TCRP

REPORT 176

TRANSIT
COOPERATIVE
RESEARCH
PROGRAM

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Quantifying Transit's Impact on GHG Emissions and Energy Use— The Land Use Component

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TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 176

Quantifying Transit's Impact on GHG Emissions and Energy Use— The Land Use Component

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TRANSPORTATION RESEARCH BOARD

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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transportation Association (APTA), Transportation 2000, also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, the National Academies, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended end users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

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The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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FOREWORD

By Dianne S. Schwager
Staff Officer
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TCRP Report 176: Quantifying Transit's Impact on GHG Emissions and Energy Use—The Land Use Component analytically examines the complex interrelationships between transit and land use patterns to better understand their contribution to compact development and the resulting greenhouse gas (GHG) reduction benefits. The report is accompanied by an Excel-based sketch-modeling tool ("calculator tool") that applies the research findings. The calculator tool estimates the land use benefits of existing or planned transit projects with a minimum amount of input data required. This research will be useful to transit agencies, planners, modelers, and researchers seeking to better understand and to quantify the impacts of transit service on compact development, energy use, and air quality in urbanized areas.

This research project was undertaken to (1) identify, describe, and quantify the synergistic interaction between transit and land use and the effects on transportation-related GHG emissions and energy use and (2) develop a methodology to quantify the transportation-related GHG emissions and energy use related to land use changes that can be attributed to transit.

The final report is a concisely written document that

- Presents transit's impact on GHG emissions and energy use, including both the ridership effects and the land use effects;
- Introduces and provides a user's guide to the calculator tool;
- Identifies future research; and
- Includes two technical appendices pertaining to the use of statistical models in this research.

The calculator tool allows the user to estimate the land use benefits of the existing regional transit system, a regional transit plan, a new transit route or improved transit service along an existing corridor, a new transit station or stop, or improved transit service to an existing station or stop. All land use benefits are estimated in terms of reduction in vehicle miles traveled, gasoline consumption reduced, and GHG emissions saved. The calculator tool is posted on the *TCRP Report 176* summary web page of the TRB website and can be accessed at www.TRB.org/main/blurbs/172110.aspx.

CONTENTS

SUMMARY

Quantifying Transit's Impact on GHG Emissions and Energy Use—The Land Use Component

Transportation systems and land use patterns coexist in a complex and ever-evolving "ecosystem." Roads and transit systems are planned and constructed in order to serve homes and businesses, but new homes and businesses also locate where they will have access to existing or planned roads and transit systems.

A growing body of research analyzes the extent to which public transportation systems beget land use changes in the form of more compact development. The evidence is mixed, but favors the theory that public transportation investments can, under the right circumstances, promote more compact development. The TCRP Project H-46 research team calls this phenomenon the *land use effect of transit* (or simply *the land use effect*). (See Figure S1.) Compact development in turn provides a host of environmental and social benefits, including helping to reduce vehicle miles traveled (VMT), fuel use, and greenhouse gas (GHG) emissions. We call these benefits the *land use benefits.* Since land use effects lead to land use benefits, these terms are sometimes used interchangeably.

The land use effect of transit is complementary to, but completely separate from, *the ridership effect of transit* (sometimes referred to as the direct effect of transit), whereby people ride buses and trains instead of driving private vehicles. The land use effect reduces the VMT of non-transit riders by fostering communities where trip distances are shorter and walking and cycling are more attractive options.

There is evidence that the land use benefits of transit are often greater than the benefits generated by transit ridership. This study develops new methods to quantify land use effects and land use benefits using regionally specific inputs.

Research Methodology

The research conducted under TCRP Project H-46 is one of only a handful of research efforts to date to use statistical modeling techniques to determine the size of the land use effect. It is the only research effort to use multiple datasets to analyze and cross-validate the land use effect at multiple geographic scales. Most other research has started with assumptions about the strength of the land use effect in order to quantify land use benefits. Statistical modeling has the advantage of quantifying the magnitude of the land use effect itself, before quantifying land use benefits. In fact, the bulk of this research effort was devoted to analyzing the land use effect.

Using statistical models allowed the research team to isolate particular transit variables that determine the magnitude of the land use effect in a region (such as transit supply and frequency), while controlling for other factors that are correlated with urban land use

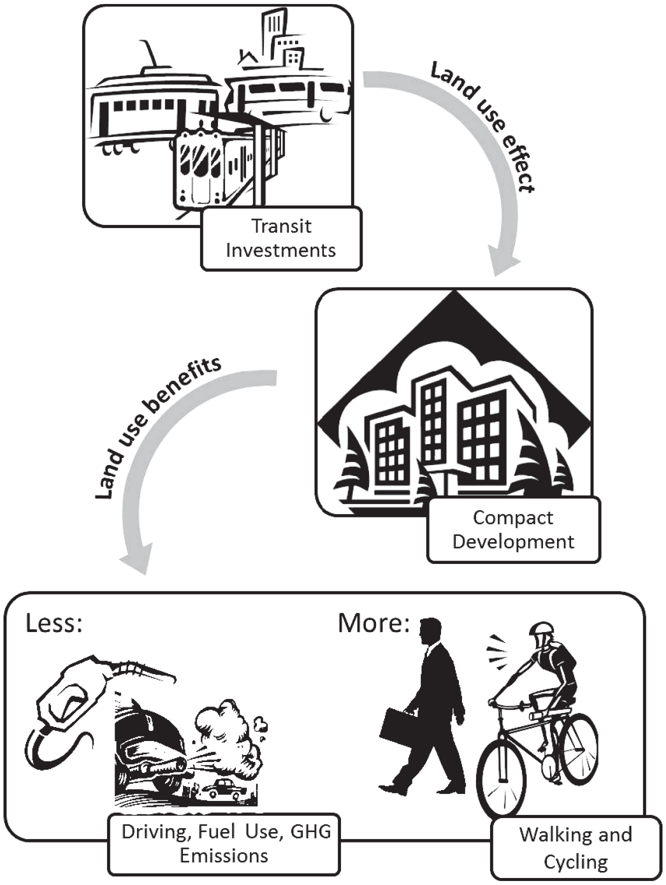

Figure S1. The land use effect of transit.

patterns (such as urban area population size and road supply). Two different datasets were used to conduct statistical analyses at different scales:

- The *urbanized area dataset*, which contains data at a macro scale on more than 300 federal-aid urbanized areas, with boundaries defined by the FHWA.
- The *neighborhood dataset*, which contains data at a micro scale for nine diverse regions in the United States: Austin, Texas; Boston, Massachusetts; Eugene, Oregon; Houston, Texas; Kansas City (Missouri and Kansas); Portland, Oregon; Sacramento, California; Salt Lake City, Utah; and Seattle, Washington (using Metropolitan Planning Organization–defined boundaries).

Research Applicability

This report contains research and findings that will be useful to

- **Transit agencies.** This research can help to quantify the benefits provided by their service and better understand the characteristics of transit service that contribute to more compact development. Land use benefits quantified in this research can be used as a regionally specific alternative to APTA's national level land use multiplier.
- **Planners.** This research can help in considering the likely land use developments associated with planned transit service and key variables that affect development activity.
- **Modelers.** This research can inform elasticities used in land use models.
- **Researchers.** This research can inform future research on the relationship between transit service and land use patterns.

Summary of Key Findings

Key findings of the research include the following:

- **Effect on population densities.** Taking the entire U.S. urban population in aggregate, gross population densities would be lower by 27% without transit systems to support compact development. In other words, U.S. cities would consume 37% more land area in order to house their current populations. The land use effect of existing transit makes U.S. cities more compact.
- **Effect on VMT, fuel use, and transportation GHG.** By providing more walking and biking opportunities and making some journeys by car shorter, the land use effect of transit produces land use benefits: an aggregate 8% decrease in VMT, transportation fuel use, and transportation GHG emissions in U.S. cities.
- **Effect of transit trips replacing automobile trips.** By transporting people on buses and trains who would otherwise travel by automobile, transit systems also produce a complementary ridership effect. In aggregate across U.S. cities, transit ridership reduces VMT, transportation fuel use, and transportation GHG emissions by 2%. This is a substantial change given that only 4% of passenger trips are currently made by transit in U.S. metropolitan areas.
- **The land use benefit of transit.** The land use benefit of transit varies across urban areas, ranging from a 1% to 21% reduction in VMT, transportation fuel use, and transportation GHG emissions compared to a hypothetical scenario without transit. Urban areas with higher route densities of transit, service frequencies of transit, and availability of light rail have higher land use benefits. Not surprisingly, higher land use benefits of transit are generally found in more densely developed areas.
- The land use effect of transit in a given region typically reduces GHG emissions more than the ridership effect. **The average ratio of land use benefits to ridership benefits** across all U.S. cities is 4:1, but the ratio varies substantially across different urban areas.[1]
- Adding a rail station to a neighborhood that did not previously have rail access is associated with a 9% **increase in activity density** (combined population and employment density) within a 1-mile radius of the rail station. The corresponding land use benefit is a 2% reduction in VMT (for households within the 1-mile radius), transportation fuel use, and transportation GHG emissions.
- **Improving employment accessibility**, by clustering new jobs around transit nodes or improving the bus and rail network in individual neighborhoods, can also have potent land use effects.
- An analysis of the Portland Westside light-rail extension found that the **land use effect increased densities** by 24% in the corridor area between 1994 and 2011. These changes correspond to a 6% household VMT reduction due to the land use effect and an additional 8% VMT reduction due to the ridership effect.

Land Use Benefit Calculator

The TCRP Project H-46 research team created the Land Use Benefit Calculator ("the calculator"), an Excel-based sketch-modeling tool, to apply the research findings. The calculator (available at www.TRB.org/main/blurbs/172110.aspx) is designed to allow transit agencies, metropolitan planning organizations, and other interested parties to estimate the land use benefits of their existing or planned transit projects with a minimum amount of input data required.

Specifically, the calculator allows the user to estimate the following:

- The land use benefits of the existing regional transit system.
- The land use benefits of a regional transit plan.

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[1] Complementary ridership effects of transit vary based solely on the level of transit ridership in individual regions.

- The land use benefits of a new transit route or improved transit service along an existing corridor.
- The land use benefits of a new transit station or stop or improved transit service to an existing station or stop.

All land use benefits are estimated in terms of the following metrics:

- VMT reduction.
- Gasoline consumption reduced.
- GHG emissions saved.

Future Research

The following future research on this topic would be useful:

- **Different approaches to measuring density.** Gross population densities, the primary measure used in this research, have a clear relationship to travel patterns. But population-weighted densities may be a better predictor of travel patterns. Calculating population-weighted densities for all urban regions will require a substantial data collection effort.
- **Innovative approaches to accounting for the influence of real estate markets and public support on the land use effect.** These are two of the most important factors in determining whether and how much development occurs around transit. Future research should quantify their impact.
- **Research on methods to match appropriate transit vehicle capacities with current or expected land use patterns.** While using higher capacity vehicles probably would not encourage densification in and of itself, transit agencies would benefit from more information about the correlation between vehicle capacity and land use patterns.

SECTION 1

Introduction

1.1 Research Problem

APTA's *Recommended Practice for Quantifying Greenhouse Gas Emissions from Transit* (2009) describes three categories of emissions displaced by transit and provides methodologies for their quantification:

- Avoided car trips through mode shift from private automobiles to transit (referred to as *the ridership effect* in this research or *the direct effect of transit* in some other studies).
- Congestion relief benefits through improved operating efficiency of private automobiles, including reduced idling and stop-and-go traffic.
- The land use multiplier, through transit enabling denser land use patterns that promote shorter trips, walking and cycling, and reduced car use and ownership (referred to as *the land use effect* in this research or *the indirect effect of transit* in some other studies).

The key methodological question for the majority of greenhouse gas (GHG) emissions displaced is how much are vehicle miles traveled (VMT) reduced through both the ridership effect and the land use effect? A large body of research examines the effect of transit service on VMT, but most of the existing research focuses on ridership effects, whereby travelers shift from driving to riding transit. However, some studies have also shown that transit lines have effects on property values and community design that can lead to compact development, mixed uses, and more walkable environments near transit stations, and research has linked these factors to reduced VMT.

While the effect of urban form variables (such as density, land use mixing, and sidewalk coverage) on VMT is well studied, there is far less consistent information on how transit systems affect urban form. There is little research available evaluating how land use changes influenced by transit systems affect GHG emissions, and transit agencies lack guidance on how to consider these effects in the planning process and in calculating their aggregate effect on GHG emissions, energy use, and other environmental and economic impacts.

1.2 Project Scope and Objectives

The overall objective of this project was to analyze the complex interrelationships between transit and land use patterns in a way that would help transit agencies to quantify and better understand their contribution to compact development and the resulting GHG reduction benefits. Specifically, the objectives of this project were to:

- Develop a methodology to quantify the transportation-related GHG emissions and energy use related to land use changes that can be attributed to transit. The methodology developed shall quantify the impact of transit on land use and the resulting impact on transportation-related GHG emissions and energy use, and shall determine what portion of land use related impacts, and thus changes in transportation-related GHG and energy use, are attributable to transit.

