THE TRANSPORTATION AND ENVIRONMENTAL IMPACTS OF INFILL VERSUS GREENFIELD DEVELOPMENT:

A COMPARATIVE CASE STUDY ANALYSIS

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1. Executive Summary

EPA modeled the transportation and environmental impacts of locating the same development on two sites—one infill, and one suburban edge/greenfield—and compared the results. This analysis was conducted in three regions: San Diego, California; Montgomery County, Maryland; and West Palm Beach, Florida.

For each site pair, modeling predicted that the infill site would outperform the greenfield site in six important dimensions:

- Average trip distance: generally shorter with the infill site.
- Per capita vehicle miles traveled: generally fewer with the infill site.
- Travel time: generally shorter with the infill site.
- Public infrastructure and household travel costs: lower with the infill site.
- Environmental impacts, including emissions: smaller with the infill site.
- Multi-modal orientation, and access to community amenities and transportation choices: greater at the infill site.

These case studies suggest that identifying public benefits from infill does not require using a particular level of travel model sophistication. The transportation effects of even moderately sized alternative development patterns were not so subtle that one needs a highly sophisticated model to identify them.

The cases suggest that, although not a panacea, in the right conditions, infill development can make travel more convenient by reducing travel time, lowering travel costs, and lessening congestion. Infill development can also cost significantly less, in total public dollars, in private transportation dollars, and in externalities. Finally, the results suggest that infill development can improve community environmental quality and inputs to quality of life such as accessibility. This study concludes that infill *can* produce non-trivial transportation, environmental, and public infrastructure cost benefits.

The predicted benefits are large enough to suggest that communities may productively investigate whether infill should be considered as one component of a strategy to accommodate growth and meet future transportation needs. Likewise, federal and state agencies, which share responsibility with communities for providing efficient transportation services and environmental protection, may also find it productive to ensure that federal and state policies allow infill where it has a place in communities' transportation and growth strategies.

2. Study Objective and Overview

Given a choice between placing a new commercial or residential development on a suburban edge/greenfield or an urban infill site, which site provides better or more efficient transportation services?[1] Which site produces fewer transportation-related burdens on the environment? In an effort to shed light on these questions, EPA modeled the impacts of locating a given development project on two sites—one infill, and one suburban edge/greenfield—and compared the results. This analysis was conducted in three regions: San Diego, California; Montgomery County, Maryland; and West Palm Beach, Florida.

In each region, EPA examined transportation system performance, travel costs, and transportation emissions for each site. The Agency obtained estimates for public infrastructure costs other than for transportation, and compared the site designs at the neighborhood level to see which provides better access to transportation choices and proximity to community services and amenities.

EPA used standard transportation modeling techniques, including the regional four-step travel model, as the basis for estimating changes in transportation and environmental performance at the regional level. Results from the regional four-step models were supplemented with site- and neighborhood-level analysis using a GIS-based analysis tool, INDEX™.

In each case analyzed, EPA concluded that the infill site would perform better than the greenfield site across most transportation, environmental, and other performance categories. In general, the models predicted that infill development would produce shorter average travel times and fewer vehicle miles of travel, while also using up less open space and producing less air pollution. Traffic congestion results varied among the case studies. Neighborhood-level analysis also revealed greater local accessibility and support for more transportation options. These results suggest that in the three regions analyzed in this study, infill would produce better transportation and environmental results than suburban edge/greenfield development (see the results summary table on page 20).

To our knowledge, no other study has compared the transportation and environmental impacts of locating essentially the same development on infill versus greenfield sites. In contrast to other studies of the transportation and environmental impacts of land use choices, this study limited the scope of inquiry to the impacts of locating a specific development project at different sites within a metropolitan area. This approach allowed all project variables to be held constant except development location. While the analysis does not attempt to develop general principles about the impacts of infill versus greenfield development, it suggests that in at least these three cases, the infill development alternative may be preferable to greenfield development along a number of transportation and environmental criteria. It suggests that local analyses of future transportation investments may do well to include infill development as an investment option.

[1] "Infill" refers to development in urban areas with existing streets, infrastructure and development. "Greenfield" refers to development on previously undeveloped ("green") parcels in suburban or non-urban locations with limited existing infrastructure and development.

3. Analysis Methodology

Each case study placed the same development on two different sites—one infill and one edge/greenfield—and modeled the impact of each infill and greenfield development on transportation and environmental performance measures. Public cost estimates were also obtained. The alternative development scenarios contained the same number of housing units and square footage of commercial space.

Site Selection

The credibility and value of the study depends on the extent to which the selected sites represent typical infill and greenfield development in the region. In each region (San Diego, CA, Montgomery County, MD, and West Palm Beach, FL), EPA worked with local government officials responsible for development policy to select one infill site and one greenfield site suitable for a development project. Local officials were eager to improve their understanding of the implications of accommodating regional growth in one kind of location versus another, in general participated enthusiastically, and made detailed recommendations that greatly aided site selection. The sites thus reflect current local development plans and trends.

In addition to local advice, the criteria for selecting the infill sites included: a central city or central business district location, the availability of redevelopable land, and the availability of project-serving infrastructure. Local assessments of redevelopment potential were based in general on the status of sites in the local planning process and on indications of developer interest. The dominant criterion for selecting greenfield sites was the likelihood, as assessed by local officials, of development occurring in the very near future.

Scenario Development

Once the sites were selected, a hypothetical development consisting of commercial and/or residential development was prepared for each site pair.

For each site pair, the project was then "placed" on both the infill site and the greenfield site through computer simulation. For infill sites, projects were overlaid on existing street grids and other infrastructure. For greenfield sites, where no infrastructure was present, the street and parcel layout was created by following the configuration of existing subdivisions in the vicinity. This approach held constant as many project variables as possible while comparing the two sites.

Each greenfield development was thus developed to be representative of local new development at the edge. Similarly, each infill redevelopment was representative of local infill opportunities.

Evaluation Tools

The regional travel and environmental impacts of development at each site were modeled using each locality's regional four-step travel demand model, together with INDEX, a regional and site-level Geographic Information System (GIS)-based tool used to measure the built environment and indicators of its performance. The four-step model provided basic transportation system performance indicators, some of which then became inputs for the GIS model. INDEX generated travel-related site design and environmental performance indicators. Local planning officials in each region provided infrastructure cost estimates.

Four-step travel demand models

"Four-step" travel demand models are widely used to forecast roadway and transit volumes across transportation networks. These models use local data for:

1. Trip generation: Estimate the total number of trips produced by households and total trips attracted by employment centers, recreational facilities, etc.

2. Trip distribution: Allocate trips generated in the first step to specific origin-destination movements.

3. Mode split: Estimate the share of trips made by mode of travel (auto, transit, walk, etc.)

4. Traffic assignment: Estimate volumes for each link the transportation system.

Model inputs include data on local transportation patterns, the transportation behavior of residents, and roadway and transit networks. Relevant model outputs include trips by purpose, mode, and travel times.

Each region in the study — San Diego, Montgomery County, and West Palm Beach — has a region-specific four-step model that it uses for long-range transportation planning. These models were used to analyze each region's pair of sites. Each model was run twice, once with inputs representing the existing region plus a developed infill site, and a second time with inputs representing the existing region plus a developed greenfield site. Each run produced different regional travel forecasts. The results then were compared. The highlights of the resulting variations in expected vehicle miles traveled (VMT), transit use, travel times and other measures are summarized in Section 4. Detailed results are presented in Appendices A, B, and C.

Because four-step models are customized to regional needs and capabilities, model sophistication varies widely from region to region. Of the three used in this study, the San Diego model is the most complex, and is regarded as one of the nation's most sophisticated travel demand models. The Florida model is less complex, while the Montgomery County model falls in between. For example, the San Diego travel demand model feeds travel times from the traffic assignment step back to the trip distribution step, helping to model traveler response to congestion. The Montgomery County model has similar feedbacks, but the South Florida model does not. Several significant advanced features of the San Diego model relevant to this study are discussed in the San Diego case section, on page 6.

