years, as increases in car weight and power have offset the more efficient technology. Federal and state efforts are under way to considerably boost vehicle efficiency and reduce GHG emissions (Bernstein, Burwell, and Winkelman, 2003). In June 2007, the US Senate passed new corporate average fuel economy (CAFE) standards that would increase new passenger vehicle fuel economy for cars and light trucks combined from the current 25 miles per gallon (mpg) to 35 mpg by 2020. California is implementing a low carbon standard for transportation fuels that entails a 10% reduction in fuel carbon content by 2020 (Ewing et al., 2008).

Even if these more stringent standards for vehicles and fuels were to go into effect nationwide, transportation-related emissions still would not come close to meeting goals for averting global climate change as shown in Figure 2. The rapid increase in driving would overwhelm both the increase in vehicle fuel economy (green line) and the lower carbon fuel content (purple line) so that CO<sub>2</sub> emissions would still be 12% above the 2005 level. This is 40% above the 1990 level (turquoise line), which is a benchmark for climate stabilization (Ewing et al., 2008).

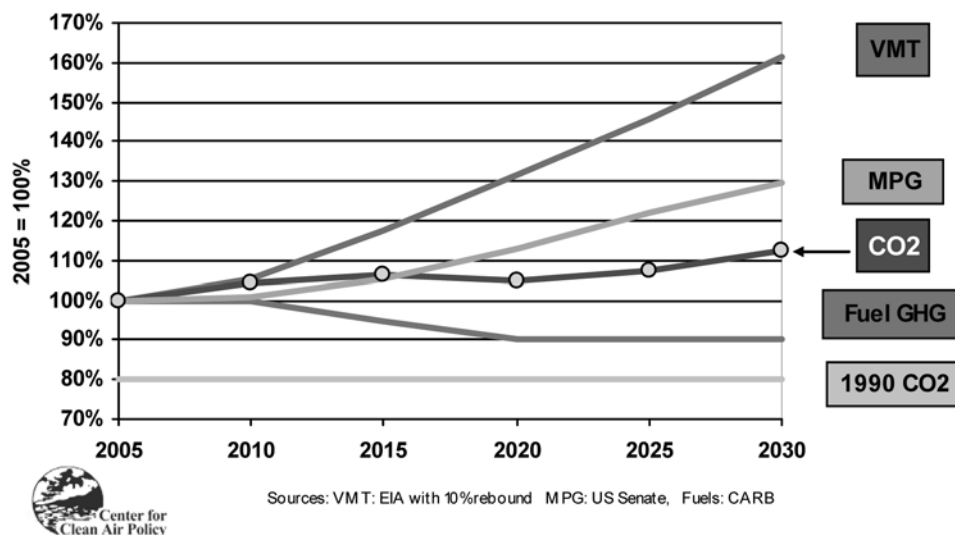
As the projections show, the US cannot achieve such large reductions in transportation-related CO<sub>2</sub> emissions without reducing the growth in miles driven.

## Influence of Development Patterns on VMT, CO<sub>2</sub>, and Climate Change

Much of the rise in vehicle emissions can be curbed by growing in a way that will make it easier for Americans to drive less. The weight of the evidence shows that, with more compact development, people drive substantially less.

Travel-reducing characteristics of the built environment include compact development, mixed-use developments, transportation networks designed to interconnect rather than divert travel along circuitous routes, and higher development densities including condominiums, townhouses (or detached houses on smaller lots), and multistory offices and retail. This type of development has seen a resurgence in recent years and goes by many names, among them *walkable communities*, *new urbanist* neighborhoods, *transit-oriented developments* (TODs), *infill*, and *brownfield* developments. Some *lifestyle centers* are now replacing single-use shopping malls with open-air shopping on connected streets, with housing and office space as part of the new development. Many communities are also revitalizing their traditional town centers and downtowns, often adding more housing to the mix. These varied development types may be referred to as *smart growth*.