- Identify, describe, and, to the extent possible, quantify the synergistic interaction between transit and land use and the effects on transportation-related GHG emissions and energy use.

The project accomplished all stated objectives, with one exception: quantification of the "synergistic interaction between transit and land use," meaning the mutually reinforcing aspects of transit service and compact urban forms. For example, transit stations that are located in areas with small block sizes and a good pedestrian environment may be more likely to attract compact development. The datasets and statistical models used in the research did not find evidence sufficient to quantify the synergistic relationships in detail.

1.3 Research Tasks

The other tasks of the project were

- **Performing a review of the literature.** A survey of current literature on the topic informed the premises of the research and key research questions.
- **Data collection.** Extensive data collection provided the basis for statistical modeling.
- **Construction of statistical models.** A series of statistical models was constructed to quantify the relationships between key transportation and land use variables at multiple geographical scales. Best-fit models were selected based on broadly accepted goodness-of-fit measures.
- **Interpretation of model results.** The models constructed were used to estimate the effects of transit service on land use patterns, VMT, energy, and fuel use. Estimates were adjusted, cross-validated, and compared to real world examples.
- **Development of the Land Use Benefit Calculator ("the calculator").** A calculator was developed to allow individual regions or transit systems to estimate the effects of their existing systems or system enhancements on VMT, energy use, and GHG emissions.
- **Pilot testing and refinement of the calculator.** Several transit agencies were engaged to test the tool, and their feedback was incorporated into a revised calculator.
- **Preparation of a final report.** This final report communicates the research methods and findings and provides a user guide to accompany the calculator.

1.4 Research Applicability

This report contains research and findings that will be useful to

- **Transit agencies.** This research can help to quantify the benefits provided by their service and better understand the characteristics of transit service that contribute to more compact development. Land use benefits quantified in this study can be used as a regionally specific alternative to APTA's national level land use multiplier.
- **Planners.** This research can help to consider the likely land use developments associated with planned transit service and key variables that affect development activity.
- **Modelers.** This research can inform elasticities used in land use models.
- **Researchers.** This research can inform future research on the relationship between transit service and land use patterns.

1.5 Report Structure

The sections in the remainder of this report are the following:

- **Section 2—Transit's Impact on GHG Emissions and Energy Use: The Land Use Component** defines the land use effect of transit in more detail and explains which effects of transit systems are captured in this research, including benefits in terms of VMT, energy, and GHG emissions reductions.

- **Section 3—Research Methodology** summarizes the statistical methodology used.
- **Section 4—The Land Use Effect of Transit: Findings** provides key findings of this research, with immediate implications for planners, drawing on the modeling exercises conducted. Key findings include benefits in terms of VMT, energy, and GHG emissions reductions.
- **Section 5—The Land Use Benefit Calculator: An Introduction** provides an introduction to the calculator, which operationalizes key findings and estimates benefits in terms of VMT, energy, and GHG emissions reductions.
- **Section 6—The Calculator: User Guide and Case Studies** provides a step-by-step user guide and case studies of the calculator's use by transit agencies.
- **Section 7—Recommended Practice for Quantifying GHG Emissions from Transit** discusses how the calculator can be applied to calculate GHG emissions displaced by transit for the purposes of a GHG inventory.
- **Section 8—Future Research** provides suggestions for future research.
- **Appendix A** and **Appendix B** provide full technical details of the modeling exercises conducted.

SECTION 2

Transit's Impact on GHG Emissions and Energy Use: The Land Use Component

Transportation systems and land use patterns coexist in a complex and ever-evolving "ecosystem." Roads and transit systems are planned and constructed in order to serve existing homes and businesses, but new homes and businesses also locate where they will have access to existing or planned roads and transit systems. A host of other factors affect this ecosystem, including land values and availability, public policies, and public support for land development (often demonstrated through government intervention).

2.1 Evidence for the Land Use Effect and Land Use Benefits

A growing body of research analyzes the extent to which public transportation systems beget land use changes in the form of more compact development. The evidence is mixed, but favors the theory that public transportation investments can, under the right circumstances, promote more compact development. The TCRP Project H-46 research team calls this phenomenon the *land use effect of transit* (or simply *the land use effect*). (See Figure 1.) There are numerous examples of recently constructed or improved rail and bus lines in the United States and abroad that have attracted new homes, drawn new jobs, and increased property values (Center for Transit-Oriented Development [CTOD] 2011, Nelson et al. 2011, Huang 1996, Cervero et al. 1995). There are also examples from the literature of new transit nodes that have attracted little to no new property development, often because they are sited in locations with poor market demand, poor job access, or limited government support for development (CTOD 2011, Cervero et al. 1995, Kolko et al. 2011). Transit service supports densification in transit-adjacent areas, but it is not sufficient for densification in the absence of other factors. There is also some evidence that transit systems, in particular suburban commuter rail systems, encourage development to spread out from the urban core (Landis and Cervero 1999, Chatman and Noland 2013). This can result in a decrease in gross population densities as the region grows in size. Still, it is clear from the literature that transit systems support compact development in most cases.

Compact development in turn provides a host of environmental and social benefits. The focus of this research is benefits in terms of travel patterns, energy use, and GHG emissions. We call these benefits the *land use benefits.* (See Figure 1.) Since land use effects lead to land use benefits, these terms are sometimes used interchangeably.

An extensive literature demonstrates that people living in compact developments, even people who do not use transit, tend to drive less and walk and bike more. In *Growing Cooler*, the authors find that for every 1% increase in density, VMT is reduced by 0.3%. In other words, the elasticity of VMT with respect to density is –0.3 (Ewing et al. 2008). This lower rate of driving saves fuel and thereby reduces GHG emissions. (Vehicles driving in denser areas do burn slightly more

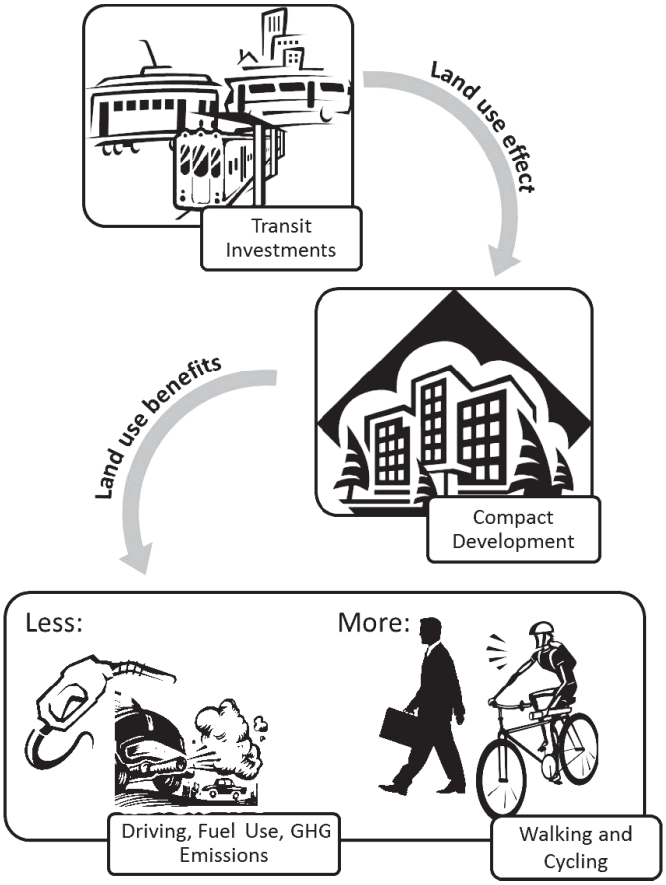

Figure 1. Land use effects and land use benefits of transit.

fuel per mile due to lower speeds and roadway congestion, but this congestion effect is dwarfed by the effect of lower VMT.) Some studies refer to the land use effect and land use benefits of transit as *the indirect effect of transit.*

2.2 The Ridership Effect

The land use effect of transit is complementary to, but completely separate from, *the ridership effect of transit* on VMT, fuel use, and GHG emissions. (Some studies refer to this as *the direct effect of transit.*) Many people riding buses and trains would travel in private vehicles instead if transit were not available. A typical estimate is that one out of every two or three transit patrons would drive a car if transit were not available (APTA 2009). Others would carpool, use another form of transportation, or not make the trip. Reducing VMT through transit ridership in turn reduces fuel consumption and GHG emissions. Transit also reduces fuel use and GHG emissions by reducing on-road congestion (APTA 2009).

2.3 Other Benefits

Besides the effects of compact development on travel patterns, there are numerous other benefits of compact development. Buildings in compact developments tend to use less energy for heating and cooling and less water for landscaping (Ewing and Rong 2008). Saving energy and water and driving less in turn produce cost savings for residents of compact areas. Compact developments are also able to make more efficient use of infrastructure, requiring fewer miles of roads, electric lines, and water and sewer lines per person than sprawling developments (Morris Beacon 2010, City of Champaign 2010, Maryland Department of Planning 2010, Smart Growth America 2013). Service costs such as police and fire are also lower per person when concentrated in a smaller area (City of Champaign 2010). Service and infrastructure cost savings mean less public spending. There are also social and health benefits to living in compact developments, as residents can have better access to services and amenities and more opportunities for physical activity in the form of walking and biking (Design, Community & Environment et al. 2006). These additional benefits of compact development are not directly treated in this research.

2.4 Focus of This Research

This research analyzes and explains the land use effect of transit and the land use benefits in terms of reduced VMT, fuel use, and GHG emissions. The research both tests the theory that transit investments can foster more compact development and quantifies the strength of the relationship.

The bulk of the research effort was devoted to analyzing the connection between transit investments and land use patterns: the land use effect (Figure 1). This link in the causal chain is the least understood and the most highly disputed. It therefore received the most attention. The second link in the causal chain is better understood. The relationship between land use patterns and VMT is one of the most frequently studied topics in the planning literature in recent years, with more than 200 studies published (Ewing and Cervero 2010). There is broad consensus on the magnitude of the relationship; however, this relationship is analyzed again herein.

SECTION 3

Research Methodology

Statistical modeling was used in this research to quantify the land use effect of transit. Using statistical models allowed the research team to isolate particular transit variables that determine the land use effect (such as transit supply and frequency), while controlling for other factors that are correlated with urban land use patterns (such as urban area population size and road supply). Two different datasets were used to conduct statistical analyses at different scales:

- The *urbanized area dataset*, which contains data at a macro scale on more than 300 federal-aid urbanized areas, with boundaries defined by the FHWA. Data incorporated include urbanized area size in square miles, demographic characteristics such as population size and average income, transit variables such as route miles by mode and transit revenue miles, and control variables such as local fuel prices. Each variable in this dataset is a single aggregate value for the urbanized area. Data are from the year 2010.
- The *neighborhood dataset*, which contains data at a micro scale for nine diverse regions in the United States (using Metropolitan Planning Organization–defined boundaries): Austin, Texas; Boston, Massachusetts; Eugene, Oregon; Houston, Texas; Kansas City (Missouri and Kansas); Portland, Oregon; Sacramento, California; Salt Lake City, Utah; and Seattle, Washington. Data incorporated include land use variables such as urban density and level of land use mixing, demographic variables such as household size, transit variables such as availability of a rail station, and data on household travel behavior including driving (VMT) and transit use (passenger miles traveled). Most variables in the dataset are calculated as averages within a small area: approximately ¼ mile squared. Data are from different years, ranging from 1991 to 2011, depending on the region.

The urbanized area dataset was used to conduct a cross-sectional analysis to examine differences in travel behavior between urbanized regions that have experienced different levels and types of transit investment. The urbanized area models enable the research team to answer the following research questions:

- What is the total land use effect of an urban area's existing transit system?
- What is the likely additional land use effect within the urban area of incremental improvements in the transit system?

The neighborhood dataset was used to model the land use effect of transit at a finer scale. Whereas the urban area model was constructed by comparing whole regions to one another, the neighborhood model incorporates small scale variations in land use patterns and travel patterns and includes both population and employment densities. It also explicitly considers more land use characteristics: land use mixing, pedestrian environment, and job accessibility. The neighborhood dataset allows the research team to compare the characteristics of transit-rich neighborhoods to those of transit-poor neighborhoods within regions in order to study the land use effect.

The neighborhood dataset was also used to conduct a longitudinal analysis of observed land use changes in Portland, Oregon, between 1994 and 2011, in order to compare results with the cross-sectional analyses.

Additional details on the statistical models are provided in Appendices A and B.