INDEX model

While the four-step regional models were used to assess regional travel outcomes, INDEX, a GIS-based modeling tool, was used to analyze the performance of the infill and greenfield sites at the neighborhood level. INDEX was used to analyze local characteristics that affect travel such as density, transit accessibility, number of stores and other destinations within walking distance of homes, and other characteristics of the site's design. INDEX was also used to model the energy use and emissions impacts of the transportation system using outputs from the four-step model.

A. Site Design Characteristics: The site design for each hypothetical development was developed, in a GIS environment, to be consistent with existing local development patterns. Designs were developed using geographic information about each site from local planning staff as well as information about similar development within the area.

B. Energy and Emissions Impacts: INDEX calculated travel-related energy use and emissions based on travel outputs from the relevant four-step model. To calculate energy use, a per-mile energy use rate was applied to each mode of travel. To calculate tailpipe emissions, INDEX applied a separate per-mile emissions rate to the auto and transit trips. Auto trips also received a trip-based emission factor to represent typical "cold start" and "hot soak" emissions that occur at the beginning and end of each vehicle trip regardless of distance traveled.[2]

After trip starts and lengths, the most important determinant of travel emissions is trip speed. In general, graphs of emissions-per-mile versus speed are U-shaped, with higher per-mile emissions at low and high speeds, and relatively lower per-mile emissions at moderate speeds.

In order to avoid overstating the emissions benefits of the infill site, where average speeds tend to be slower, a 15% higher emission factor was used for the infill sites. This was a conservative weighting in favor of the greenfield sites. (See further discussion in the Technical Appendix.)

Infrastructure costs

Rather than modeling infrastructure costs, EPA asked local officials to estimate the costs of necessary public infrastructure for each site. Private infrastructure costs were not examined in this study. The only private costs examined were the personal per-mile costs of driving, which include vehicle depreciation and operating costs.

In not estimating private infrastructure costs, we do not minimize their importance. However, unlike the other measures on which this analysis focuses, private infrastructure costs have been investigated elsewhere for infill and greenfield development.

[2] Both per-mile and trip-end emissions factors were developed by Criterion and SANDAG during a previous Criterion contract with SANDAG, and updated as part of this study. The official EPA emissions model, MOBILE 5, takes a more complex approach to quantifying the individual determinants of auto emissions, including varying emissions by the age of the local fleet. These factors were taken into account when SANDAG and Criterion developed the simplified emissions factors. SANDAG considers them robust enough to use in lieu of a full MOBILE 5 run (except when making regulatory submissions). For more discussion, please see the Technical Appendix.

4. Study Areas and Site Pairs

Each regional analysis examined a development project with a different mix of land uses. Table 4.1 summarizes these.

Table 4.1: Land Uses Modeled by Case Study Location

Case Study Location	*Land Uses Modeled*
San Diego	*Office/light industrial/commercial/residential*
Montgomery County	*Residential*
West Palm Beach	*Retail/hotel/residential*

Case Study One – San Diego, California

Case study one analyzed the relative impacts of regionally central versus regionally peripheral development in the San Diego region. This case study was coordinated with staff at the San Diego Association of Governments (SANDAG). San Diego has both a rapidly growing urban periphery and a central business district (CBD) that is a regional activity center.

San Diego methodology details

SANDAG uses the transportation planning model Tranplan, developed by the Urban Analysis Group. San Diego's model is one of the most advanced four-step transportation models in the United States, a judgment confirmed by the modelers on the evaluation panel for this report. Three San Diego model features were valuable to this study: its high resolution, its ability to model congestion, and its land use-specific trip generation rates.

A. High level of detail: SANDAG's model includes 4,545 regional analysis zones, 10 trip types, and 80 land use categories to which trips are distributed using separate trip attraction rates. This level of detail helped to more accurately model the impact of a development project that is a fairly small addition to the region's built environment.

B. Sophisticated feedback mechanism: The San Diego model takes a sophisticated approach to modeling traveler response to congestion. A basic four-step model determines trip distribution and mode split based on travel time, yet definitive estimates of travel time are not available until the end of the travel modeling process — after the completion of traffic assignments. The SANDAG travel model resolves this inconsistency by feeding travel times from the traffic assignment step back to trip distribution. This feedback loop helps model traveler response to congestion. Since a major concern about infill development is that travel in town often occurs under more congested conditions, it was useful to have the model handle congestion in an advanced way.

The SANDAG model also incorporates time-of-day sub-modeling, and detailed transit treatment.[3] The time-of-day factoring is especially sophisticated in that it calculates trips by time of day

[3] SANDAG can turn on different parts of its model to get different levels of output detail. For this study, SANDAG ran the second-stage (most advanced) analysis.

according to both trip type and land use. As a result, not only will more work trips be expected during rush hour, but they will also be expected to be associated with work trip-generating and work-trip attracting land uses.

C. Land use-specific trip generation rates: The San Diego model uses land use-specific trip generation rates. Recent studies have found that trip generation can be affected by urban design and form as well as by travel times and costs. Since the study compares not only different locations, but also the urban/suburban designs in which the sites are located, the design effect may be important. San Diego's survey data show, and its model thus generates, more total trips from urban parcels such as the studied infill site; the additional trips are almost all non-auto. (San Diego is the only model of the three used that varies trip generation rates by land use.)

San Diego infill site

Figure 4.1 shows the San Diego neighborhood where infill was simulated. Five miles east of downtown San Diego, it had already been chosen for a previous SANDAG brownfield redevelopment study on the basis of its inner city location, the availability of abandoned industrial land suitable for redevelopment, and the presence of infrastructure available to accommodate redevelopment. The 300-acre mixed-use neighborhood contains single and multiple-family dwellings, small retail stores, an elementary school, churches, and various community services. Given San Diego's interest in redeveloping portions of the neighborhood and the community's expressed decisions about redevelopment, it was realistic to assume that the modeled development is feasible. The neighborhood's 300 acres are divided among roughly 1,000 parcels. Of this total, about 77 acres, or 200 parcels, were used to accommodate the hypothetical development. The 200 parcels are located at dispersed points across the site at appropriate densities given existing development.

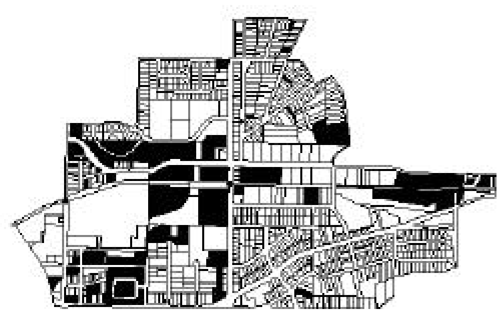

Figure 4.1 San Diego Infill Site
Infilled parcels highlighted. (Maps not to same scale.)

San Diego greenfield site

Figure 4.2 shows the San Diego greenfield site. The 160-acre greenfield site is located 15 miles north of San Diego's CBD and was selected because of its location in one of San Diego's highest-growth areas. The site is at the edge of existing suburban development in an area dominated by low-density, single-family dwellings, with limited amounts of strip-style retail and other commercial use. SANDAG recommended using this site as the basis for the analysis because San Diego's growth management plan gives priority to the site's development relative to other sites

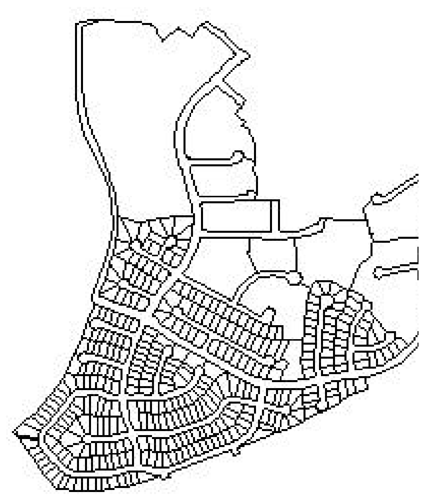

Figure 4.2: San Diego Greenfield Site

in the region. San Diego has a highly structured growth management system that designates the "next" development areas, and this site was designated as a "priority one" area.