When viewed in total, evidence on land use and driving shows that compact development will reduce the need to



**Figure 2.** Projected growth in greenhouse gas (GHG) carbon dioxide (CO<sub>2</sub>) emissions from cars and light trucks. MPG, miles per gallon; VMT, vehicle miles traveled. Source: EIA. 2007.

drive by between 20% and 40%, as compared with development on the outer suburban edge with isolated homes, workplaces, and other destinations. A midrange estimate would be a 30% cut in VMT with compact development. Making reasonable assumptions about growth rate, market share of compact development, and relationship between CO<sub>2</sub> reduction and VMT reduction, smart growth could, by itself, reduce total transportation-related CO<sub>2</sub> emissions from current trends by 7%–12% by 2050, an important offset to the CO<sub>2</sub> growth trends otherwise projected (Figure 2) (Ewing et al., 2008).

A crucial challenge in accomplishing these objectives is equipping the development review processes, including environmental impact assessment, with the empirical evidence needed to accurately capture the effects of the built environment on VMT and CO<sub>2</sub> and to differentiate quantitatively between the impacts of smart growth and those of other forms of development.

## Quantitative Evidence That Compact Development Reduces Travel

As smart growth development forms have become more common, planning and environmental experts have documented travel reductions that result from compact, mixed-use, transit-served communities. Studies have looked at the issue from varying angles, including

- research that compares overall travel patterns among regions and neighborhoods of varying compactness and auto orientation,
- studies that follow the travel behavior of individual households in various settings,
- models that simulate and compare the effects on travel of different future development scenarios at the regional and project levels, and
- site-specific trip generation counts that compare trip rates at sites with different development characteristics or context.

Studies of all four types have found significant potential for compact development to reduce the miles that residents drive.

A comprehensive sprawl index ranked 83 of the largest metropolitan areas in the US by their degree of sprawl, measuring density, mix of land uses, strength of activity centers, and connectedness of the street network. Even

accounting for income and other socioeconomic differences, residents drove far less in the more compact regions. On a daily basis, sprawling Atlanta, Georgia, generated 34 VMT per capita, compared with less than 24 VMT per capita in more compact Portland, Oregon (Ewing, Pendall, and Chen, 2002; McCann and Ewing, 2003).

Regional planning studies have also found relationships between development patterns and driving. Many regions throughout the US have undertaken regionwide growth visioning and scenario planning to select a coordinated land-use and transportation *blueprint* to guide regional strategies and policies. Such blueprints are intended to inform city and county General Plans and other planning and spending decisions. In 23 regional growth simulations comparing the effect of a metropolitan-wide business-as-usual scenario with more compact growth options, compact scenarios averaged 8% fewer total miles driven than business-as-usual scenarios, with a maximum reduction of 31.7%. The lowest VMT scenarios were those with higher degrees of land-use mixing, infill development, and population density, as well as a larger amount of expected growth (Bartholomew, 2007).

At the level of the individual development project, simulations have been conducted that predict the degree to which travel impacts would change if the development project were sited and designed differently. Unlike regional scenario studies, project-level simulations have the advantage of focusing on the subset of the regional population for whom the built environment actually varies. *Site plans* can range in density, diversity, or design, without introducing variations in regional location or proximity to transit. *Regional location* can vary from transit-served brownfields to auto-only greenfields, without any difference in site plans. Or both can vary. The amount of development (housing and employment) is generally held constant in project-level simulations, but acreage may vary among cases.

### Case Study 1: Atlantic Station

One of the best known of the project-level studies evaluated the impact of building a very dense, mixed-use development at an abandoned steel mill site in the heart of Atlanta versus spreading the equivalent amount of commercial space and number of housing units in the prevailing patterns at three suburban locations. Environmental review of the Atlantic Station project relied upon a thorough technical analysis of the relative impact of the project when compared with other alternatives for accommodating the region's projected population and employment

growth. At the time the project was first proposed, the Atlanta region was out of compliance with federal transportation conformity requirements for air quality and, as a result, couldn't construct roadway connections needed for highway and transit access (Walters, Ewing, and Schroeder, 2000).