SECTION 4

The Land Use Effect of Transit: Findings

4.1 Summary of Key Findings

There are two key aspects of the land use effect:

1. The effect of existing transit systems and
2. The effect of current or potential future transit system expansions or enhancements.

The research team used slightly different methods for analyzing each effect.

4.1.1 Effect of Existing Transit Systems

The effect of existing transit systems is best examined at the regional level, in order to capture the entire transportation and land use ecosystem, as described above. Each urban region of the United States has had many years to arrive at a relative equilibrium of transportation and land use, despite some ongoing marginal changes. In particular, large, older cities on the East Coast and in the Midwest and some West Coast cities like San Francisco and Los Angeles have rich histories of development around transit infrastructure. The effect of the existing transit system measures the cumulative effect of that entire history to the present day.

To describe the land use effect of existing transit systems in a different way, consider the difference between a city with a compact core and a historically robust transit system, such as New York, and a city with little distinct core and far less transit, such as Dallas. The regional population density of New York is 4,176 people per square mile, and average daily per capita VMT is 15.8. The regional population density of Dallas is 2,149 per square mile, and average daily per capita VMT is 24.2. Without its dense transit network, New York may have developed more like Dallas, with lower population densities and a more car-dependent transportation system. Of course, transit is not the only factor that shapes land use and travel patterns. Other factors include geography and economic and technological variables. The statistical analysis in this research calculates the share of the "compactness" of a given region that can be attributed to transit: the land use effect of transit.

Key findings about the land use effect of existing transit systems are as follows:

- **Effect on population densities.** Taking the entire U.S. urban population in aggregate, gross population densities would be lower by 27% without transit systems to support compact development. In other words, U.S. cities would consume 37% more land area in order to house their current populations. The land use effect of existing transit makes U.S. cities more compact.
- **Effect on VMT, fuel use, and transportation GHG.** By providing more walking and biking opportunities and making some journeys by car shorter, the land use effect of transit produces an aggregate 8% decrease in VMT, transportation fuel use, and transportation GHG emissions in U.S. cities.

- **Effect of transit trips replacing automobile trips.** By transporting people on buses and trains that would otherwise travel by automobile, transit systems also produce a complementary ridership effect. In aggregate across U.S. cities, transit ridership reduces VMT, transportation fuel use, and transportation GHG emissions by 2%. This is a substantial change given that only 4% of passenger trips are currently made by transit in U.S. metropolitan areas.
- **The land use benefit of transit** varies across urban areas, ranging from a 1% to 21% reduction in VMT, transportation fuel use, and transportation GHG emissions compared to a hypothetical scenario without transit. Urban areas with higher route densities of transit, service frequencies of transit, and availability of light rail have higher land use effects. Not surprisingly, higher land use effects of transit are generally found in more densely developed areas.
- The land use effect of transit in a given region typically reduces GHG emissions more than the ridership effect. **The average ratio of land use benefits to ridership benefits** across all U.S. cities is 4:1, but the ratio varies substantially across different urban areas.[2]

The statistical models developed in this research find that roads have the opposite effect on land use. Generally speaking, transit competes with the private automobile as a mode of personal transportation. There is a discernible tradeoff between investing in roads and investing in transit, and this tradeoff extends to the land use effect. Travel by private automobile consumes more space than travel by transit, with drivers requiring both roadway and parking space for their vehicles.

4.1.2 Effect of Current or Potential Future Transit System Expansions or Enhancements

The marginal effect of transit system expansions or enhancements is measured at a different scale. These include expansions of individual or multiple routes, enhancements to transit level of service on individual or multiple routes, or additions of new transit modes. Each of these improvements has the ability to incrementally increase the land use effect of transit over time. The marginal effect measures the change in land use patterns and associated travel patterns that are attributable to the improvement. Since land development is a relatively slow process, with even proactively planned developments sometimes taking more than a decade from planning to occupancy, it can take many years to realize the land use effect of new investments.

Key findings about the land use effect of system expansions or enhancements at the regional level are as follows:

- Increasing transit route densities (route miles/land area) by 1% in a region is associated with an increase in population density of 0.2%. The corresponding land use benefit is a 0.05% reduction in VMT, transportation fuel use, and transportation GHG emissions.
- Increasing transit service frequencies by 1% in a region has nearly the same effect: an increase in population density of 0.2%. The corresponding land use benefit is a 0.04% reduction in VMT, transportation fuel use, and transportation GHG emissions.

Key findings about the land use effect of system expansions or enhancements at the neighborhood level are as follows:

- Adding a rail station to a neighborhood that did not previously have rail access is associated with a 9% increase in activity density (combined population and employment density) within a 1-mile radius of the rail station. The corresponding land use benefit is a 2% reduction in VMT (for households within the 1-mile radius), transportation fuel use, and transportation GHG emissions.

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[2] Complementary ridership effects of transit vary based solely on the level of transit ridership in individual regions.

- Improving employment accessibility by clustering new jobs around transit nodes or improving the bus and rail network in individual neighborhoods can also have potent land use effects (described in more detail in Section 4.4.2).
- An analysis of the Portland Westside light-rail extension found a land use effect of 24% increase in densities in the corridor area between 1994 and 2011. These changes correspond to a 6% household VMT reduction due to the land use effect and an additional 8% VMT reduction due to the ridership effect.

4.2 How to Measure Density?

In order to study the land use effect, what constitutes compact development and how it is measured must be clarified. Typical characteristics of compact development versus sprawling development are higher densities, more land use mixing, better access to transit, a more pedestrian-friendly environment, and closer access to regional destinations, especially jobs. These characteristics in particular are the ones associated with lower VMT.

Density is the most commonly referenced and most easily measured indicator of compact development. Density is commonly measured in terms of population and/or jobs per square mile. But density can be characterized at different geographical scales. Both local and regional densities matter to travel patterns. Local densities are easily observed—development patterns are clearly denser in Rosslyn, Virginia, than in Fairfax, Virginia. At the regional scale, density is more challenging to characterize, as metropolitan regions are made up of numerous cities and neighborhoods that can vary widely in development style.

At the regional scale, gross density is the easiest to measure, dividing total regional population by total regional land area. Gross regional density is a reasonable measure of density for the purposes of this research because higher gross densities are associated with lower per capita VMT (as discussed in the following section), but gross densities also mask important subregional variations. The New York City and Los Angeles Metropolitan Statistical Areas have very similar gross population densities at 2,826 and 2,646 people per square mile, respectively (U.S. Census Bureau 2012). But the New York City region has a super dense core with sprawling suburbs. The Los Angeles region has little distinct core, but moderate uniform density throughout. In New York, many people are living at much higher local densities than almost anyone in Los Angeles.

Population-weighted density is an emerging alternative way to measure regional densities accounting for local variations. Densities are first calculated at the local scale, for example population per square mile in each census tract. Regional density is then calculated as the average of local densities, with each census tract's density weighted by its population. In this way, census tracts where more people live (which tend to be more densely populated tracts), are given more weight in the calculation. Population-weighted density is a better regional measure of the typical local density experience of residents. The population-weighted density of New York at 31,251 people per square mile compares with that of Los Angeles at 12,114 (U.S. Census Bureau 2012).

In this research, gross density is used as the measure of regional density because gross density is readily measurable with available data, whereas population-weighted densities are extremely time intensive to calculate for multiple custom geographies.[3] Gross density is also a reasonable predictor of travel patterns and has been used extensively in the literature on the topic. However, it should be kept in mind that gross density is a relatively simple proxy measure to describe complex variations in urban form. The land use effect of transit can contribute to changes in urban form that are not fully captured by gross density. Using gross density in statistical models could

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[3] Regions were defined by FHWA boundaries for metropolitan areas.

understate the magnitude of the land use effect. Still, using gross density to analyze the land use effect provides a solid link between transit systems and travel patterns.

4.3 Land Use Benefits of Existing Transit Systems

Transit systems in every U.S. city have a land use effect, and these effects vary in magnitude based on the density and quality of transit service. The research team estimated the strength of the effects between key variables in order to construct a model of the transportation and land use ecosystem. By manipulating inputs to the model, the size of the land use effect is estimated in two stages. First, effects of transit on land use (the land use effect) are estimated. Second, effects of land use on VMT, fuel consumption, and GHG emissions (land use benefits) are estimated.

The effect of existing transit systems is measured using linear structural equation modeling (SEM) based on data from a sample of over 300 urbanized areas. The transportation, demographic, and land use data used are from 2010. Complete technical details of the model are provided in "Appendix B: Statistical Models in Depth."

4.3.1 National Land Use Benefits

Taking the entire U.S. urban population in aggregate, gross population densities would be lower by 27% without transit systems to support compact development. In other words, U.S. cities would consume 37% more land area in order to house their current populations. That is a dramatic difference in urban character, with direct implications for travel patterns, energy use, and GHG emissions. Higher densities bring destinations closer together, allowing for shorter car trips and more walking, bicycling, and carpooling. Using the elasticity of VMT with respect to density of −0.3 (as discussed in Section 3), the U.S. population living in cities without transit would see its VMT increase by 8% due to lower population densities.[4] The ridership effect, when transit riders would be forced to begin driving, would increase VMT an additional 2%, for a total VMT increase of 10% if transit were eliminated altogether.

These numbers must be understood relative to the scale of investment in different transportation modes. In every city in the United States, infrastructure dedicated to private vehicle travel dwarfs public transportation infrastructure. There are 8.6 million lane miles of roadways in the United States.[5] In comparison, there are 244,000 directional route miles of transit service.[6] Not surprisingly then, transit represents a very small proportion of total travel in the United States. Only 4% of all trips are made by transit. In contrast, 84% of trips are made by driving or riding as a passenger in a private vehicle (10.4% of trips are walking trips and 1% are made by bicycle).[7]

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[4] The elasticity of VMT with respect to density of −0.3 is based on the findings of Ewing and Cervero in "Travel and the Built Environment: A Meta-Analysis" (2010). While the models constructed in this study suggest lower elasticities, these represent only the relationship of density to travel patterns. Other key "D" variables, including **D**iversity (land use mixing), **D**esign (pedestrian environment), and **D**estinations (regional accessibility) are not included in the model. Given that denser places usually score higher on the other "D" variables as well, it is appropriate to adjust the elasticity upward to account for these missing variables.

[5] Bureau of Transportation Statistics. Table 1-6: Estimated U.S. Roadway Lane-Miles by Functional System. Office of the Assistant Secretary for Research and Technology, U.S. DOT. http://apps.bts.gov/publications/national_transportation_statistics/html/table_01_06.html.

[6] APTA. *2012 Public Transportation Fact Book.* Washington, D.C., September 2012. http://www.apta.com/resources/statistics/Documents/FactBook/APTA_2012_Fact%20Book.pdf.

[7] 2009 National Household Travel Survey (NHTS) Includes all buses, trains, streetcars, trolleys, and ferries. Excludes taxicabs.

Table 1. Transit land use benefits and ridership benefits for sample cities.

Urbanized Area	Land Use Benefit (%VMT Reduction)	Ridership Benefit (%VMT Reduction)	Total Benefit (% VMT Reduction)
New York–Newark, NY-NJ-CT	19%	16%	34%
San Francisco–Oakland, CA	18%	9%	27%
Ames, IA	21%	4%	25%
Portland, OR-WA	19%	4%	23%
Champaign, IL	16%	4%	20%
Washington, DC-VA-MD	12%	9%	20%
Los Angeles–Long Beach, CA	15%	4%	19%
Seattle, WA	14%	5%	19%
Chicago, IL-IN	12%	7%	19%
Salt Lake City, UT	15%	3%	18%
Philadelphia, PA-NJ-DE-MD	12%	5%	17%
Boston, MA-NH-RI	11%	6%	17%
Eugene, OR	13%	3%	16%
Sacramento, CA	13%	2%	15%
Houston, TX	10%	2%	12%
Austin, TX	9%	2%	11%
Atlanta, GA	8%	3%	11%
Kansas City, MO-KS	5%	1%	6%
Greenville, SC	3%	0%	3%

Note: Cities in this table were selected to represent a range of different population sizes and land use benefits. Cities are ranked from highest to lowest total benefit (combining land use and ridership benefits).

Therefore, a combined 10% increase in VMT without transit (combined ridership and land use benefits) indicates the broad influence of transit systems on travel patterns.

4.3.2 Different Cities, Different Land Use Benefits

Land use benefits can be estimated for individual cities using basic data on the transit system extent and level of service. In brief, cities with higher transit route densities and levels of service and cities with light-rail transit (LRT),[8] have higher land use benefits. (More information about the specific data points and calculation methods are provided in "Appendix A: Key Results from Statistical Models.")

The research team calculated land use benefits individually for all 300+ cities in the urbanized areas dataset. The resulting land use benefits for the full sample of 300+ cities range from a 1% decrease to a 21% decrease in VMT. These estimates are based on gross population densities.