San Diego hypothetical development project

The new development project designed for both sites was modeled on an existing SANDAG study carried out for the selected infill neighborhood as part of a brownfield study that determined public preferences for development types and quantities. The resulting scenario for both sites included a mix of housing, commercial, and educational uses, shown in Table 4.2.

Table 4.2: San Diego Development Project

Land use Type	Quantity
Residential	350 dwelling units
Low-rise office	262,500 sq. ft.
Light industrial	622,000 sq. ft.
Neighborhood commercial	204,200 sq. ft.
Strip commercial	10,000 sq. ft.
Postal distribution	80,000 sq. ft.
Vocational education	135,000 sq. ft.

These uses were placed on the infill and greenfield sites in designs and densities consistent with the dominant development pattern of each area. Thus, the greenfield development site design was at a lower density than the infill site and matched the density of surrounding development. Conversely, the infill was at a density matching the surrounding urban neighborhood and occupied fewer acres than the greenfield development.

Case Study Two – Montgomery County, Maryland

Case study two analyzed the relative impacts of regionally central versus regionally peripheral development in Montgomery County, Maryland. Expected impacts of development in Silver Spring, a first-ring suburb of Washington, DC, were compared with expected impacts of a greenfield development in Clarksburg, in northern Montgomery County. Silver Spring has excellent transit access, extensive office development surrounding a Metrorail station, and a CBD with considerable redevelopment potential. Clarksburg is a designated growth area on the urban fringe. The case study was coordinated with staff from the Montgomery County Department of Parks and Planning (MCDPP), Transportation Planning Division.

Montgomery County Methodology Details

MCDPP's travel planning model Travel/2 was used. Travel/2 is a companion version of the widely used EMME/2 four-step model. MCDPP's model is less sophisticated than the SANDAG model used in the San Diego case study. However, Travel/2 is in the upper tier of four-step models in the U.S., according to modelers on the evaluation panel for this study. Unlike many four-step models, Travel/2 has feedback loops that modify destination, route, and mode choices based on travel time.

Montgomery County infill site

Figure 4.3 shows the Montgomery County neighborhood where infill development was simulated. The dispersed site covers several parcels within Silver Spring's CBD. The parcels were chosen by MCDPP staff based on the parcels' CBD location, whether the parcels' size made them suitable for redevelopment, and the presence of infrastructure available to accommodate redevelopment. County staff selected six development sites totaling 24 acres based on redevelopment designations in the local land-use plan.

Figure 4.3 Montgomery County Infill Site
Infill parcels highlighted.

Montgomery County greenfield site

Figure 4.4 shows the Montgomery County greenfield site. MCDPP planning staff recommended the 365-acre site near Clarksburg based on its location in one of the region's prime growth areas, approximately 20 miles north of the Silver Spring CBD. It is situated at the edge of existing suburban development in an area dominated by low-density, single-family dwellings and surrounding agricultural land and open space. The 365 acres are part of a larger area for which Montgomery County has completed a master plan for continued suburban development.

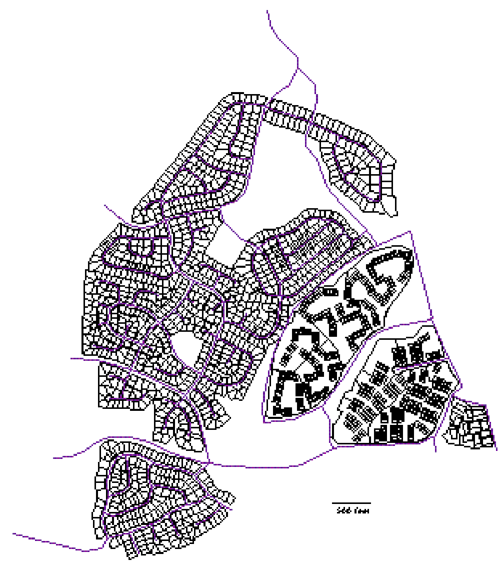

Figure 4.4 Montgomery County Greenfield Site

Montgomery County hypothetical project development

The development project for the Silver Spring and Clarksburg sites consisted of 2,000 dwelling units divided into various residential types as summarized in Table 4.3. In each case, the 2,000 units are estimated to house 5,740 residents. Although the densities were much higher for the infill development, dwellings in each development would have essentially comparable amounts of living space.[4]

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[4] Since the modeling was completed, ground has been broken on several Silver Spring infill projects, including the Cameron Hill residential development, and the 740,000 square foot Silver Triangle retail and office project. The residences are selling before construction, and Silver Triangle has numerous occupancy commitments, including the 1,100 employees at Discovery Communications. Although this mix is different than that modeled, the success of the retail, office, and residential components of the current development suggests the potential for all kinds of development in Silver Spring.

Table 4.3: Montgomery County Development Project

Greenfield	***Infill***
55% Single family detached	*4% Ground-level multifamily*
35% Single family attached	*21% Low-rise multifamily*
10% Ground-oriented multifamily	*75% High-rise multifamily*

As in San Diego, these uses were placed on the infill and greenfield sites in designs and densities consistent with the dominant development pattern of each area.

Case Study Three – West Palm Beach, Florida

Case study three was coordinated with staff from Palm Beach County, the City of West Palm Beach, and Florida International University. An infill site located about half a mile west of the city's CBD was compared to a greenfield site about ten miles west of the city center that was recently approved for a regional shopping center and mixed-use project.

West Palm Beach methodology details

The Florida Standard Urban Transportation Modeling System (FSUTMS) was used to calculate travel behavior and development impacts at the two selected West Palm Beach sites. FSUTMS was run with the assistance of Reid Ewing at Florida International University. INDEX was used to calculate all other statistics such as measures of travel choice and land use impacts. Estimates of infrastructure costs were not available for the West Palm Beach case study.

West Palm Beach infill site

Figure 4.5 shows the West Palm Beach infill and greenfield site locations. The 162-acre infill site is located approximately half a mile west of the city’s CBD and was selected in coordination with City of West Palm Beach planning staff.

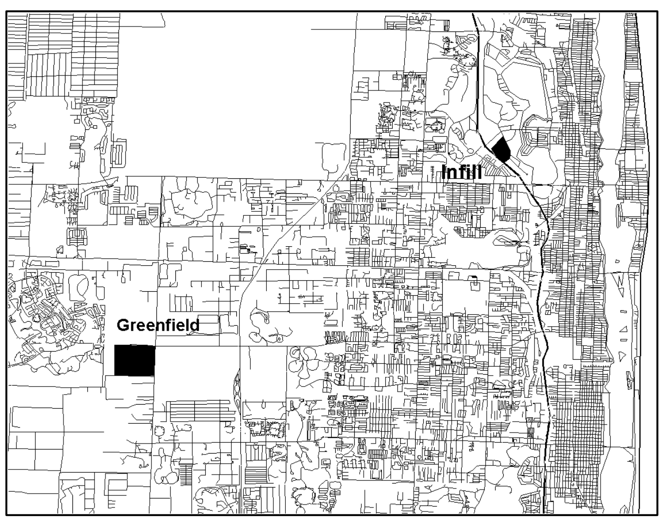

Figure 4.5: West Palm Beach Sites

The infill location is composed of two parts: an existing 72-acre retail shopping center and an adjacent 90-acre vacant site. Using the existing shopping center as part of the modeled new infill development was necessary to ensure a fair comparison with the large greenfield project, which includes a new regional shopping center.

West Palm Beach greenfield site

The greenfield site was selected in consultation with Palm Beach County planning staff. It is a 488-acre site located about ten miles west of the city center.