The 1998 project analysis included the following:

- *Regional location analysis.* The proposed Atlantic Station site was compared to three greenfield sites large enough to accommodate the proposed development. The sites were at increasing distances from the urban core: a perimeter beltway location, a suburban location, and an exurban location, each with a development density and site plan typical of their location.
- *Site plan analysis.* Three alternative plans for the site were compared, incorporating different intra-site densities, land-use mixes, street networks, and streetscape design elements, and their relative effects on reducing vehicle trips and VMT were calculated.

The diagram on the left in Figure 3 summarizes the findings of the regional location analysis. The analyses showed that redevelopment of the Atlantic Station site (then known as Atlantic Steel) would produce less VMT and vehicle emissions than placing the same amount of development on alternative sites in outlying areas (Sandy Springs, Cobb/Fulton, and Henry County), locations that could receive the development were it not to be placed on the Atlantic Station infill site. The infill location would generate as much as 35% less VMT and emissions than the comparison sites.

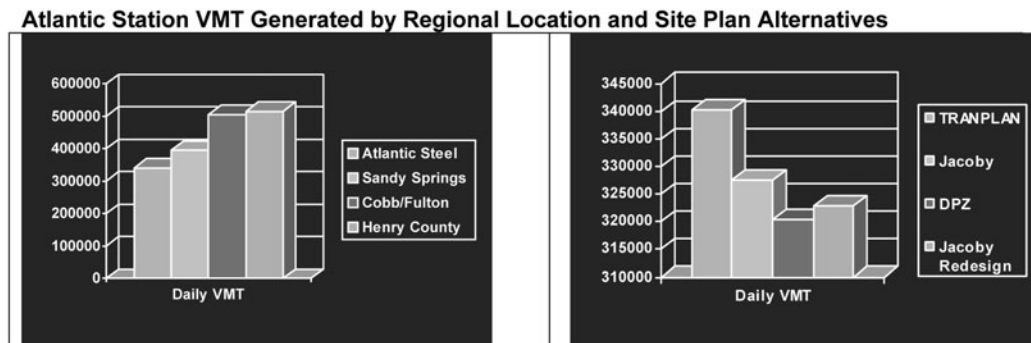
The diagram on the right in Figure 3 presents the results of the site plan analysis. It compares the VMT generated by the Atlantic Station site design compared with business-

as-usual development on the same site (TRANPLAN), the developer proposed Jacoby site design, and two design refinements (DPZ and Jacoby redesign), both of which created a more interconnected and walkable pattern of streets and pedestrian connections and a more complete blending of compatible land-use types within the site. The ultimately selected Jacoby redesign generates about 2% less VMT than the original Jacoby proposal and 5% less VMT than the business-as-usual land-use case [Environmental Protection Agency (EPA), 1999; Hagler Bailly, Inc., 1998].

Based on these results, the federal government was able to declare the development a "transportation control measure" that could help improve the region's air quality. The EPA ultimately waived the conformity requirement for this project (EPA, 1999; Hagler Bailly, Inc., 1998). The Atlantic Station project, as illustrated in Figure 4, has become a highly successful reuse of central city industrial land and is reportedly meeting the trip-reduction targets established by EPA through its 1998 analysis.

### Case Study 2: Canada Housing and Natural Resources Study

The Canada Mortgage and Housing Corporation and Natural Resources Canada commissioned a comprehensive evaluation of regional travel data to develop a statistical model of GHG emissions. The study quantified the relationships between neighborhood characteristics, housing design, and locational factors on VMT and CO<sub>2</sub>. Using the data from the 115,000-household Greater Toronto Area household travel survey, the study provided statistical relationships between travel emissions and a broad array of influential factors, including household size, income, and autos; location relative to central business district, jobs, and transit; and



**Figure 3.** Atlantic Station vehicle miles traveled (VMT) generated by regional location and site plan alternatives.



Figure 4. Atlantic Station today. Source: Jacoby Development Company.

neighborhood density, diversity, and design. Influential neighborhood characteristics included housing density; mix of jobs, housing, and retail; and street network connectivity and street widths, walkability, and presence of bike lanes.