Table 1 shows estimated land use benefits for a sample of cities. For comparison, ridership benefits (the additional VMT that would be created if transit riders began driving instead) estimated by the model are also shown.[9] The model estimates the highest land use benefits for historic transit cities like New York and San Francisco; for newer cities, such as Portland, which have invested heavily in transit in recent years; and for some smaller cities such as Ames, Iowa, and Champaign, Illinois, that have compact cores and a relatively high level of transit service concentrated in a

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[8] As discussed below, light rail transit is associated with higher gross population densities. The same is not consistently true of heavy rail transit, possibly due to the potential of rail extensions into the suburbs to promote sprawl.

[9] Ridership effects shown are the average of two different methods discussed in Appendices A and B of this report.

relatively small urban area. The latter tend to be college towns where a high proportion of the population is made up of students, many of whom use transit regularly and do not own a car. The model estimates the lowest land use benefits for sprawling regions like Atlanta and Kansas City.

The land use benefits in Table 1 quantify the reduction in driving that each region's transit system produces by fostering compact development patterns. For example, the New York–Newark urbanized area (at 4,176 people per square mile) without its public transportation would resemble cities like Buffalo, New York (1,686 people per square mile), or Austin, Texas (1,750 people per square mile), in urban density. Housing the New York–Newark population at those densities would consume an additional 6,862 square miles of land. The average resident of the New York–Newark area currently drives 15.8 miles a day; without transit, residents would drive 24.1 miles a day. An additional 4.5 miles a day (19% reduction in Table 1) are attributable to the land use effect; lower densities would reduce opportunities for walking and bicycling and lengthen some car trips. An additional 3.8 miles a day (16% reduction in Table 1) are attributable to the ridership effect, as people that currently ride transit daily would increase their car travel in the absence of transit.

If the Portland, Oregon, urbanized area (3,325 people per square mile) had never had public transportation, Portland would resemble a city like Ithaca, New York (1,351 people per square mile) or Fort Collins, Colorado (1,422 people per square mile) in development style. Housing the Portland population at those densities would consume an extra 788 square miles of land. The average resident of the Portland area currently drives 18.9 miles a day; without transit, residents would drive 24.5 miles a day. An additional 4.6 miles a day (19% reduction in Table 1) are attributable to the land use effect. An additional 1 mile a day (4% reduction in Table 1) is attributable to the ridership effect.

It is important to keep in mind that the model results are influenced by the FHWA urbanized area boundary for each city. Estimated land use benefits vary in proportion to the density and frequency of transit within the area defined. Urbanized areas that include larger proportions of suburban development may show lower land use benefits than urbanized areas with boundaries that follow the urban core more closely, since suburban areas tend to have less transit service. Interested readers can experiment with defining custom boundaries for their regional boundaries in the calculator created as a part of this research (available at www.TRB.org/main/blurbs/172110.aspx). Estimated ridership benefits vary in proportion to each area's transit mode share.

While land use benefits are typically higher than ridership benefits, there is no consistent relationship between the land use benefit and the ridership benefit across urbanized areas. For the average city, the ratio of land use benefits to ridership benefits is 4:1. For the cities listed in Table 1, ratios range from 10:1 to 1:1.

Table 2 lists land use effects for the sample of cities in terms of total GHG emissions reduced. GHG emission reduction benefits are a product of the percentage VMT reduction due to the land use effect and the regional population. Larger urban areas have higher land use benefits in terms of total emissions reduced. The New York–Newark region has the highest effect of any U.S. urbanized area, with 20 billion pounds of CO_2e emissions avoided due to land use benefits. Smaller cities invariably have lower total emission reductions, even if they have relatively high land use benefits in percentage terms.

4.4 Land Use Benefits of Transit System Improvements

Incremental improvements to transit service have measurable incremental land use effects. Improvements include adding new bus routes or rail lines, increasing service on existing routes, and improving the overall level of access to regional employment via transit. The land use effects of improvements are measured separately at the regional level and at the neighborhood level.

Table 2. Total transit land use benefits on emissions in sample cities.

Urbanized Area	Land Use Benefit (%VMT Reduction)	Population	Land Use Benefit (Total Annual CO_2e emissions reduced in lbs)
New York–Newark, NY-NJ-CT	19%	18,536,839	20,045,872,992
Chicago, IL-IN	12%	8,674,561	4,407,347,990
Los Angeles–Long Beach, CA	15%	12,148,231	3,852,288,008
Washington, DC-VA-MD	12%	4,429,831	3,069,333,392
San Francisco–Oakland, CA	18%	3,334,957	2,363,357,979
Philadelphia, PA-NJ-DE-MD	12%	5,451,310	2,262,825,320
Boston, MA-NH-RI	11%	4,270,765	1,903,891,133
Atlanta, GA	8%	4,469,203	1,307,149,408
Seattle, WA	14%	3,062,739	1,209,678,011
Houston, TX	10%	4,796,260	682,165,334
Portland, OR-WA	19%	1,849,891	542,068,124
Sacramento, CA	13%	1,598,186	215,465,156
Salt Lake City, UT	15%	1,021,020	198,035,588
Austin, TX	9%	1,254,769	188,973,381
Kansas City, MO-KS	5%	1,597,839	97,779,018
Eugene, OR	13%	248,288	50,825,317
Champaign, IL	16%	143,107	35,880,621
Ames, IA	21%	59,018	10,883,718
Greenville, SC	3%	341,875	7,238,189

4.4.1 Regional Level

At the regional level, land use effects of transit system improvements are measured using elasticity values derived from the urbanized area models. Increasing transit route densities by 1% in a region is associated with an increase in population density of 0.2%. The corresponding land use benefit is a 0.05% reduction in VMT, transportation fuel use, and transportation GHG emissions. Increasing transit service frequencies by 1% in a region has nearly the same effect: an increase in population density of 0.2%. The corresponding land use benefit is a 0.04% reduction in VMT, transportation fuel use, and transportation GHG emissions. These effects include both bus and rail service.

The effect of transit system improvements at the regional level is measured using a log SEM model based on data from a sample of over 300 urbanized areas. The transportation, demographic, and land use data used are from 2010. A more detailed description of the model is provided in "Appendix A: Key Results from Statistical Models." Complete technical details of the model are provided in "Appendix B: Statistical Models in Depth."

For example, Los Angeles Metro's ambitious transit expansion program can be evaluated in terms of its likely land use effects in future years. Los Angeles County is part of the Los Angeles-Long Beach urbanized area, with a gross population density of 6,251 people per square mile. The region's transit assets include more than 900 directional route miles of rail and almost 11,000 directional route miles of bus service. Los Angeles Metro is the largest transit provider in the area.

According to Metro's most recent Long-Range Transportation Plan, an additional 430 new directional route miles of high-quality transit (including rail and bus rapid transit) are due to be added to the transit system by 2040. Assuming 60 vehicle trips serve each route in each direction per day and assuming average land use effects, this expansion program will lead to a 1% increase in population density in the region in the long term. The corresponding land use benefit is a reduction of regional VMT by 0.3%, saving 12 million gallons of gasoline per year and reducing GHG emissions by 116,000 tons per year.

It is important to keep in mind that the effects projected here are average effects observed in existing urban areas, and that effects for individual transit system enhancements could be substantially higher or lower depending on various factors, as discussed further in Section 4.5.

4.4.2 Neighborhood Level

At the neighborhood level, improvements in local transit systems and transit access generally attract denser development. On average, adding a rail station to a neighborhood that did not previously have rail access is associated with a 9% increase in activity density (combined population and employment density) within a 1-mile radius of the rail station. Assuming that the location is generally suitable for rail service but does not currently have service, a neighborhood with 10,000 residents and 10,000 jobs could be expected to add a combined 1,800 residents and workers over time in response to a new rail station. Residents of the neighborhood can be expected to reduce their VMT, transportation fuel use, and transportation GHG emissions by 2% due to the land use effect, with additional reductions due to the ridership effect of transit.

The effect of transit system improvements at the neighborhood level is measured using multilevel modeling (MLM) based on data from nine metropolitan regions. The date of the transportation, demographic, and land use data used varies by region. A more detailed description of the model is provided in "Appendix A: Key Results from Statistical Models." Complete technical details of the model are provided in "Appendix B: Statistical Models in Depth."

These changes are average results expected over time. Changes around individual stations may vary substantially based on local factors. The recent experience of Evanston, Illinois, with station area developments around both existing stations and improved transit service helps to illustrate how observed changes in density relate to the model results.

Evanston is a first ring suburb of Chicago. The city was originally built around transit, including streetcar and commuter rail, but had been losing population to more automobile-oriented suburbs for several decades when planning for a transit-oriented resurgence began in the 1980s. While Evanston already had five urban rail stops (served by the Chicago Transit Authority [CTA]) and two commuter rail stops (served by Metra), the city dramatically increased its support for development in station areas. The 1986 comprehensive plan called for higher density development focused around four of its most active rail stations, including zoning changes. The city also invested in sidewalk, streetscape, and utility improvements in station areas to support development. The first new downtown Evanston high rise in more than 20 years was built in 1991. Figure 2 shows the Optima Towers, built on Fountain Square in 2002, two blocks from Davis Street Station.

Image: Flickr User Aaron Weathers

Figure 2. New development near Davis Street Station, Evanston, Illinois.

The CTOD TOD Database (TOD for "transit-oriented development) provides several data indicators of the success of this TOD-based turnaround in terms of reversing Evanston's overall population decline and concentrating growth around its high-capacity transit lines.

Table 3 presents a summary of population and employment data from the CTOD database, for the four station areas (½-mile radius) around Evanston's core TOD stations. These data are compared to the same data for

- The station area around the Central-Metra station (not included in the city's TOD-based growth efforts).
- The station areas around the CTA-elevated and Metra stations in Wilmette, just north of Evanston.
- The Chicago region.

Table 3. Change in activity density in Evanston station areas (½-mile radius), 2000–2010.

Location		Activity Density (Population and Jobs per Acre)		
		2000	2010	Percent Change
Evanston—TOD Core Station Areas	Davis	19.6	23.0	17%
	Dempster	11.7	13.3	13%
	Main	8.8	9.1	3%
	South Blvd	10.0	9.4	–6%
	Combined	12.5	13.6	9%
Evanston Control Station	Central-Metra	4.4	4.2	–6%
Wilmette	CTA	4.3	3.6	–15%
	Metra	4.6	4.5	–2%
	Combined	4.5	4.1	–8%
Metropolitan Region	**All Areas**	**3.8**	**3.9**	**2%**

Source: CTOD TOD Database. http://toddata.cnt.org/. Jobs figures are available for 2002 and 2009 and are used as proxies for 2000 and 2010 figures.

Areas within a half mile of the four stations increased their activity density by an average 9% over approximately 10 years.[10] (When compared to the base trend of population and employment growth in the Chicago region, the station areas saw a net 7% increase in activity density.) This change in density is expected to lead to a 2% reduction in VMT, transportation fuel use, and transportation GHG emissions by households living in the area. Notably, the average density increase masks a wide range of variation within individual station areas, where density changes over the period range from a 6% decrease to a 17% increase. Numerous factors determine the ultimate land use effect of individual transit investments, as discussed further in Section 4.5.

Average changes around the core Evanston station areas from 2000 to 2010 are very similar to the average results predicted in this research of adding a new rail station to an area that did not previously have rail. Notably, Evanston's recent experience was anchored largely by pre-existing transit service, though some new transit service was added.

Improving employment accessibility can also have potent land use effects. Access to jobs and to the shopping, dining, and entertainment opportunities associated with some jobs is an important factor in residential location choice and therefore an important factor for developers considering building in particular neighborhoods. The best-fit neighborhood model from this research finds that for every 1% increase in the share of regional jobs accessible by transit,[11] there is an associated 0.5% increase in neighborhood activity density. The corresponding land use benefit is a 0.1% reduction in VMT, transportation fuel use, and transportation GHG emissions. The importance of job accessibility is also seen in case studies of individual transit lines researched by the CTOD. An examination of development patterns around three new rail lines in Minneapolis, Denver, and Charlotte qualitatively assessed the importance of six factors in catalyzing new development around individual rail stations: proximity to downtown; proximity to employment centers; availability of vacant and underutilized land; walkability of the neighborhood; local transit connectivity; and local household income. Proximity to employment centers was the only factor found to have a consistently strong positive relationship with development patterns around rail stations on all three lines (CTOD 2011).

In Charlotte, the new LYNX Blue Line stretches 10 miles from Uptown Charlotte southward to suburban Pineville. Figure 3 provides a map of the line. Development has been strongest in the South End neighborhood, adjacent to Uptown employment centers. The South End is physically cut off from Uptown by a freeway. Transit connections tapped into pent-up development demand in the South End by helping overcome this barrier, improving connections and accessibility between the South End and Uptown.