West Palm Beach hypothetical development project

The greenfield site was selected because it is the location of a recently approved regional shopping center and mixed-use project consisting of 19 million sq. ft. of retail; 65,000 sq. ft. of office, a 125-room hotel, and 400 units of multi-family housing. This approved, but not yet constructed, project was used as the case study's hypothetical development scenario.

Table 4.4: West Palm Beach Development Project

Land Use Type	*Quantity*
Retail	*1,900,000 sq. ft*
Office	*65,000 sq. ft*
Hotel	*125 rooms*
Multi-family housing	*400 units*

As in the other two cases, these uses were placed on the infill and greenfield sites in designs and densities consistent with the dominant development pattern of each area.

5. Results

In general, the results show that, in comparison with the greenfield alternative, the infill development would:

- cut travel time
- increase non-auto mode shares
- reduce air pollutant emissions and loss of open space
- lower travel and infrastructure costs
- improve measures of community quality of life.

Because each case study represents a unique region, development, and model combination, comparisons across regions or extrapolations to other areas should be made with caution.

Case Study One – San Diego, California

Highlights:

- ***Travel would be more convenient and cheaper with the infill site.***
- ***Public infrastructure expenditures would be lower for the infill site.***
- ***Environmental impacts would be lower with the infill site.***

This summary of the results for the San Diego case study is based on outputs from SANDAG's transportation model and the INDEX community indicators model. Full results are presented in tables in Appendix A (San Diego Performance Indicators). The expected impacts of development at the two sites differ in the following ways:

Travel would be more convenient and cheaper with the infill site

- Average drive-alone trip times from the infill site would be 48% less.
- Congestion (driving in Level of Service F[5]) would be 75% lower within one mile of the infill site.
- Average travel costs would be 42% lower with the infill site.
- Per capita vehicle miles traveled would be 48% lower.
- Auto use as a percentage of all trips would be 11% lower.

Autos would continue to be the dominant mode of transportation with both the infill and greenfield sites. The use of other modes, however, would be considerably higher with the infill site than the greenfield site: 13% of trips are made by transit/bike/walking at the infill site compared to 2% of

[5] Highest level of congestion

trips at the greenfield site. While SANDAG's model predicted that average drive-alone travel speeds would be somewhat slower at the infill site during off-peak travel times, total travel time would be considerably lower at the infill site and vicinity congestion would be much lower.

The predicted travel time advantage for the San Diego infill site is primarily the result of shorter average trip distances expected with the infill site. The infill site creates shorter trips because more destinations are located within the immediate neighborhood. Those located outside the neighborhood also tend to be closer to the regionally central site. Shorter trips produce fewer vehicle miles traveled (VMT) and reduce household travel costs. Congestion is expected to be lower in part because of lower overall VMT, but also because the infill site's grid-based street pattern is better able to handle congestion by diverting traffic onto a wide array of alternate routes. In contrast, the greenfield site uses a collector system that funnels traffic onto a handful of main arteries that become congested at peak times.

Public infrastructure costs would be much lower at the infill site

- Infrastructure costs per dwelling would be 90% lower at the infill site.

The public infrastructure costs associated with the San Diego infill site would be considerably less than those at the greenfield site because almost all of the necessary infrastructure already exists, is under-used, and can absorb additional demand. The infrastructure needs anticipated for the infill site are street and sidewalk improvements, estimated to cost less than $1 million. In contrast, the greenfield site would require new sewer, water, sidewalk, and road infrastructure at an estimated cost of between $5 to $8 million. Depending on local agreements, some portion might be borne by developers. The lowest portion of the greenfield costs that could be borne by the public, for trunk infrastructure,[6] would be at least $4 million more than the infill site. In that case, private non-building infrastructure costs associated with the greenfield would be $3 million, versus essentially nothing for the infill site.

In addition to infrastructure costs, many analysts now calculate a measure of "social costs," which include costs of air pollution and other environmental externalities. Infill site vehicle travel externality costs would be 48% less than with the greenfield site.[7]

Environmental impacts would be lower with the infill site

- The infill site does not use open space, saving 160 acres of open space compared to the greenfield site.
- Greenhouse gas emissions with the infill site would be 48% lower.

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[6] Trunk infrastructure includes any sewer, water, wastewater, or transportation infrastructure that serves more than just individual properties.
[7] An estimated external social cost of 27.9¢ per VMT, developed by DeCorla-Souza at the Federal Highway Administration, was used. Note that the important result is the difference between the two sites, not the absolute level of externality cost per VMT. Numerous studies have estimated these costs. Essentially all agree that they are positive. If one believes that there are external social costs to driving, then the infill site imposes about half as many.

- Ozone (smog) precursor emissions of NO_x and VOC at the infill site would be 51% and 43% lower, respectively.

The environmental impacts of the San Diego infill site would all be lower than those at the greenfield site.

Multi-modal orientation and community accessibility would be higher at the infill site

- Neighborhood “completeness” of services and amenities would be 108% higher.
- Transit-oriented residential and employment density would be 77% and 12% higher, respectively.
- Bicycle network connectivity would be 61% higher.

These indicators measure both the transportation choices available and some of the factors that determine whether those choices are exercised. As such, they are inputs to the performance of the transportation system. The measures allow one to evaluate which site would produce a more “accessible” environment for residents and employees. For example, “neighborhood completeness” measures whether shops, recreation, schools, and other neighborhood destinations are present in the neighborhood—that is, accessible. This factor affects travel choices and also is a measure of accessibility. Accessibility is one factor in a neighborhood’s quality of life.

The question of urban design was not central to the study. The study’s goal was to compare development that differed only in its location, but was otherwise as similar as possible. However, community accessibility results are different, and favor the infill site. This is a product of the infill site’s location amidst existing destinations, near to transit, and on a pedestrian and bicycle-friendly street grid. The result is not a product of designing the infill to be more accessible than the greenfield.

Transportation and environmental factors only partially determine community quality of life. The overall quality of life in a community is difficult to quantify. In a sense, all of the performance indicators in this study, including congestion and travel time, affect community quality of life. Indicators such as transit-oriented residential and employment density as well as transit service density measure how easy it is for those without an automobile to access employment and housing options. Neighborhood completeness measures the extent to which the neighborhood contains common destinations. Bicycle network connectivity measures ease of access by bicycle.

In general, the infill site performs significantly better than the greenfield site for most access and other performance measures that affect community quality of life.

Case Study Two – Montgomery County, Maryland

Highlights:

- ***Vehicle miles traveled would fall with the infill site, but congestion would increase.***
- ***Public infrastructure and household travel costs would be much lower with the infill site.***
- ***Environmental impacts would be lower with the infill site.***

This summary of the results for the Montgomery County case study is based on performance indicator outputs from MCDPP's Travel/2 transportation model and the INDEX community indicators model. The full set of results is presented in tables in Appendix B (Montgomery County — Performance Indicators).

Montgomery County's infill site performed better than the greenfield in most indicators. However, the results were more mixed than those in the other two case studies. The expected impacts of development at the two sites differ in the following ways.

Travel would be more congested, but cheaper, and VMT would be lower with the infill site

- Average VMT per capita would be 58% lower with the infill site.
- Infill vicinity congestion would be 1114% of that at the greenfield site.
- Average household travel costs would be 54% lower at the infill site.

The Silver Spring infill site and vicinity would experience considerable congestion, while the greenfield site and vicinity would experience very little. However, the large increase in the infill congestion measure may overstate the likely change. Average peak auto speeds average 25 miles/hour. Thus, despite an over 1000% increase in the number of vehicle miles experiencing congested conditions, the model does not predict gridlock. Rather, the large change in the congestion measure appears to be a function of the measurement approach, in which a given vehicle mile traveled either experiences congested conditions or does not. The additional vicinity traffic appears to push to the "congested" level many vehicle miles of travel that were already close to it. Infill VMT per capita is less than half of greenfield per capita VMT. The net effect on average travel times is difficult to discern, as the Montgomery County model did not report a single average trip time measure. Rather, the model reported travel times from each site to the top-ten regional trip attractors, weighted by mode. Travel time from the infill site to six of ten attractors was less than from the greenfield site.