The resulting predictive models were applied to a range of prototypical neighborhood scenarios, focusing on three urban context situations (central area, inner suburbs, and outer suburbs), and three neighborhood design concepts:

- *Conventional suburban*: low density, exclusively residential, with wide cul-de-sac streets.
- *Medium density*: higher-density mix of multifamily and single-family housing; moderate amounts of local retail and jobs; a blend of cul-de-sac and connected streets; and higher levels of transit service.
- *Neotraditional development*: highest density and highly mixed land uses, including sufficient local jobs per household and fully supporting local retail interspersed with the residential properties; and fully interconnected, walkable streets and pedestrian networks.

The comparative analysis discovered that considerable differences in trips, VMT, and GHG emissions per household result from changes in density and urban design alone and from regional location alone, as well as from a combination of neighborhood design and location. Changes due to location alone are listed in Table 1 (IBI Group, 2000).

These findings support the notion that development form and context both contribute to notable reductions in vehicle travel and emissions. Specific variations in travel and emissions related to neighborhood characteristics alone and related to combined effects of neighborhood design and context are presented in the following sections.

Table 1. Effect of regional location on vehicle miles traveled (VMT) and greenhouse gas emission per household in Toronto<sup>a</sup>

| Location shift <sup>b</sup>       | Neighborhood type   | Reduction in VMT per household |
|-----------------------------------|---------------------|--------------------------------|
| From outer suburb to inner suburb | Conventional suburb | -27%                           |
|                                   | Medium density      | -35%                           |
|                                   | Neotraditional      | -39%                           |
| From inner suburb to central area | Conventional suburb | -20%                           |
|                                   | Medium density      | -29%                           |
|                                   | Neotraditional      | -35%                           |
| From outer suburb to central area | Conventional suburb | -42%                           |
|                                   | Medium density      | -54%                           |
|                                   | Neotraditional      | -60%                           |

<sup>a</sup> Even without changes in neighborhood design, changes in regional context can have dramatic effects, ranging from VMT reductions of

- about 20% for relatively small shifts of conventional suburban development from fringe locations to inner suburbs, to
- about 40% for relatively small location shifts of neotraditional development, or relatively large shifts of suburban neighborhood forms (from outer suburbs to central area), and
- up to 60% for shifts of neotraditional development from outer suburban to central locations (IBI Group, 2000).

<sup>b</sup> Outer suburb: 18 miles from the central business district (CBD); inner suburb: 6 miles from the CBD; and central area: 3 miles from the CBD.

## Summary of Site-Specific Studies on Development Form and VMT

The Atlantic Station and Toronto studies, in addition to similar studies in San Diego, California; Wilmington, Delaware; Portland, Oregon; Oak Ridge, Tennessee; and San Antonio, Texas, have forecasted the impacts of site design on vehicle trips, VMT, and/or CO<sub>2</sub> emissions. Table 2 presents the findings. In each case, alternative development plans for the same site are compared to a baseline or trend plan.