In practical terms, transit employment accessibility can be improved in one of several ways:

- **Providing new transit service with connections to employment centers.** The Charlotte Blue Line is an example.
- **Improving the speed, frequency, or connectivity of existing transit service so that employment centers can be reached more quickly.** Evanston's Davis Station area revival included improved service on the CTA Purple Line. Both bus agencies serving the station also increased their service frequencies, added stops, improved routes, and increased coordination with train schedules.

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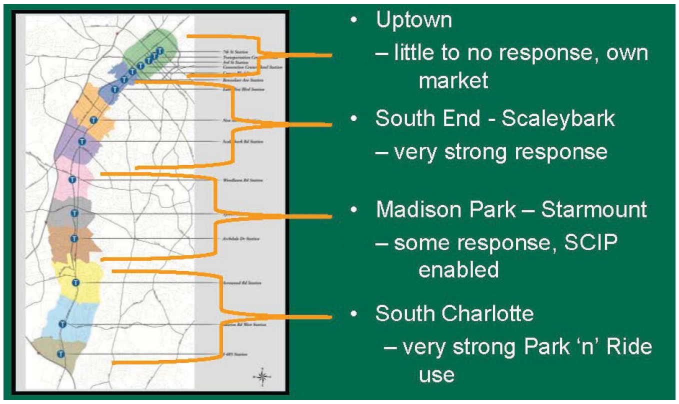
[10] The neighborhood model examines changes in activity density within 1 mile of transit stations, while the CTOD database captures changes within a ½-mile radius. Thus, the comparisons provided here are not exact but are provided to illustrate general trends. If there is a 9% change expected within a 1-mile radius, and the majority of changes happen closer to the station, it is likely that changes within the ½-mile radius only are actually higher.

[11] Defined as jobs accessible within 30 minutes of transit travel time from a transit stop within a ½ mile of the household.



- Uptown
  - little to no response, own market
- South End - Scaleybark
  - very strong response
- Madison Park – Starmount
  - some response, SCIP enabled
- South Charlotte
  - very strong Park ‘n’ Ride use

Map and Information: City of Charlotte. SCIP = South Corridor Infrastructure Program.

Figure 3. Development response patterns along the Blue Line in Charlotte, North Carolina.

- **Clustering future job growth in other parts of the region near high-quality transit nodes.** A longer term option, improving the region-wide proximity of jobs to high-quality transit, makes living near transit a more desirable option throughout the transit network.

The key findings described here can be used to predict average land use effects and land use benefits in response to transit system enhancements. Since predictions provided are averages, they will be more accurate when applied to larger improvement programs and multiple stations. It is important to keep in mind that land use effects, particularly at the local level, will vary substantially in response to a number of factors, discussed further in Section 4.6.

4.5 Portland’s Westside Light-Rail Extension

The datasets used in the neighborhood model provided an opportunity to conduct a parallel longitudinal analysis of actual changes in land use patterns along Portland’s Westside LRT line (western portion of the Blue Line) between 1994 and 2011. The 15-mile section, with 17 stations, opened in 1998. Much of the alignment is through land that was ripe for development or redevelopment. Station areas have had many years to densify and thereby affect travel behavior.

Land use changes in the light-rail corridor were compared to land use changes in a control corridor, using a statistical model. With the comparison highway corridor as a baseline, Portland’s Westside LRT extension is associated with an increase in activity densities within the 2.5-mile catchment area of 24% and an increase in average daily transit trips per household of 60%. These changes correspond to a 6% household VMT reduction due to the land use effect and an additional 8% VMT reduction due to the ridership effect.

For comparison, the other statistical models developed in this study would predict a density increase of 6% in the area surrounding the Blue Line extension, given average responses seen across multiple urban areas and average levels of public support and land potential. The observed increase in activity densities of 24% demonstrates the high degree of variation in the land use effect of individual transit investments. The Westside LRT corridor identified for this test had both many sites ripe for redevelopment and one of the highest levels of government support for TOD of any city in the country. The result of these factors was an increase in densities four times that of the average seen in U.S. cities.

Additional detail is provided in the appendices to this report.

4.6 Factors that May Influence the Land Use Effect

More than just transit investments influence land use development patterns, even in areas immediately adjacent to transit. Public support and market forces play an important role in determining land use patterns. Time is another factor; new development around transit stations can happen relatively quickly, within 5 to 10 years of investments, or can happen decades later. The pedestrian environment in station areas also determines the propensity of new residents to walk and bike when they are not riding transit.

There is some disagreement in the literature over how strongly and how consistently transit investments attract new development. A significant number of studies (Cervero et al. 1995, King 2011, Kolko et al. 2011) have found that transit alone does not spur new development and that other built environment features are equally, if not more, important in influencing development growth patterns.

The models developed in this research use typical existing interactions between transit investments and land use patterns to predict the effects of future investments, but the results must be interpreted in the context of other factors as well. Not all of the factors discussed here can be considered in the models developed. The models predict aggregate results, at the transit system level or for groups of stations, with greater accuracy than they predict results for individual transit stations. *Therefore, planners should carefully consider the potential for other factors, discussed in more detail below, to influence the land use effect, particularly where smaller geographies are of interest.*

4.6.1 Public Support and Land Potential

Public support for making necessary land use changes and market potential for development are the primary determinants of development in individual station areas and transit corridors. These factors impact the land use effect by influencing development densities around transit, which in turn influence the travel patterns of non-transit riders and transit riders alike.

A recent study from the Institute for Transportation and Development Policy (ITDP) reviewed 21 LRT, bus rapid transit (BRT), and streetcar corridors in 13 cities across the United States and Canada to assess the effect of transit investments on development adjacent to the transit corridors. Investment levels were measured in terms of dollars spent. Each corridor was rated on transit level of service (relative to the ITDP's BRT Standard), land potential (a measure of the pre-existing attributes of a city or corridor that support development), and public support. Factors were assessed individually for their effects on land use development, using a mixture of quantitative and qualitative information (ITDP 2013).

For land potential, the ITDP study found that regional market strength, as rated by PricewaterhouseCoopers, was a poor predictor of investment around transit lines. The strength of the local land market around the transit line was much more influential. ITDP classified each transit corridor's local land market strength based on ownership, adjacent uses, topography, and availability for redevelopment. Where governments provided at least moderate support for development around transit lines, the strength of the local land market was found to be a good predictor of development levels.

ITDP found a nearly direct correlation between the level of investment and the strength of government support. ITDP classified each transit corridor's level of public support based on the level of activity in rezoning, investing in related infrastructure, land use planning, outreach to developers, providing financial incentives, environmental clean-up, land assembly, and marketing activities. The level of transit service along transit corridors, as analyzed in the ITDP study, was the least influential indicator of development, although not inconsequential.

The findings of the ITDP study are consistent with other studies in the field that have used more rigorous statistical methods. An extensive analysis of the San Francisco area's BART heavy-rail transit system and its effects on development patterns (Cervero et al. 1995) found that the availability of vacant and developable land was an important predictor of whether land use changes occurred near stations. Local real estate markets and public support, in the form of financial incentives and assistance in land assemblage from local redevelopment authorities, played a key role in development outcomes in the first 20 years after BART's opening.

Given the importance of public support and land potential in determining the land use effect of transit, particularly in the short term, this research considered ways to quantify the effect of these factors. The research team gathered information from the CTOD National TOD Database about job and population growth in transit station areas from 2000 to 2010. The team examined growth trends with respect to the ratings developed by ITDP for various new transit corridors in terms of land potential (limited, emerging, strong) and government TOD support (weak, moderate, strong). There were no evident correlations between the ITDP ratings and observed growth patterns. There are two possible explanations for this. First, the TOD Database contains data for a limited time period, which is likely not long enough to capture the land use effects of new investments. Second, every region is subject to varying short- and long-term demographic and economic factors that affect local growth patterns independently from transit investment. The question of how to assess public support and land potential as factors in the land use effect should be the subject of future research.

When applying the results of this research, *planners should be aware that land use intensification around individual transit corridors, stations, and stops (and by extension, land use benefits in terms of VMT, gasoline consumption, and GHG emissions) could be higher or lower than predicted by the models*, due to the presence or absence of public support and market factors. For example, a separate analysis of the Westside light-rail line in Portland found a 24% increase in local densities attributable to the transit investment over a 17-year period, with a corresponding 6% decrease in household VMT (the land use benefit). (See Section 4.5.) This change is far higher than that predicted by the models and can be attributed to the Portland region's strong integrated transportation and land use planning framework and a strong local market for development along the route, which combined to support relatively high building rates. Conversely, transit investments that are located in less supportive political and market environments can see zero development activity for many years.

4.6.2 Type and Quality of Transit Service

The models constructed for this research suggest that the type and quality of transit service have important impacts on the land use effect of transit, even if they are not the primary factors determining development patterns. These impact the land use effect by influencing development densities around transit, which in turn influence the travel patterns of non-transit riders and transit riders alike.

In one model, the average frequency of transit across the entire system has the same value in predicting land use as the density of transit service provided (in route miles per square mile). In another model, the number of jobs accessible by transit within 30 minutes has a direct effect on land use density in the local area. It follows that improving transit levels of service, and thereby increasing the number of jobs accessible within 30 minutes, would tend to increase land use densities. These results suggest that level of service is just as important as having transit service available, and that increasing levels of service on existing routes may have benefits over route expansion.

Traditionally, rail transit has been associated with a higher level of service, including greater reliability, separated guideways, higher speed, and shorter headways, than bus service. If typical bus headways are 20 to 30 minutes and typical rail headways are 10 to 15 minutes, one would

Table 4. Average land use benefits by transit system type among sample urbanized areas.

	% VMT Reduction
Urban Areas with Rail Service	14%
Urban Areas without Rail Service	8%

expect twice the land use effect from a rail transit system as from a bus transit system. And in fact, the land use effect of existing systems with rail is nearly twice that of existing systems without rail, as shown in Table 4. While urban areas with rail service also have bus service making up a substantial share of their total transit systems, bus headways are likely to be more frequent in urban areas large enough to sustain rail service.

There is some evidence that transit service, and particularly commuter rail service, can contribute to accelerating sprawl at the urban edge (Chatman and Noland 2013, Landis and Cervero 1999). The model used to assess land use effects of existing systems supports the notion that different types of transit service have different land use effects. More LRT is associated with higher gross population densities. The same is not true of heavy-rail transit, possibly due to the potential of rail extensions into the suburbs to promote sprawl. However, setting aside variations in land use patterns within a region, the models show that the total effect of more transit service is an increase in gross population density and a corresponding decrease in VMT.

The advantage of rail over bus in generating higher land use effects may erode with the advent of BRT systems that match or even exceed the level of service provided by rail in some cases. In fact, the model results suggest that a bus system providing the same level of service as rail can generate the same land use effects. Recent studies of property development around new BRT lines have also demonstrated this potential (ITDP 2013, Nelson et al. 2011, Cervero and Kang 2011).

Some have suggested that fixed-guideway transit has the potential to generate greater land use effects than non-fixed-guideway transit because the fixed infrastructure investment implies a long-term commitment by public agencies to provide transit service. The research conducted under TCRP Project H-46 finds that transit that provides higher frequency service and greater access to jobs—two qualities generally associated with fixed-guideway transit—generate higher land use benefits.

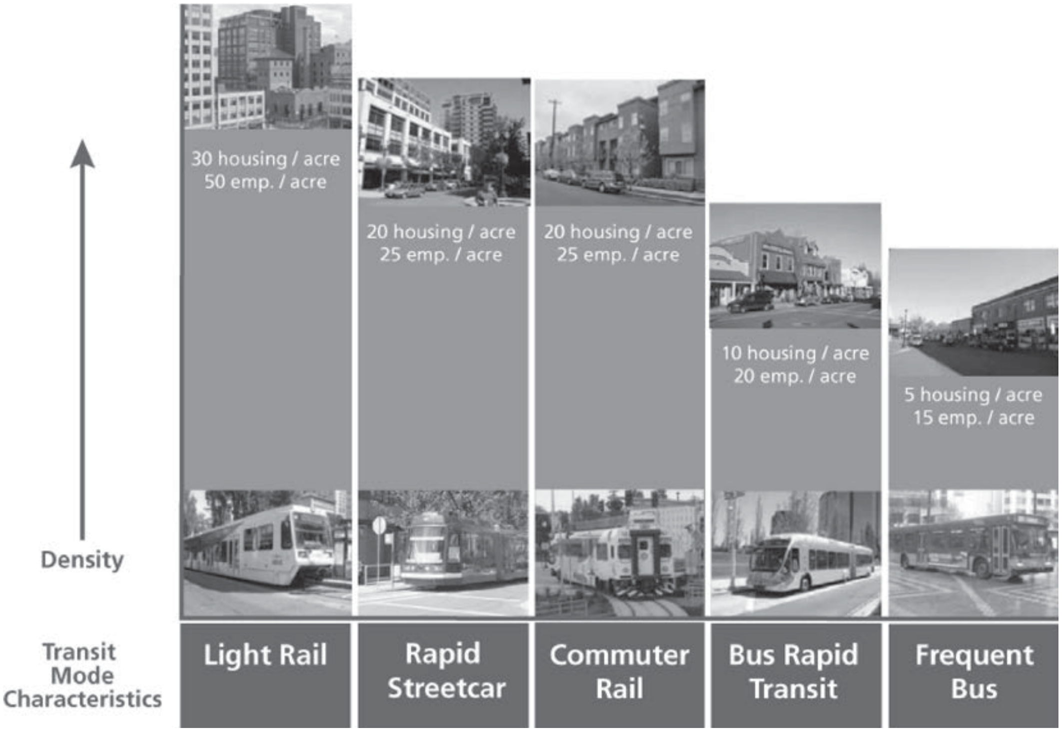
4.6.3 Vehicle Capacity

While there is an obvious correlation between land use densities and the capacity of transit vehicles serving the area, providing higher capacity transit vehicles is not likely to generate additional land use effects *in and of itself.*

Figure 4 shows how different transit modes are associated with different types of development. Transit vehicle capacities tend to be higher in higher density areas. From the perspective of transit service planning, it makes sense to provide more transit capacity where more riders live and work.