The lower VMT per capita would make travel costs per household significantly lower at the infill site. Mode shifts to transit are anticipated to be quite significant at this infill site, much more so than in either of the other two site pairs. Mode shifts would result in part because of substantially higher transit accessibility at the infill site.

Public infrastructure costs would be lower at the infill site

- Infrastructure costs per dwelling would be 92% lower at the infill site.

The Montgomery County infrastructure cost estimates are based in part on a recent cost of service study for the greenfield site only, and are thought to be more accurate than those quoted for San Diego. As in San Diego, the results suggest that infrastructure costs are much lower at the infill site, primarily because most public infrastructure for the infill site already exists and can absorb additional demand. Total infill site infrastructure costs would be $2.5 million compared to $33 million for infrastructure at the greenfield site.

Environmental impacts would be lower at the infill site

- The infill site does not use open space, saving 365 acres of open space compared to the greenfield site.
- Greenhouse gas emissions at the infill site would be 49% lower.
- Ozone (smog) precursor emissions of NO_x and VOC at the infill site would be 46% and 52% lower, respectively.

Multi-modal orientation and community accessibility would be higher at the infill site

- Infill transit-oriented residential density would be 1,035% higher.
- Infill transit service density would be 127,900% higher.

The large percentage increases are a function of the low amount of service at the greenfield site. Extremely large percentage increases such as this are less important for their actual magnitude than as an indication that the sites are fundamentally different in character.

In measures of access to non-auto modes, the infill site outperforms the greenfield site. Greater land use density and diversity at the infill site would make the transit there more effective. Better street connectivity for pedestrians creates greater accessibility to shopping and employment.

Case Study Three – West Palm Beach, Florida

Highlights:

- ***Travel would be more convenient and cheaper at the infill site.***
- ***Environmental impacts would be lower at the infill site.***

This summary of results for the West Palm Beach case study is based on performance indicator outputs from the Florida Standard Urban Transportation Modeling System (FSUTMS) and the INDEX community indicators model. The full set of results is presented in tables in Appendix C (West Palm Beach, Florida — Performance Indicators).

As in the previous case studies, the West Palm Beach case study found that the infill site would generally be expected to perform better.

Travel would be more convenient and cheaper with the infill site

- Average drive-alone trip travel time would be 32% lower at the infill site.
- Average per capita VMT would be 61% lower at the infill site.
- Congestion would be the same at both sites.
- Average household travel costs would be 58% lower at the infill site.

Both West Palm Beach sites would experience some congestion. However, the infill site shows considerably lower per capita VMT and lower overall trip travel times. In turn, household travel costs are lower for the infill site.

Environmental impacts would be lower with the infill site

- Open space loss at the infill site would be 73% lower.
- Greenhouse gas emissions at the infill site would be 52% lower.
- Ozone (smog) precursor emissions of NO_x and VOC at the infill site would be 50% and 54% lower, respectively.

Multi-modal orientation and community accessibility would be greater at the infill site

- Infill pedestrian network connectivity would be 100% greater.
- Infill neighborhood completeness would be 54% greater.

By almost all indicators, West Palm Beach’s infill site outperforms the greenfield site.

6. Summary and Conclusions

The highlighted results of each case study are summarized in Table 6.1, which compares the impact of infill development to greenfield development across key performance indicators. This table compares the results from each region's full model runs.

For each site pair, modeling predicted that the infill site would outperform the greenfield site in six important performance dimensions:

- Average trip distance: generally shorter with the infill site.
- Per capita vehicle miles traveled: generally fewer with the infill site.
- Travel time: generally shorter with the infill site.
- Public infrastructure and household travel costs: lower with the infill site.
- Environmental impacts, including emissions: smaller with the infill site.[8]
- Multi-modal orientation, and access to community amenities and transportation choices: greater at the infill site.

In these three cases, infill benefits appear to be a function of conditions that include existing congestion levels, and regional and local accessibility to activities from the infill sites.

These case studies suggest that identifying public benefits from infill does not require using a particular level of travel model sophistication. In these case studies, the transportation effects of even moderately sized alternative development patterns were not so subtle that one needs a highly sophisticated model to identify them. We did not test whether more sophisticated models produce more accurate estimate of benefits.

The cases suggest that, although not a panacea, in the right conditions, infill development can make travel more convenient by reducing travel time, lowering travel costs, and lessening congestion. Infill development can also cost significantly less, in total public dollars, in private transportation dollars, and in externalities. Finally, the results suggest that infill development can improve community environmental quality and inputs to quality of life such as accessibility. This study concludes that infill *can* produce non-trivial transportation, environmental, and public infrastructure cost benefits.

The predicted benefits are large enough to suggest that communities may productively investigate whether infill should be considered as one component of a strategy to accommodate growth and

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[8] The emissions measures include both auto and transit emissions to the extent that regional models supported transit emission modeling. Because the three models and developments vary significantly in their use and treatment of transit, some reviewers asked whether EPA could present results that might appear more comparable across case studies, such as reduction in auto emissions alone. This study's primary goal was not to draw generalizable conclusions about the magnitude of impacts from infill versus greenfield development decisions, and so does not present auto-only results. We note that transit emissions widen the total difference between auto-only infill and greenfields emissions in Montgomery County and West Palm Beach slightly, and narrow it slightly in San Diego. The general VMT and emissions outperformance of the infill sites did not change.

meet future transportation needs. Likewise, federal and state agencies, which share responsibility with communities for providing efficient transportation services and environmental protection, may also find it productive to ensure that federal and state policies allow infill where it has a place in communities' transportation and growth strategies.

Table 6.1 Infill Development Produces…

	Per capita VMT	Travel time	Vicinity congestion	NO_x emissions	CO_2 emissions	Infrastructure costs	Household travel cost
San Diego	52% of greenfield	Auto: 50-52% of greenfield Transit: 39-102% of greenfield	24% of greenfield	49% of greenfield	52% of greenfield	10% of greenfield	58% of greenfield
Montgomery County	42% of greenfield	Auto: 95-285% of greenfield Transit: 27-84% of greenfield	1114% of greenfield	54% of greenfield	51% of greenfield	8% of greenfield	46% of greenfield
West Palm Beach	39% of greenfield	Auto: 68% Transit: n.a.	99.8% of greenfield	50% of greenfield	48% of greenfield	n.a.	42% of greenfield

Technical Appendix

This appendix contains additional technical detail and discussions.

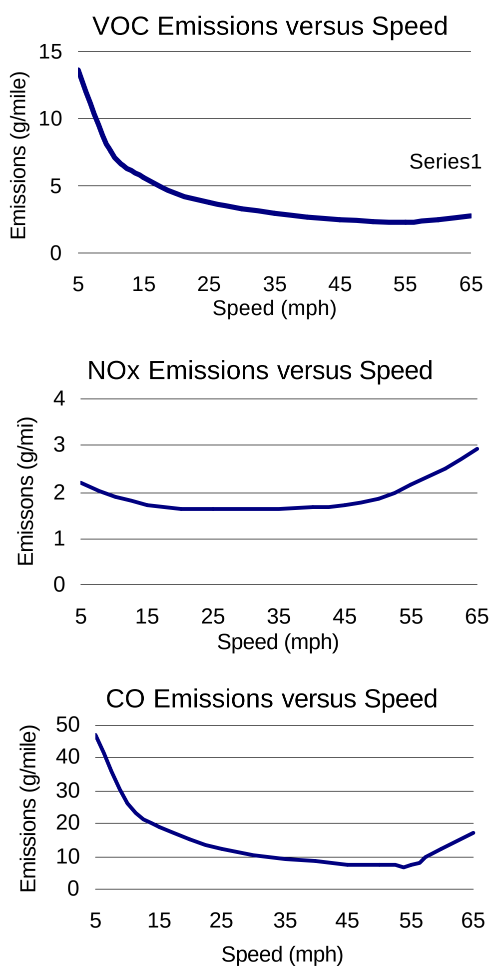
Emissions

Criteria emissions factors

Criterion's criteria pollutant emissions factors are based on CARB EMFAC 7F 1.1, using California statewide fleet averages for light duty vehicles, medium duty vehicles, and motorcycles in 1995. The VOC and NO_x factors are for summer, and the CO is from winter. Using these factors, Criterion established composite trip-end and VMT factors. The trip-end factors are (cold starts + hot starts + soaks)/total trips. The VMT factors are (running exhaust + running losses)/VMT. The case study analyses used both trip-end and VMT factors.