**Table 2.** Effect of site design and mix on vehicle miles traveled (VMT) and greenhouse gas emissions

| Study region                | Project site                    | Site design alternatives  | Density relative to baseline design   | Difference in development mix or site configuration relative to baseline design  | Change relative to baseline VMT (or CO <sub>2</sub> ) per capita |
|-----------------------------|---------------------------------|---|---|--|--|
| Atlanta                     | Atlantic Station                | DPZ   | Similar to baseline   | More mixed use, improved walkability   | -5.8%  |
| San Diego                   | Vista area                      | Jacoby redesign<br>Quality of Life<br>Advanced  | Similar to baseline<br>Lower<br>Higher  | Compromise between baseline and DPZ<br>"Quality of Life" design<br>Energy efficient  | -5.2%<br>4%  |
| San Diego                   | Euclid area                     | 2015 PLACE's<br>Community preferred   | NA<br>NA  | NA<br>NA   | -67%*<br>-13%  |
| Wilmington                  | Edgemore                        | Merchant's Square<br>redevelopment  | Higher than base but lowest<br>of the 3 alternatives                            | Adds 1,250 jobs and sidewalk improvements  | -5%<br>-19%  |
| Portland                    | River district                  | Enhanced land use<br>Transit station community<br>Advanced<br>Developers<br>Preferred | Middle of the 3 alternatives<br>Highest of the 3 alternatives<br>NA<br>NA<br>NA | Above + 143 units of multifamily housing<br>Above + new rail station<br>Maximizes energy efficiency<br>Balances market and policy        | -17%<br>-19%<br>-53%*<br>-85%*                                   |
| San Antonio                 | Broadway corridor               | City of San Antonio future<br>Scheme 4 future   | 151%<br>227%  | Compromise between other two scenarios<br>Emphasis on multifamily dwelling units<br>150% more housing, twice as many jobs<br>as existing | -68%*<br>-1.5%<br>-5.8%  |
| Toronto suburban edge site  | Conventional design             | Medium-density design   | 117% more dense   | Partial grid vs discontinuous streets; higher<br>jobs per capita, transit service  | -3.3%  |
|                             | Conventional design             | Neotraditional design   | 13 times more dense   | Full grid vs discontinuous streets; highest<br>jobs per capita, transit service  | -2.1%  |
|                             | Medium-density design           | Neotraditional design   | 5.5 times more dense  | Full grid vs partial grid; highest jobs per<br>capita and transit service  | -4.6%  |
| Toronto Inner suburban site | Conventional suburban<br>design | Medium-density design   | 117% more dense   | Partial grid vs discontinuous streets; higher<br>jobs per capita, transit service  | -4.6%  |
|                             | Conventional suburban<br>design | Neotraditional design   | 13 times more dense   | Full grid vs discontinuous streets; highest<br>jobs per capita, transit service  | -2.9%  |
|                             | Medium-density design           | Neotraditional design   | 5.5 times more dense  | Full grid vs partial grid; highest jobs per<br>capita and transit service  | -7.1%  |
| Toronto central area site   | Conventional suburban<br>design | Medium-density design   | 117% more dense   | Partial grid vs discontinuous streets; higher<br>jobs per capita, transit service  | -7.9%  |
|                             | Conventional suburban<br>design | Neotraditional design   | 13 times more dense   | Full grid vs discontinuous streets; highest<br>jobs per capita, transit service  | -3.7%  |
|                             | Medium-density design           | Neotraditional design   | 5.5 times more dense  | Full grid vs partial grid; highest jobs per<br>capita and transit service  | -10.0%   |

\*May include other energy-reducing measures beyond land use and VMT reduction.  
NA, not available.

Sources: Allen and Benfield, 2003; EPA, 2001a,b, 1999, 2006; Hagler Bailly, Inc., 1998; Hagler Bailly, Inc., and Criterion Planners/Engineers, 1999; IBI Group, 2000.

Results suggest that VMT and CO<sub>2</sub> per capita decline as site density increases and the mix of jobs, housing, and retail uses becomes more balanced. However, the limited number of studies, differences in assumptions and methodologies from study-to-study, and the variability of results make it difficult to generalize.

Comparing the findings for the Toronto cases in Table 2 to those in Table 1 indicates that the effects of site design change alone (Table 2) represent approximately one-fourth of the combined effects of site design change and regional location change together (Table 1).

## Synthesis of Studies on Influence of Regional Location on VMT

Approximately ten studies have considered the effects of regional location on travel and emissions generated by individual developments. The studies differ in methodology and context. Some employ full-scale regional four-step travel forecasting models, whereas others rely on best-fit regression equations based on statistical analysis of empirical data on past trends, and some studies include changes in site design. But they tend to yield the same conclusion: infill locations generate substantially lower VMT per capita than do greenfield locations. As shown in Table 3, the reduction percentages vary from 13% to 61%. Results also indicate that vehicle trips and CO<sub>2</sub> per capita are higher for greenfield locations than for infill sites (Allen and Benfield, 2003; EPA, 1999, 2001a,b, 2006; Hagler Bailly, Inc., 1998; Hagler Bailly, Inc., and Criterion Planners/Engineers, 1999; Natural Resources Defense Council, 2000; Walters, Ewing, and Schroeder, 2000).