The statistical models in this study have illuminated three primary transit characteristics that shape the land use effect:

- Transit access (represented by route density at the regional level or station proximity at the neighborhood level).
- Transit frequency.
- Transit employment accessibility (which captures transit speed, frequency, and network connectivity).



Source: Nelson/Nygaard. emp. = employees

Figure 4. Typical land use densities associated with different types of transit.

Transit vehicle capacity was not incorporated in the statistical models in this research because available data on transit vehicle capacity were not sufficiently detailed; however, it is unlikely that including a transit vehicle capacity variable would have substantively changed the model results.

Literature on property value impacts of transit investments has not discussed transit vehicle capacity as a driving factor. (Property values are a reasonable proxy for land use effects because rising real property values indicate that more people want to locate in a given area, which in turn makes developing at higher densities more viable.) The economic theory behind these studies is that the improved access to destinations offered by transit drives increased property values. Transit access, speed, frequency, and network connectivity—not transit vehicle capacity—are the variables that determine access to destinations. Only consistent and severe overcrowding on transit vehicles would impact access to destinations.

Transit vehicle capacity should meet the needs of the riding population in any given area. Living or working in a neighborhood may become less desirable if the transit service provided is overcrowded. But if developers believe that transit agencies will provide sufficient vehicle capacity to serve new development as it becomes occupied, then transit vehicle capacity should not be a driving factor in the land use effect. In other words, transit vehicle capacity should be seen as a planning decision that responds to the land use effect, rather than shapes it.

4.6.4 Road Supply

Generally speaking, transit competes with the private automobile as a mode of personal transportation. This competition extends to the land use effect as well, where there is a discernible tradeoff between transit supply and road supply.

Applying the models developed for this research, the research team estimates that a 1% increase in freeway lane miles per capita in an urban area is associated with a 0.1% decrease in population density. A 1% increase in non-freeway lane miles per capita is associated with a 0.5% decrease in population density in the region.

4.6.5 Time for Development

Common sense suggests that time is an important factor in determining the scale of the land use effect of transit. Development happens on the time scale of decades, with multiple years needed to acquire parcels, design and finance development, acquire permits, and complete construction. The land use effect of transit is realized when new development occurs, bringing more residents and jobs into compact, mixed-use areas where destinations are closer together and more accessible by foot and bicycle. If new development takes decades to happen around new transit investments, the land use effect of transit will likewise take decades to be realized. The San Francisco Bay Area's BART system is an example of this phenomenon. While some station areas attracted development in the first few decades after the transit system opened, many more station areas are seeing development only now, 40 years after the transit service opened. Much older transit stations also continue to attract development. For example, Evanston, Illinois, saw a boom in development around transit stations in the 1990s, 70 years after the transit service in question was in place (CTOD 2011).

On the other hand, some cities see development that coincides with the opening of new transit or even precedes the opening of new transit lines. Phoenix, Charlotte, and Minneapolis have all seen construction projects start around their new transit lines before the lines themselves were even completed (CTOD 2011). Developers anticipated the market opportunities provided by transit access and acted early.

The 2013 ITDP report cited above considered the impact of timing on the land use effects of new transit corridors. The transit corridors considered by the study have all opened in the last 10 to 20 years. ITDP found little correlation of transit system age with the amount of development adjacent to the corridors. Land potential and government support far outweighed time since opening as predictors of development (ITDP 2013).

Statistical modeling conducted for this research included a longitudinal analysis of urbanized areas between 2000 and 2010 and found no land use effects during the period, suggesting that land use effects take longer than 10 years to develop after a transit investment. In Portland, an examination of development around the Westside Blue Line extension showed land use effects far higher than the effects predicted by the statistical models in only 17 years. See the following section for further details.

Based on the evidence above, the research team concluded that time has a highly unpredictable relationship to the land use effect. It is reasonable to expect a minimum of 10 years for land use development around transit to occur, but it may take many more years. The importance of government support and market factors in determining the rate of development cannot be understated. To make more accurate predictions of timeframes for development in individual regions, planners should consult historical development data for their region or conduct a market forecast study for the neighborhood or corridor of interest.

SECTION 5

The Land Use Benefit Calculator: An Introduction

5.1 Capabilities of the Calculator

The TCRP Project H-46 research team created the Land Use Benefit Calculator ("the calculator"), an MS-Excel-based sketch-modeling tool, to apply the research findings discussed in Section 4. The calculator (available at www.TRB.org/main/blurbs/172110.aspx) is designed to allow transit agencies, metropolitan planning organizations, and other interested parties to estimate the land use effects of their existing or planned transit projects with a minimum amount of input data required. Default inputs for most urban regions are provided for the year 2010.

Specifically, the calculator allows the user to estimate

- The land use benefits of the existing regional transit system.
- The land use benefits of a regional transit plan.
- The land use benefits of a new transit route or improved transit service along an existing corridor.
- The land use benefits of a new transit station or stop or improved transit service to an existing station or stop.

All land use benefits are estimated in terms of the following metrics:

- VMT reduction.
- Gasoline consumption reduced.
- GHG emissions saved.

The calculator also estimates ridership benefits for convenient comparison to the land use benefits; however, for new projects, more accurate ridership benefits should be estimated using ridership forecasts developed by the transit agency.

For new transit projects, the calculator uses inputs in terms of

- Transit route miles.
- Transit revenue service miles.
- Job accessibility by transit.

These are the variables that the statistical analysis described in Section 4 found to have a significant and positive effect on land use densities, and generating more compact development is essential to creating land use benefits. Other aspects of transit service, including right-sizing vehicle capacity, providing rider amenities (such as integrated payment systems and real-time arrival information), and marketing campaigns, are important aspects of transit planning and encouraging ridership; however, these other variables do not have a measurable effect on land use.

For all transit improvements, the land use benefits estimated will be realized in the long term. Land use patterns take years or even decades to respond to changes in transportation systems.

Periods of slow regional population growth or local property market downturns can delay expected development activity. The calculator does not explicitly consider real estate market supply and demand factors (including population growth forecasts) or the effect of public policies related to compact development around transit. Rather, the calculator predicts the land use effects that are attributable to transit given average levels of real estate activity and public support. Transit investments in areas of high development potential could see much larger land use benefits.

5.2 Structure of the Calculator

The Land Use Benefit Calculator consists of seven tabs:

1. Intro—collects basic information about the geography of analysis and provides guidance about which type of analysis to use.
2. Learn more—provides more information about using pre-defined and custom regions.
3. Custom base—allows the user to provide information for a custom baseline region.
4. Benefits of current system—Estimates benefits of the current regional transit system.
5. Region—estimates benefits at the regional level for a regional transit expansion.
6. Corridor—estimates benefits at the corridor level for corridor improvements. (A corridor consists of the area within 1 mile on either side of a route served by one or more transit lines.)
7. Station area—estimates benefits of a new transit station or stop or improved transit service to an existing station or stop for the area within 1 mile of the station or stop.

The User Guide in Section 6 provides a step-by-step guide to navigating the calculator in four steps:

- Step 1: Select Your Baseline Region.
- Step 2: Select Your Analysis Type.
- Step 3: Enter Data on Your Project.
- Step 4: View Information on the Benefits of Transit.

Case studies of applications of the calculator in Philadelphia and Salt Lake City are also provided.

5.3 Relationship to Other Modeling Tools

The Land Use Benefit Calculator is a sketch-modeling tool that incorporates new research on the influence of transit systems on land use patterns. No other modeling tool in use by transportation planners—including travel demand models, land use models, and sketch models—accounts for the effects of public transportation on VMT in the same way:

- **Travel demand models.** Both traditional four-step models and newer activity-based models start with a fixed land use scenario. Models that incorporate the transit mode will predict the effect of transit investment on VMT, but only through the ridership effect. The land use benefits of transit, which are realized as transit fosters more compact development and thereby allows people to make more trips by bicycling, walking, and shorter car trips, are not accounted for.
- **Land use models (including integrated travel demand and land use models).** Land use models can theoretically be used to estimate land use benefits of transit, if run in conjunction with a travel demand model. Land use models start with a baseline land use scenario and predict changes in land use over time in response to demographic and economic factors, including accessibility of various land uses via the transportation system. A hedonic pricing model is used to predict the change in value of individual parcels due to changes in the transportation

system, but models are generally not able to account separately for the effects of different transportation modes. Parcels that increase in value are more likely to be developed, resulting in an increase in density around transit. The resulting higher density land use scenario could then be fed into a travel demand model to estimate a VMT reduction. By running land use and travel models in feedback until they reach equilibrium, users could assess both the long-term effect of transit on land use and the effect of these land use changes on travel patterns. However, this is a labor-intensive process, and the research team is not aware of any agency using their land use and transportation models in this fashion to analyze or compare specific transit projects; these models are usually used to look at the effect of a suite of multimodal investments in the context of a long-term plan.

- **Sketch models.** A new generation of sketch models is emerging that allows states and regions to estimate the VMT reduction potential of various strategies such as transit expansion, pricing, travel demand management programs, and smart growth land use scenarios. GreenSTEP is one example in use in Oregon. While simpler to use than full-fledged travel demand models and land use models, these sketch models lack the ability to account for the influence of transit on land use patterns. As a result, the Land Use Benefit Calculator can be used to supplement the results of other sketch models that analyze a broader range of VMT reduction strategies. Pilot tester Lane Transit District (Eugene, Oregon) specifically used the Land Use Benefit Calculator to supplement the GreenSTEP scenarios developed for the regional transportation plan.

The Land Use Benefit Calculator is unique in that

- Land use benefits can be estimated for any urban area and for a broad range of transit plans and projects using a small number of readily available inputs, often without the need to conduct runs of more complex models.
- Land use benefits are estimated using a statistical model developed for that purpose.
- Land use benefits are explicitly isolated from ridership benefits.

SECTION 6

The Calculator: User Guide and Case Studies

The calculator (available at www.TRB.org/main/blurbs/172110.aspx) works through the following four steps:

- 6.1 Step 1: Select Your Baseline Region.
- 6.2 Step 2: Select Your Analysis Type.
- 6.3 Step 3: Enter Data on Your Project.
- 6.4 Step 4: View Information on the Benefits of Transit.

The following sections provide instructions on completing each of these steps.

6.1 Step 1: Select Your Baseline Region

The tool calculates the benefits of a transit project based on the land use and transportation characteristics of the greater region in which your project is located. The region should correspond to your transit service area in terms of population density, transit service density and frequency, and daily per capita VMT. It is more important that these values are reasonably representative of your transit service area than that the boundary of the region is a close fit to your service area boundary. There are multiple ways to define a baseline region using the calculator.

6.1.1 Selecting an Urbanized Area on the Introduction Sheet

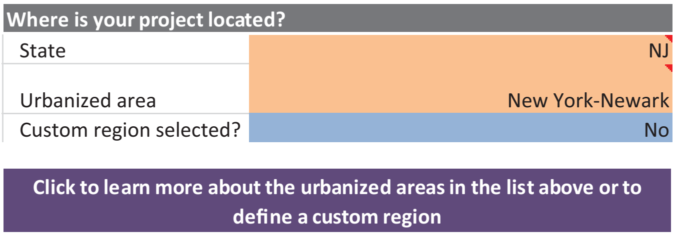
The easiest way to select a baseline region is to choose from the list of federal-aid urbanized areas (areas that the federal government uses when allocating transportation funding) on the *Intro* sheet of the calculator, using the table shown in Figure 5. Default inputs for these areas are provided for the year 2010. (Data points can be updated by defining a custom region.)