Criterion developed these emissions factors to facilitate precisely the kind of analysis done in this study. The composite factors do not capture the full complexity of MOBILE or EMFAC runs, but do capture the important determinants of fleet emissions, and do give a robust estimate of the likely emissions impacts of policy options, at low cost.

Figure A.1. Emissions vs. speed



Although the use of California emission factors in the two case study locations outside California is not ideal, its main impact on the results is on the absolute level of the estimates, rather than on the relative performance. Because the study investigates relative performance, there is no reason to believe that the results are not robust relative to each other, or that the use of Criterion's composite factors biases the results in favor of one site or another.

Variation of emissions factors with speed

Emissions versus speed graphs are generally U-shaped. Figure A.1 shows emissions per mile in the EPA's MOBILE 5 emissions model. Any vehicle has an operating speed at which emissions are as low as possible for that vehicle. Above or below that speed, emissions increase. Given emissions that change with speed, a fully comprehensive assessment would have used speed-sensitive emissions rates to account for the effects of higher per-mile emissions in congested or high-speed travel. Speed-sensitive emission rates would be relevant in this case because the various sites are expected to generate various levels of congestion.

Thus, there is a possibility that the emissions we have forecast may deviate somewhat from those actually generated by the expected development. The magnitude of the potential deviation is related to the shape of the emission curves.

Although the emission factors we used do not vary with speed, they have been found by SANDAG to capture well the emissions of the average trip in analyses such as those performed in this study. To minimize the risk of overstating emissions impacts due to greenfield development, we assumed that faster, exurban traffic emitted fewer emissions per mile than in-town traffic. We did this by reducing SANDAG's emissions factors for exurban traffic by 15% per mile for all criteria pollutants (that is, all pollutants other than CO_2).

This is a conservative approach (that is, it favors the greenfield site) because it gives an advantage only to greenfield travel, while two conditions of infill travel—at opposite ends of the speed/ emissions curve—would also give an advantage to infill in a full accounting. First, congestion is found around both infill and greenfield sites; some greenfield sites also see severe stop-and-go congestion and thus slow-speed emissions. Second, the higher speeds of some greenfield-based trips, once past the congestion, are far enough past the low point on the speed/emissions curve that a speed penalty should be applied.

Effects on emissions

The 15% advantage given to the greenfield developments in fact appears adequate—and more than adequate in the case of NO_x—to account for any actual advantage. The average speeds associated with the infill and greenfield sites are not, in most cases, different enough to move a substantial distance along the speed/emissions curve.

NO_x

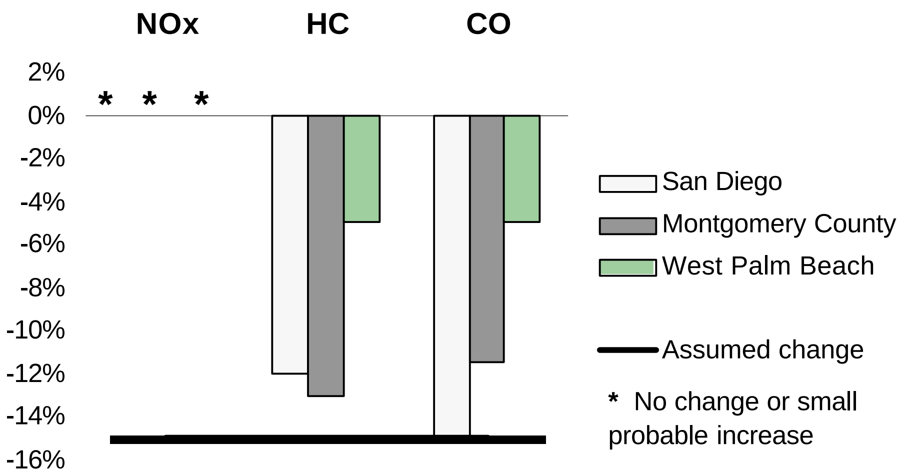
In San Diego, the average auto speed from the greenfield is predicted to be 32 mph, 6 miles an hour faster than from the infill site. But in moving from 26 mph to 32 mph, the NO_x emissions curve does not rise at all. If the speed profile of the greenfield site shifted uniformly to faster speeds, then the 15% emissions advantage applied to the greenfield site is not only unwarranted, but in fact, ignores the fact that more autos will now be emitting in the higher-NO_x part of the speed curve. As Figure A.1 shows, changes between 20 mph and 45 mph do not affect NO_x emissions.

San Diego and West Palm Beach show average speed changes within this range. Montgomery County's splitting out of trips originating and trips terminating complicates matters. Speeds for "trips originating" in both greenfield and infill sites in Montgomery County are on the flat part of the curve. For trips terminating at each site, the average speed for the greenfield is on the rising part of the NO_x curve, and for the infill site, on the flat part of the curve. *Thus, in all cases, the changes in average speed either produce no NO_x advantage for the greenfield site, or produce a NO_x disadvantage.* These average speeds may hide increases in very low speeds on some trips, where NO_x rises. Thus, we cannot say with certainty that the 15% emissions advantage given to the greenfield development is more than enough to account for any slow-speed congestion effects for NO_x in the infill sites. However, it certainly appears to do so.

VOC

The VOC emissions curve is shaped differently, but the 15% benefit given to the greenfield again appears to compensate. On the basis of average speed alone, grams/mile emissions would decrease for the greenfield sites by approximately 12% in San Diego and less than 5% in West Palm Beach. In Montgomery County, greenfield trips terminating would show an approximately 22%

Figure A.2. Speed-based emissions changes: *Likely* disadvantage of infill sites versus the *modeled* disadvantage.



grams/mile average emissions decrease compared to the infill, while trips originating would show change less than 4%, or an average of 13%.

CO

The CO curve looks much like the HC curve, so it is not surprising to find again that the assumed 15% greenfield advantage is adequate. In San Diego, a uniform speed shift would produce a greenfield advantage of 15%, in West Palm Beach, roughly 5%, and in Montgomery County, less than 3% for originating trips and roughly 20% for terminating trips, for a county average of roughly 11.5% percent.

In sum (see Figure A.2), there is little reason to suspect that the simplified approach to modeling the emissions effects of speed changes has biased the results in favor of the infill sites.

Transportation Models

SANDAG's Tranplan model[9]

The study used a transportation planning computer package called Tranplan, developed by the Urban Analysis Group, as adapted and used for all regional transportation planning in San Diego. In addition to the San Diego Association of Governments (SANDAG), users of this model include:

[9] Adapted from SANDAG material.

- Caltrans (freeway planning)
- transit agencies (bus and rail patronage studies)
- local jurisdictions (circulation element studies)
- developers (site-specific impact reports)
- the Air Pollution Control District (vehicle emissions).

Public agency users are also sources of data. The body of this paper briefly describes how SANDAG's adaptation of Tranplan models transportation behavior. Some additional features of the SANDAG model are relevant to this study:

1. Fine-grain detail. SANDAG's last major model refinement took place in 1994. The improvements made include:

- increasing the number of regional analysis zones from 773 to 4,545
- increasing the number of trip types from five to ten
- increasing to 80 the number of land use categories to which trips are distributed using separate trip attraction rates.