In Figure 5, the distribution of data points indicates that, although higher density is associated with reduced VMT, other factors are at work. Regional location explains much of the scatter, preventing the points from falling along a uniform line, and the relationship between density and VMT is due in part to regional location, as well. Independent of the scatter, the evidence suggests that the combined effects of site design and location can produce VMT reductions ranging from about 20% to over 60% as densities increase by 200% or more.

The data clearly suggest that a smart-growth scenario that combines infill location with higher density and urban design and transit proximity can produce VMT reductions that are, in most cases, in the range of about 30% to 60%. When compared with the results the site design studies,

which indicate VMT effects ranging from about 2% to 19%, it is evident that the effect of regional location compounds the trip-reducing effects of development mix, density, and site design alone. Project-level simulations demonstrate that, when we combine smart-growth location with use mix and site design, considerable reductions in VMT are well within the range of possibility.

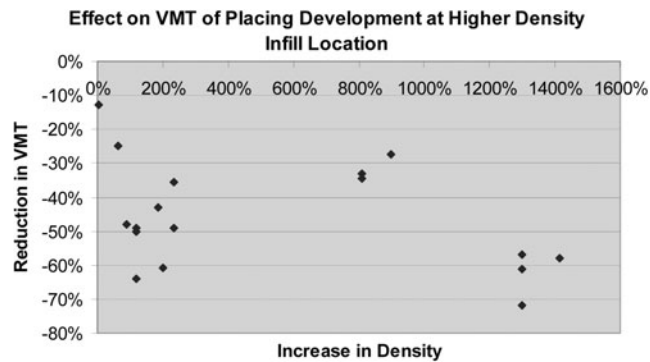
Accommodating growth in compact development and walkable neighborhoods has been shown to reduce VMT per capita for two reasons: (a) changing the travel choices of those who live such neighborhoods regardless of their predisposition on travel mode and distance (mode and destination shifts), and (b) providing opportunities for those who prefer to live in such neighborhoods and drive less to find suitable housing and to travel in their preferred lower-impact fashion (self-selection).

Almost all studies indicate a statistically significant influence of built environment factors on vehicle travel, even independent of the effects of self-selection (Boarnet and Crane, 2001; Mokhtarian and Cao, 2007). Those who prefer to live in walkable neighborhoods generate 30% less VMT than those who would prefer to live in walkable residential but who cannot find such housing and instead live in auto-oriented neighborhoods. A study by Mokhtarian and Cao (2007) in the San Francisco Bay Area found that, for nonwork trips, residents of traditional neighborhoods are six times as likely to walk as are residents of suburban neighborhoods, and that key variables influencing this higher walk rate include a variety of businesses within 1,000 feet of the household and the perceived attractiveness of the neighborhood. Using targeted surveys of eight neighborhoods in three regions in Northern California, Handy, Cao, and Mokhtarian (2005) found that both the percentage of residents having at least one walk trip and the average walking distance increase dramatically as a function of the following neighborhood characteristics: housing density; number of different businesses; average block length; connectivity, or percentage of four-way intersections; parking pressure, measured in terms of population and employment density; and housing age, with residents of housing built before 1950 having about three times the probability of walking and about three times the average daily walking distance as residents of post-1970 housing. The Victoria Transport Policy Institute (2008) reports that doubling urban densities can result in a 25%–30% reduction in VMT (or a slightly less when the effects of other variables are controlled), and even greater travel reductions are possible if clustering is implemented with other Trans-