Select a state from the state drop-down menu, and then the urbanized area drop-down menu will return a list of all the urbanized areas located within that state. Urbanized areas that span multiple states are listed under each state included in the urbanized area. For example, portions of the New York–Newark urbanized area, shown in Figure 5, are in New York, New Jersey, and Pennsylvania. Accordingly that urbanized area is provided as an option under all three states.

If you have questions about these areas or do not see your region listed, click on the purple button below the table to navigate to the *Learn More* sheet.

6.1.2 Exploring Urbanized Area Transportation and Land Use Characteristics on the *Learn More* Sheet

The *Learn More* sheet provides users with more information about the urbanized areas used in the calculator and allows users to define a custom region rather than using an urbanized area.



Where is your project located?	
State	NJ
Urbanized area	New York-Newark
Custom region selected?	No

Figure 5. Urbanized area selection table on the calculator Intro sheet.[12]

How do you want to define your baseline region?

● Select a federal-aid urbanized area

○ Define a custom region

Urbanized area characteristics - Year 2010	
State	NY
Federal aid urbanized area	New York-Newark
Transit network	
Total transit directional route miles	20,220
Heavy rail	545
Light rail	114
Commuter rail	2,186
Non-rail	17,375
Total annual transit revenue miles	350,972,240
Road network	
Total roadway lane miles	27,032
Freeways	7,225
Other roads	19,807
Land use	
Gross population density (people / sq. mi.)	4,176
Total population	18,536,839
Total land area (sq. mi.)	4,439
Travel characteristics	
Transit passenger miles, per capita per day	2.96
Vehicle miles traveled (VMT), per capita per day	15.8

Figure 6. Urbanized area characteristics table.

Use the drop-down menus in the Urbanized Area Characteristics table shown in Figure 6 to select a state and urbanized area, and the table will return information on the transit and road network, land use characteristics, and travel characteristics in that urbanized area.

You can use the Urbanized Area Characteristics table to determine whether characteristics, especially density, transit service, and VMT of the urbanized area are a reasonable match for the characteristics of your transit service area. Note that this table is for informational purposes; users will still need to select a baseline urbanized area using the menu on the *Intro* page.

Once you view information about the urbanized areas associated with your transit service area, make a selection in the section titled *How do you want to define your baseline region?*

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[12] Screenshots in this section are provided in color to show the actual look of the tables in the calculator; however, if the user is printing the document, it is not necessary to do so in color for the screenshots to be understandable.

by clicking on one of the two radio buttons and then clicking the purple button below the menu:

- If you choose *Select a federal-aid urbanized area*, clicking this button will return you to the introduction page so that you can select an urbanized area to use as a baseline region from the drop-down menu.
- If you choose *Define a custom region*, clicking this button will bring up a worksheet where you will enter inputs about your custom baseline region.

6.1.3 Defining a Custom Region

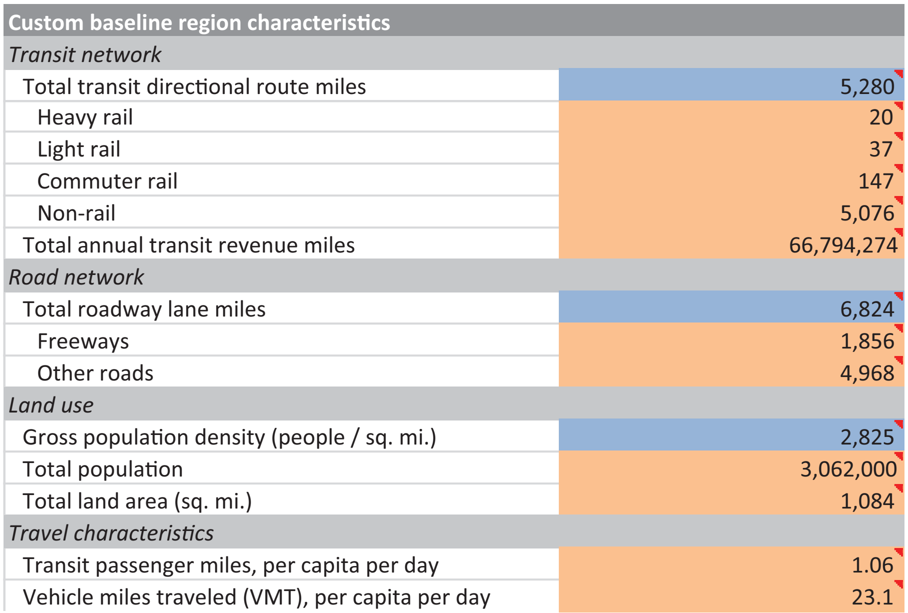
Defining a custom area is labor-intensive and requires extensive land use and transportation data. Reasons to define a custom area are

- If the urbanized area most closely associated with your transit service area is not included in the calculator.
- If the urbanized area that best aligns with your transit service area is significantly smaller than your transit service area. If your transit service area covers multiple urbanized areas, consider creating a custom region to include all relevant urbanized areas.
- If the urbanized area that best aligns with your transit service area is significantly larger than your transit service area. For megaregions such as New York and Los Angeles, a single urbanized area can encompass areas with dramatically different transportation and land use characteristics. In these cases, users may want to consider defining a custom area for the subregion of the urbanized area served by their agency.

You should not create a custom region to cover a single corridor or other subarea within your larger transit service area. Instead, you can use the corridor or station area modules to examine the benefit of specific projects within your transit service area.

Figure 7 shows the custom baseline region characteristics table. This table prompts you to enter several different types of data about your baseline region, including

- Information on the transit network, which can be collected directly from transit agencies or from the National Transit Database.



Custom baseline region characteristics	
Transit network	
Total transit directional route miles	5,280
Heavy rail	20
Light rail	37
Commuter rail	147
Non-rail	5,076
Total annual transit revenue miles	66,794,274
Road network	
Total roadway lane miles	6,824
Freeways	1,856
Other roads	4,968
Land use	
Gross population density (people / sq. mi.)	2,825
Total population	3,062,000
Total land area (sq. mi.)	1,084
Travel characteristics	
Transit passenger miles, per capita per day	1.06
Vehicle miles traveled (VMT), per capita per day	23.1

Figure 7. Custom baseline region characteristics table.

- Information on land use and population, which can come from the census or local planning agencies.
- Information on the road network, which can come from local or regional transportation agencies.
- Information on travel behavior, which can come from regional planning agencies or the National Transit Database.

Once you have completed filling in the table, click the button at the top of the page to return to the *Intro* page and select an analysis type.

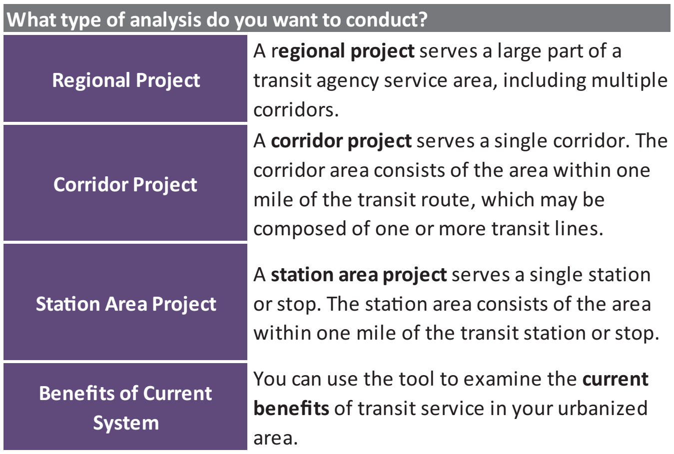
6.2 Step 2: Select Your Analysis Type

After selecting an urbanized area or defining a custom region, select from one of four analysis types using the menu shown in Figure 8 and clicking on the corresponding purple button.

The first three options (regional project, corridor project, and station area project) estimate the benefits of transit projects of varying scales, while the fourth option estimates the benefits of the current transit system in your region:

- A **region** consists of a transit agency service area. Regional projects include systemwide investments in increasing transit frequency or expanding routes across a large area. Common regional projects include regional transportation plans and long-range transit plans.
- A **corridor** consists of the area within 1 mile on either side of a route served by one or more transit lines. Corridor-level projects increase transit frequency or add service along a portion or the entirety of a route. Common corridor projects include corridor management plans or upgrades from local service to BRT. Since corridors consist of multiple station or stop areas, you can also use the station area module to analyze the benefits of increasing speed or upgrading transit service along a corridor in more depth by completing the station area module for each station located along the corridor.
- A **station or stop area** consists of the area within 1 mile of a transit station or stop. Station area projects create new rail stations or bus stops or improve existing transit service to provide access to a greater number of destinations from the station or stop area.
- You can use the calculator to examine the **benefits of the current transit system** in your urbanized area.

Figure 9 illustrates the difference between the three scales of analysis.



What type of analysis do you want to conduct?	
Regional Project	A **regional project** serves a large part of a transit agency service area, including multiple corridors.
Corridor Project	A **corridor project** serves a single corridor. The corridor area consists of the area within one mile of the transit route, which may be composed of one or more transit lines.
Station Area Project	A **station area project** serves a single station or stop. The station area consists of the area within one mile of the transit station or stop.
Benefits of Current System	You can use the tool to examine the **current benefits** of transit service in your urbanized area.

Figure 8. Analysis selection menu.

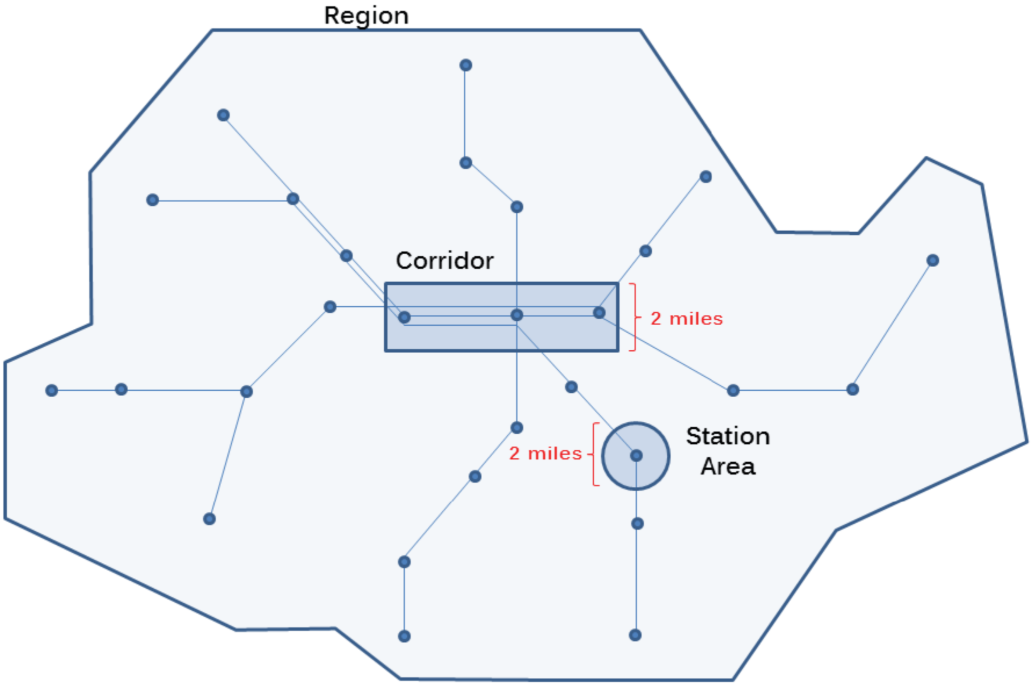


Figure 9. Map illustrating the different scales of analysis used in the calculator.

The calculator is capable of analyzing different types of transit improvements at different scales. Figure 10 summarizes the different types of projects that the calculator is capable of capturing at each scale of analysis.

The calculator uses different inputs to characterize transit improvements at different scales. It captures improvements that can be quantified in terms of new service (i.e., new route miles or increased accessibility to destinations), increased frequency (i.e., new revenue miles or increased

	Road Improvements	Transit Improvements			
	Building roads	Building new transit	Increasing transit service frequency	Increasing transit speed	Upgrading bus to rail / BRT
Regional Project	✓	✓	✓		
Corridor Project*		✓	✓	see note below	✓ (via increase in revenue miles)
Station Area Project		✓	✓ (via accessibility)	✓ (via accessibility)	✓ (via accessibility)

**Note: since corridor projects are composed of multiple station area projects, you can also use the station area module to analyze the benefits of increasing speed or upgrading service along a corridor by completing the station area module for each station located along the corridor.*

Figure 10. Summary table of project types captured at different scales.

accessibility to destinations), increased speed (i.e., accessibility to destinations), or upgrades from conventional bus service to rail and BRT. Where BRT service is comparable to rail service—providing high-frequency service every 15 minutes or more frequently during peak periods and a dedicated right-of-way along the entire transit line—a BRT station can be considered equivalent to a rail station in the calculator. Other types of bus service, including "BRT light," can be analyzed in other ways. For example:

- If you are estimating the benefits of increasing the frequency of service on an existing bus line, use the corridor-scale analysis.
- If you are estimating the benefits of adding some BRT features to increase speed and/or frequency of a bus line, use station area-scale analysis, and enter the resulting increase in accessibility to jobs.
- If you are estimating the benefits of upgrading from conventional bus service to full BRT, use the station area-scale analysis, and enter both that the station area will be served by a new rail stop and the resulting increase in accessibility to jobs.
- If you are estimating the benefits of upgrading from conventional bus service to rail service, use the station area-scale analysis and enter both that the station area will be served by a new rail stop and the resulting increase in accessibility to jobs.