2. Feedback through the model. SANDAG can turn on different parts of its model to obtain different levels of output detail. (see Figure A.3). For this study, SANDAG ran the second-stage (advanced) analysis. The second-stage analysis is not usually run. As SANDAG's modeling manual explains:

> First stage applications make use of simplified trip distribution and mode choice procedures. Second-stage applications make use of peak and off-peak period travel times from first-stage highway assignment. These travel times are used to redistribute trips and determine mode choice.
>
> Processing would stop after the first stage for most applications. Federal guidelines for modeling air quality and major investment impacts require more elaborate procedures. These studies would use second-stage transportation models in order to better match transportation demand with transportation supply.

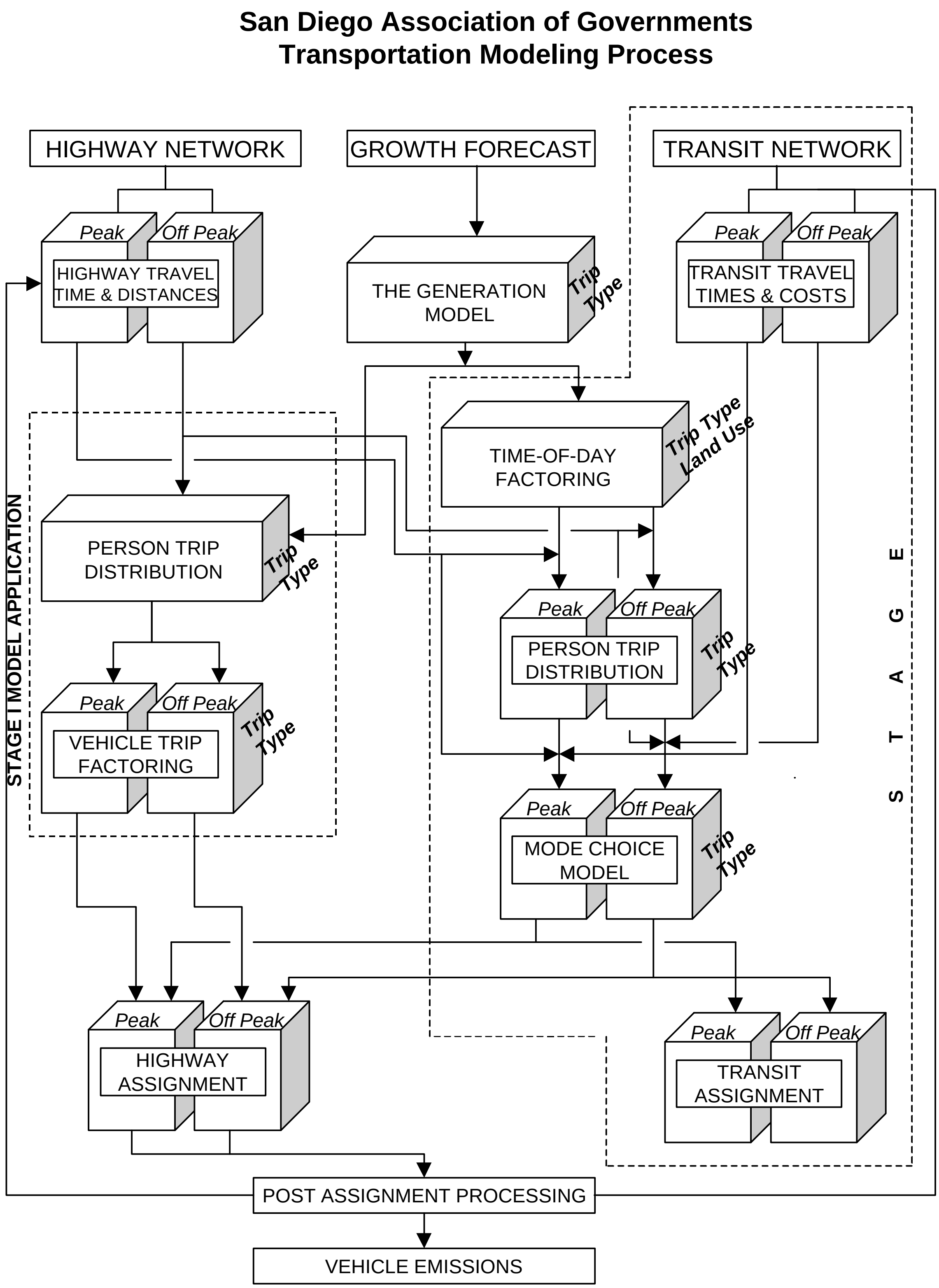
The first stage requires 7.5 hours to run on a Sun SPARC workstation, and the second stage, 20 hours. The computer run times reflect the different level of detail in each stage.

SANDAG's second stage includes a feedback loop from the first stage back to the trip distribution step of the model. This feedback models what happens when travelers encounter congestion—they change their travel plans. Since a major concern about infill development is that travel in town often occurs under more congested conditions, it was useful that the model handled congestion in an advanced way. The feedback improves the accuracy of every output, but is particularly important in improving estimates of congestion and travel responses to congestion.

3. Time-of-day modeling. The second-stage application also adds separate time-of-day sub-modeling, and detailed transit treatment. The time-of-day factoring calculates trips by time of day according to both trip type and land use. So not only will more job trips be made during rush hour, but they will also be associated with job-trip-generating and -attracting land uses.

4. Land-use-specific trip generation rates. The SANDAG model adjusts trip generation rates by land use type. Since the case study compares not only different locations, but also designs appropriate to the different locations, the design effect is important. San Diego's model generates more trips from urban parcels—such as the case study infill sites.

Figure A.3: SANDAG model structure



Montgomery County's TRAVEL/2 model[10]

Several features of Montgomery County's model, TRAVEL/2, deserve mention. TRAVEL/2 uses 292 traffic zones within Montgomery County, with a total of 651 zones in the region modeled. The modeled region covers the area between and including:

- Harford Co. north of Baltimore, MD
- Charles Co., MD and Prince William Co., VA, south of Washington, DC
- Frederick Co., MD, west of Washington, DC.

The estimation and calibration of TRAVEL/2 use data from Washington Metropolitan Council of Governments' Household Travel Survey, Montgomery County Planning Department (MCPD) Trip Generation Studies, the MCPD Census Update, the MCPD Travel Time and Delay Study, Metrorail Passenger Studies, and MCPD Traffic Counts databases.

The following features are relevant to this study.

1. Capture of complex choice making across space and modes. The Washington, DC metropolitan area is a large multi-nucleated metro area in which residents make complex travel decisions involving numerous strong destination centers, including two large central cities, Washington and Baltimore. Residents also choose between a rich set of modes: auto with and without dedicated HOV facilities, bus, heavy rail (subway), light rail, and commuter rail, and non-motorized modes (walking and biking). TRAVEL/2 captures this complex set of decisions in modeling seven single or mixed-mode trip types: walking to transit, driving to transit, receiving a ride to transit, driving alone, traveling in a two-person carpool, traveling in a carpool with three or more persons, and walking or bicycling.

2. Feedback through the model. As shown in Figure A.4, TRAVEL/2 uses an iterative procedure to estimate travel demand, the impact of travel demand on travel time, and the changes in travel demand that result from changed travel times due to congestion. This enables an estimate of demand to influence travel time and vice versa, meaning that the travel time between two points is not fixed in advance and varies depending on the level of congestion on the transportation network under test.