**Table 3.** Effect of regional location on travel and emissions

| Study region          | Infill site                 | Greenfield sites considered | Density on greenfield relative to infill site | Increase in density at infill site compared with greenfield site | Reduction in VMT per capita at infill site compared with greenfield site | Reduction in CO <sub>2</sub> at infill site compared with greenfield site |
|-----------------------|-----------------------------|-----------------------------|---|--|--|---|
| Atlanta               | Atlantic Station            | Perimeter (Sandy Spring)    | 96% as dense                                  | 4%   | -13%   | NA  |
| Atlanta               | Atlantic Station            | Cobb/Fulton                 | 11% as dense                                  | 809%   | -33%   | NA  |
| Atlanta               | Atlantic Station            | South Henry County          | 11% as dense                                  | 809%   | -34%   | NA  |
| Baltimore             | US Steel shipyards          | Unidentified greenfield     | 30% as dense                                  | 233%   | -35%   | -26%  |
| Baltimore             | Chesapeake Center/Exxon     | Carroll County              | 30% as dense                                  | 238%   | —  | -27%  |
| Dallas                | South Side on Lamar         | Route 121 McKinney          | 10% as dense                                  | 900%   | -28%   | -38%  |
| Nashville             | Unidentified infill         | Unidentified greenfield     | 62% as dense                                  | 61%  | -25%   | NA  |
| Sacramento            | North Natomas               | Unidentified greenfield     | 30% as dense                                  | 233%   | -49%   | NA  |
| Sacramento            | Antelope                    | Unidentified greenfield     | 35% as dense                                  | 186%   | -43%   | NA  |
| San Diego             | Unidentified infill         | Unidentified greenfield     | 53.3% as dense                                | 88%  | -48%   | -48%  |
| Montgomery County, MD | Unidentified infill         | Unidentified greenfield     | 6.6% as dense                                 | 1,415%   | -58%   | -49%  |
| West Palm Beach, FL   | Unidentified infill         | Unidentified greenfield     | 33.2% as dense                                | 201%   | -61%   | -52%  |
| Toronto               | Medium-density inner suburb | Conventional suburb         | 46% as dense                                  | 117%   | -49%   | -48%  |
| Toronto               | Neotraditional inner suburb | Conventional suburb         | 7% as dense                                   | 1,300%   | -57%   | -56%  |
| Toronto               | Medium-density central area | Conventional suburb         | 46% as dense                                  | 117%   | -64%   | -62%  |
| Toronto               | Neotraditional central area | Conventional suburb         | 7% as dense                                   | 1,300%   | -72%   | -70%  |
| Toronto               | Medium-density central area | Conventional inner suburb   | 46% as dense                                  | 117%   | -50%   | -48%  |
| Toronto               | Neotraditional central area | Conventional inner suburb   | 7% as dense                                   | 1,300%   | -61%   | -60%  |

NA, not available.



**Figure 5.** Relationship between development density increase and vehicle miles traveled (VMT) reduction.

portation Demand Management (TDM) strategies such as parking management and transit improvements. Increasing urban densities to 40 residents and to 100 employees per acre increased transit use from about 2% to about 11% total mode share. Boarnet, Nesamani, and Smith (2003) also concluded that land-use patterns have significant impacts on both trip generation and VMT even beyond the effects of socio-demographics.

Furthermore, national demographic studies indicate that the net change in housing demand between 2003 and 2025 will be for a net increase of over 35 million small lot and attached residential units, while demand for large lot residential units will experience a net decline of almost 2 million units in that same period (Nelson, 2006).

A variety of factors contribute to the trip-reducing effects of compact land-use patterns relative to dispersed suburban patterns, among them: density, diversity (land-use mix), design (walkability and connectivity), destination accessibility, transit proximity, development scale, and demographics. Trip reductions of 30% or more are difficult to achieve through increases in density alone. Most research on the subject indicates that each factor contributes to different degrees to the overall trip reduction, with the consensus from a Delphi panel of national experts on the influence of land use on travel behavior indicating that density, diversity, and design elasticities range from about 5% to 10% each, while destination accessibility elasticities can exceed 20%–30%. Achieving trip reductions of 20% or more generally requires that development incorporate not only higher densities but also several other of the aforementioned locational and design characteristics (Lee and Walters, 2003).

## Incorporating Evidence into Analysis

### Travel Forecasting Models

Because many travel forecasting models lack smart-growth sensitivity, analysts are supplementing conventional models with the results of empirical research on how key factors influence the rate of vehicle use per capita. Four of these factors are often referred to as the 4Ds:

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

Research that resulted in the 4D characteristics also produced estimations of *elasticities* regarding vehicle travel per capita with respect to changes in each of the 4D variables (Cervero and Kockelman, 1997; EPA, 2001b; Walters, Ewing, and Schroerer, 2000). Elasticities quantify the relationship between an independent variable, such as density, and a dependent variable or outcome, such as VMT per capita. An elasticity of, for example, 0.05 indicates that for each 100% change in an independent variable, there is a 5% change in the dependent variable. The 4D elasticities have been used in a variety of application tools to assess the potential vehicle travel reduction benefits of smart-growth land-use strategies, including