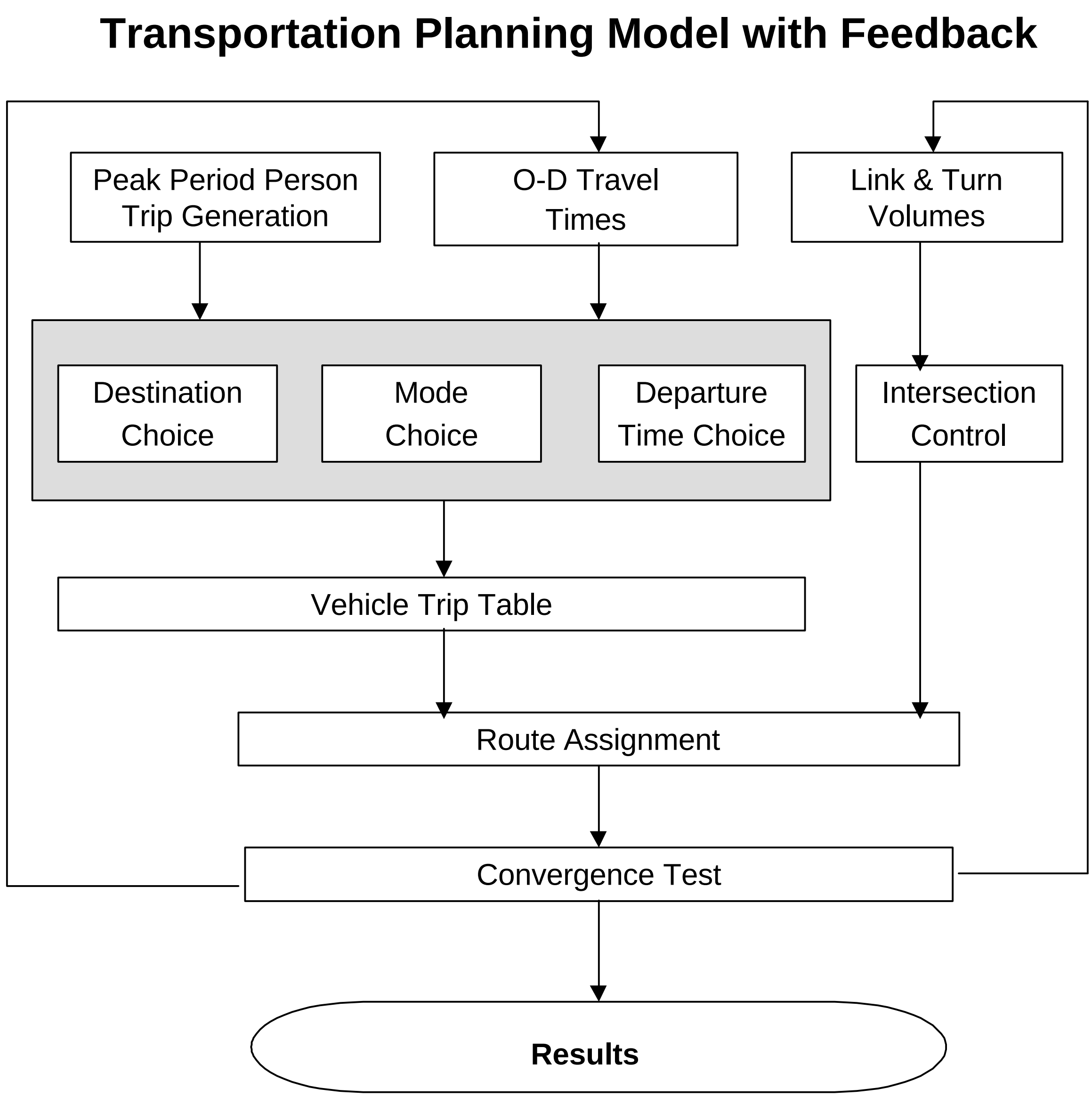
As explained in the San Diego discussion, the feedback loops are particularly useful for this study. Since a major concern about infill development is that travel in town often occurs under more congested conditions, it was useful that the model handled congestion in an advanced way. The feedback improves the accuracy of every output, but is particularly important in improving estimates of congestion and all potential travel responses to congestion.

3. Time-of-day modeling. TRAVEL/2 allows trip making to change by time-of-day. The trip generation process calculates person trip volumes for a three-hour afternoon peak period, but the auto assignment that completes the modeling is for the afternoon peak hour. Departure time, a special feature of the TRAVEL/2 model, uses travel survey data to determine the fraction of

[10] Adapted from Montgomery County Planning Department, Transportation Division, "The TRAVEL/2 Transportation Model."

afternoon trips that will occur during the 4:30 – 5:30 peak hour. As the network becomes more congested, some trips may begin earlier or later to avoid peak hour congestion.

Figure A.4: Montgomery County TRAVEL/2 model structure



The Florida Standard Urban Transportation Modeling Structure

The Florida Standard Urban Transportation Modeling Structure (FSUTMS) is the Florida Department of Transportation's transportation demand modeling tool. It is a reasonably standard four-step model. Like most standard four-step models, FSUTMS uses only household type, household size, and vehicle ownership as the structure variables in the definition of trip generation tables. Thus, it implicitly assumes that geographic locations have no (or insignificant) impact on the trip generation patterns.

Additional Detail on the Analysis Process

The main body of this paper briefly describes the individual analysis steps. This section describes those steps in more detail. We use San Diego terms here, but all three cases followed the same basic steps.

1. SANDAG prepared its Tranplan-based model as it does for its standard model runs.

SANDAG has a standard land use forecast, based on its Regional Growth Plan and internal forecasts. This forecast was the basis for the model run for each site. SANDAG also used the standard transit routes and street networks that it uses for the other transportation planning purposes listed above. As MPO and central modeling office, SANDAG had ready access to these data.

2. SANDAG ran its regional transportation model twice.

The model ran once with the new employment and residences located on, and generating trips from, the infill site, and once with new employment and residences located on, and generating, trips, from the greenfield site. Otherwise, the base regional land use forecast did not change.

A. These runs produced *regional* transportation behavior and resulting VMT, transit use, and other mode shares, congestion measures, travel times, and other travel measures.

B. SANDAG also reported one *vicinity* measure, the vicinity being the area within one mile of the development site boundary. This is the basis of the measure "local congested travel," which measures the percent of vicinity VMT on roads operating at Level of Service F (severe congestion) or worse.

3. Criterion calculated site design performance measures.

Quantifying design characteristics is a fairly straightforward matter of measurement using GIS site information. Criterion obtained GIS coverages for each site from SANDAG, and then filled each site with geographic data describing the developments. Most of the measurement from then on is a straightforward matter of measuring and summing. For example, to measure Employee Transit Proximity (the proportion of site employees within a ¼ mile of a transit stop), INDEX draws a ¼-mile circle around all transit stops. Next it looks at the site's parcel description data to count all the employees in each circle, and then sums. An example of a more complex measurement is that of community land use diversity. Here, INDEX calculates an index of diversity developed by University of California-Berkeley Professor Robert Cervero, which weights parcel diversity by both size and proximity to dissimilar-use parcels. INDEX then uses its GIS capabilities to measure both distances and areas, while looking up parcel uses.

SANDAG gave to Criterion the parcel descriptions for each of the two developments, as well as the area within a mile of the development sites. SANDAG's electronic descriptions of local land use are rich enough that INDEX could measure distances to particular destinations (schools, shopping, etc.) outside the site without having to code those locations into SANDAG's descriptions. Criterion had only to add to them the descriptions for the new development. In the greenfield site, that meant all descriptions, including:

- road and sidewalk alignments and centerline distances
- business and residential locations
- number of employees or residents in each newly-developed building
- parcel descriptions including land uses and shapes.

In the infill site, the roads and sidewalks were already set, so Criterion added business and residential locations for new development among the existing development, and the number of employees or residents in each newly developed building.

Once complete, Criterion used INDEX to measure and rate the land use descriptions for each site on several design characteristics that affect transportation behavior.

Criterion combined the SANDAG travel results (VMT, number of person trips, mode splits) with site residential and employment populations to produce two measures: site VMT/capita and "auto use."

Finally, INDEX calculated the energy use and emissions from the travel behaviors predicted by the SANDAG model. (See the section on emissions factors above.)

Results Appendices

The three four-step models used produced slightly different types of travel statistic outputs. The following detailed results reflect that, and so are not parallel in places.

The detailed results present numerous performance measures not highlighted in the discussion in the main body of the report.