- Sacramento Region [Sacramento Area Council of Governments (SACOG)]—for regional “blueprint” testing of alternative future land-use and growth scenarios
- San Luis Obispo [San Luis Obispo Council of Governments (SLOCOG)]—for testing of alternative future land-use and growth scenarios
- Contra Costa County [Costa County Transportation Authority (CCTA)]—for the long-range visioning process “Shaping Our Future” (Bartholomew, 2005)
- Humboldt County—for county General Plan development
- Fresno and Madera Councils of Government—as part of the San Joaquin Valley Growth Response Study (California Department of Transportation)

In addition, a fifth D, *Distance to rail transit*, has been used for analysis of transit-oriented land-use designs by the Bay

**Table 4.** Observed trip generation rates for transit-oriented, infill, and mixed-use development

| Location   | Sample                | Trip generation<br>(% below ITE trip rates) | TOD rail service         |
|--|-----------------------|---|--------------------------|
| Mixed-use development (Fehr & Peers, 2007b)  |                       |   |                          |
| Sacramento & San Francisco Bay Area  | 3 mixed-use projects  | 35%   | None                     |
| TOD (Fehr & Peers 2007a; Latham, 2001; Transit Cooperative Research Program, Report 128, 2008) |                       |   |                          |
| San Francisco Bay Area   | 2 apartment complexes | 40%   | BART: heavy rail         |
| Washington, DC, Metro  | 5 apartment complexes | 60%   | DC Metro: heavy rail     |
| Portland, OR   | 5 apartment complexes | 50%   | Portland MAX: light rail |
| East Bay Area, CA  | 4 apartments, 1 condo | 48%   | BART: heavy rail         |
| Philadelphia/Newark  | 2 apartment complexes | 30%   | SEPTA/NJT: commuter rail |
| Portland, OR   | 3 apartment complexes | 32%   | Portland MAX: light rail |
| Infill development (Association of Bay Area Governments and Kimley-Horn, 2008)                 |                       |   |                          |
| Downtown Berkeley  | 6 apartment buildings | >50%  | BART (limited parking)   |

BART, Bay Area Rapid Transit; ITE, Institute of Transportation Engineers; MAX, Metropolitan Area Express; SEPTA/NJT, Southeastern Pennsylvania Transportation Authority/New Jersey Transit; TOD, transit-oriented development.

Area Rapid Transit (BART) and Caltrans rail transit systems that operate in the San Francisco Bay Area.

The application of the 4D elasticities in these locations has demonstrated their usefulness as a planning and evaluation aid in visioning or long-range planning processes.

### Project-Specific Trip Generation Rates

Research is also currently under way by several transportation planning organizations on the degree to which individual smart-growth characteristics reduce vehicle trip generation of individual development projects. Preliminary results from several of these studies indicate that trip generation may be lower than the suburban trip generation rates published by the Institute of Transportation Engineers (ITE) that are commonly used in traffic impact analysis. Table 4 indicates the degrees to which these studies suggest that auto use is reduced by transit proximity, mixed-use development, and infill development.

### Conclusion

The growing body of quantitative evidence indicates that development form influences vehicle use and that compact smart-growth development reduces VMT in measurable ways. New empirically based methods are emerging whereby transportation and environmental professionals can incor-

porate these facts into their evaluation of proposed development projects and assessments of infrastructure impacts, mobility, emissions, and global warming.

Recent and pending legislation that will require environmental documents to address global warming impacts creates a challenge for environmental analysts—the absence of a unified set of scientific information on the underlying relationships between development form and transportation-related CO<sub>2</sub> generation. This article presents a distillation and reconciliation of various forms of prior research on the subject, producing a unified quantitative understanding of the mechanisms that relate urban development forms with VMT and CO<sub>2</sub>. The findings will enable environmental planners and analysts to improve the insightfulness and accuracy of the next generation of environmental documents.

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