Note that improvements that cannot be quantified in terms of new service or improved frequency or employment accessibility cannot be analyzed using the calculator. For example, the calculator does not analyze effects of enhancements such as real-time arrival information or special branding and outreach campaigns for individual transit routes. For further examples of how transit agencies have used the calculator to estimate the benefits of different project types, see the case studies in Sections 6.5 and 6.6.

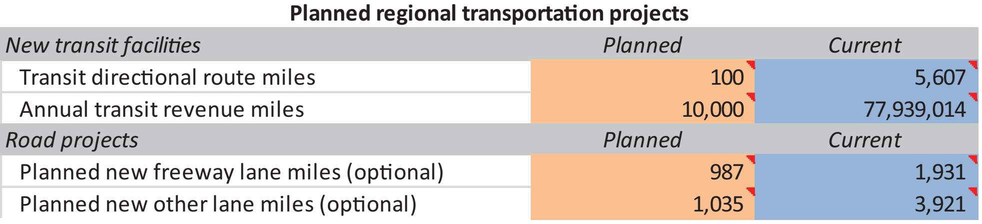
Once you have selected an analysis type, click on the corresponding purple button in the menu shown in Figure 8, and the calculator will navigate to the appropriate sheet for you to begin inputting data on your project.

6.3 Step 3: Enter Data on Your Project

Once you select an analysis type, you will navigate to a new sheet where you will enter data on your planned transportation project. The calculator uses different inputs to characterize transit projects at different scales. Inputs are based on variables that have a statistically significant effect on compact development and transit ridership, as indicated from the research described in Section 4. The following sections describe the key data inputs for each type of analysis included in the calculator.

6.3.1 Regional Analysis

The regional analysis captures the benefits of projects that increase the coverage or frequency of transit across a large area. Figure 11 shows the input table for analyses of regional projects.



Planned regional transportation projects

New transit facilities	*Planned*	*Current*
Transit directional route miles	100	5,607
Annual transit revenue miles	10,000	77,939,014
Road projects	*Planned*	*Current*
Planned new freeway lane miles (optional)	987	1,931
Planned new other lane miles (optional)	1,035	3,921

Figure 11. Input table for planned regional transportation projects.

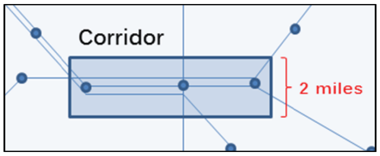
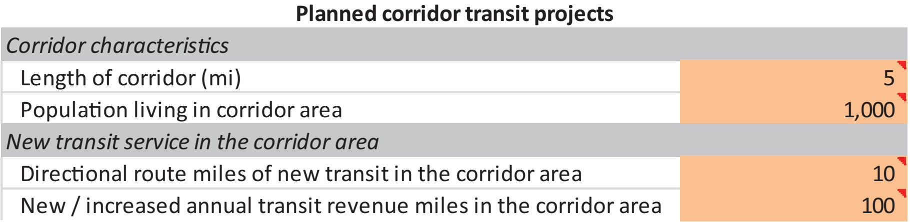


Figure 12. Diagram illustrating area used in the corridor analysis.



Planned corridor transit projects

Corridor characteristics	
Length of corridor (mi)	5
Population living in corridor area	1,000
New transit service in the corridor area	
Directional route miles of new transit in the corridor area	10
New / increased annual transit revenue miles in the corridor area	100

Figure 13. Input table for planned corridor transit projects.

The table shows information on the current transit and road facilities for reference, in order to give users a sense of the scale of new planned projects.

The key inputs for regional projects are transit route miles and revenue miles. Users must input both in order for the calculator to accurately estimate benefits. Users also have the option of entering data on planned road projects if analyzing a multimodal plan such as a regional transportation plan. New road construction encourages driving, diminishing the benefits of new transit.

6.3.2 Corridor Analysis

The corridor analysis captures the benefits of transit projects that increase transit frequency or add service in any part of a corridor area defined by the user. The corridor area should be defined as the area within 1 mile of the primary travel route of interest. Figure 12 shows an example diagram of a corridor.

Figure 13 shows the input table for analyses of corridor projects.

The key inputs for corridor projects are transit route miles and revenue miles. Users must input both in order for the calculator to accurately estimate benefits. Users must also enter the length of the corridor and the population living in the area surrounding the corridor. The length is the length of the corridor in question, not the total length of the transit routes serving the corridor. Population estimates will ideally be for the number of people living within 1 mile on either side of the corridor.

6.3.3 Station or Stop Area

The station or stop area analysis captures the benefits of improved transit service for the area within 1 mile of a transit station or stop. Figure 14 shows an example diagram of a station area. Though users can apply this calculator to anything from a rail station to a local bus stop, land use changes are most likely to occur near fixed-route rail or BRT stops or stops with high frequency (i.e., every 15 minutes during peak periods).

Figure 15 shows the input tables for analyses of station or stop area projects.

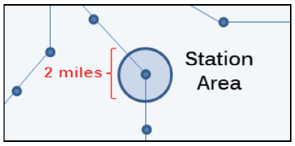
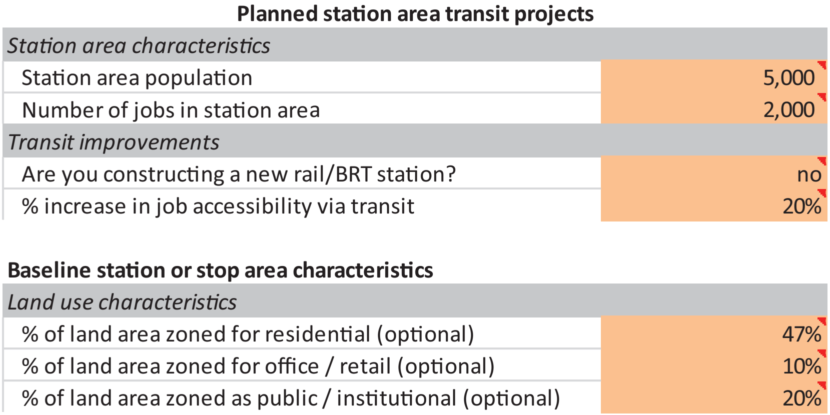


Figure 14. Diagram illustrating area used in station or stop area analysis.



Planned station area transit projects

Station area characteristics	
Station area population	5,000
Number of jobs in station area	2,000
Transit improvements	
Are you constructing a new rail/BRT station?	no
% increase in job accessibility via transit	20%

Baseline station or stop area characteristics

Land use characteristics	
% of land area zoned for residential (optional)	47%
% of land area zoned for office / retail (optional)	10%
% of land area zoned as public / institutional (optional)	20%

Figure 15. Input tables for station or stop area analysis.

The key inputs for station area projects are whether the project includes a new rail/BRT station and the increase in the number of jobs accessible by transit. Users must input at least one of these in order for the calculator to estimate benefits. Users must also enter the number of jobs and people in the station area. Users should be aware of the following:

- You should only enter yes in response to *Are you constructing a new rail/BRT station?* if the station area does not contain any other rail/BRT stations.
- If you are evaluating a new BRT station, only enter yes in response to *Are you constructing a new rail/BRT station?* if the BRT line offers full BRT service that is comparable with a rail line, that is, high-frequency service every 15 minutes or more frequently during peak periods and a dedicated right-of-way along the entire transit line.
- The increase in job accessibility measures the percentage increase in the number of jobs available within a 30-minute transit ride. For example, if 100,000 jobs are currently accessible within 30 minutes by transit from the area, and improvements in transit service or land use changes will increase that number to 110,000, users would enter 10% in this cell. Accessibility is a key determinant of whether transit is a viable travel option. Ideally, the regional travel demand model would be used to estimate increases in job accessibility. In the absence of modeled values:
  - As a general rule of thumb, a 100% increase in transit frequency is associated with a 20% increase in accessibility, based on a statistical analysis of the relationship between accessibility and transit frequency using nationwide data from the EPA Smart Location Database.[13]
  - One agency pilot testing the calculator assumed that a 25% increase in transit speed would produce a 25% increase in job accessibility. This is a reasonable placeholder assumption if no modeled estimates are available, but should be considered in the context of the location of job centers accessible via transit.
- Planning agencies often consider the broader neighborhood surrounding a transit station to be the station area; the statistical analysis underlying this calculator focuses on the area within a 1-mile radius of a station or stop, so the resulting estimates will be most accurate if you enter the number of jobs and people living within that area.

Users also have the option of defining the land use mix in the station area using the baseline station or stop area characteristics table. People drive less in mixed-use areas, so the calculator adjusts baseline VMT downward if people enter a mix of uses.

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[13] http://www.epa.gov/smartgrowth/smartlocationdatabase.htm

6.3.4 Benefits of Current Transit Service

This analysis describes the benefits of the current transit system for a region based on the baseline urbanized area or custom baseline region defined by the user. No additional inputs are necessary.

6.4 Step 4: View Information on the Benefits of Transit

Once you enter data on your project, the calculator will display estimates for the environmental benefits of the project in green cells on the same sheet in which you entered data. The calculator focuses on three different environmental benefits of transit:

- Reduced VMT.
- Reduced gasoline usage.
- Reduced GHG emissions.

All benefits are calculated against a baseline determined using the baseline urbanized area or user-defined region.

The calculator displays benefits in two ways, using two separate columns in the table of benefits:

- Per capita per day.
- Total per year.

Per capita values capture changes in typical travel behavior, while total annual benefits allow comparisons between projects at different scales. Since transit has the biggest effect on areas immediately surrounding stations, smaller-scale projects, such as station area and corridor projects, will tend to produce greater per capita benefits. But since these areas are smaller, fewer people are affected, resulting in smaller total annual benefits.

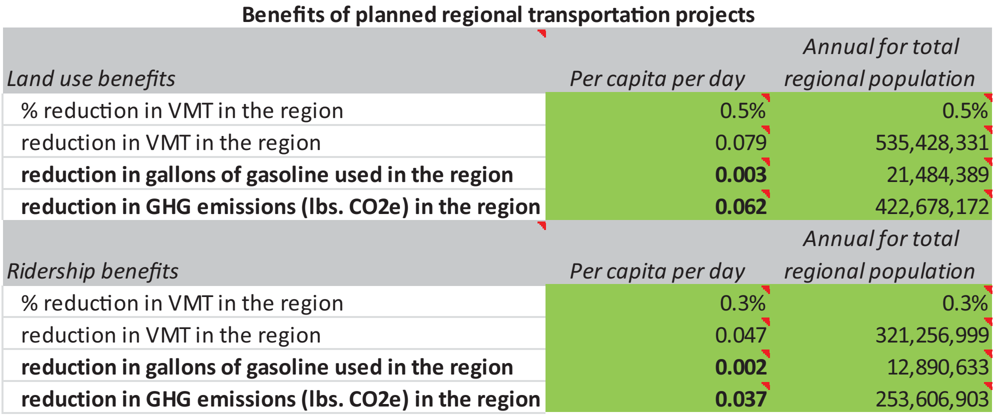
The calculator quantifies benefits due to two different effects of transit on vehicle travel:

- **Ridership effects,** whereby travelers shift from driving to riding transit. Although the calculator estimates the reduction in VMT due to ridership effects, a reduction that is roughly proportional to the increase in transit passenger miles due to improved transit service, the ridership benefits estimated by the calculator are not meant as a substitute for more precise ridership forecasts that transportation agencies routinely produce to analyze new projects.
- **Land use effects,** whereby transit stations anchor development that is more compact, mixed-use, or walkable, all of which reduce VMT. The land use effect of transit is realized when new development occurs, but the development process can be long and complex. If new development takes decades to happen around new transit investments, the land use benefits of transit will likewise take decades to be realized.

The benefits shown by the calculator vary slightly according to the analysis type selected. The following subsections summarize and contain additional notes on the benefits shown for each analysis type.

6.4.1 Regional Analysis

Figure 16 shows the table of benefits for analyses of regional transportation projects. The numbers shown in the table are placeholders provided to illustrate the structure of the calculator's outputs, rather than actual analysis results.



Benefits of planned regional transportation projects

Land use benefits	*Per capita per day*	*Annual for total regional population*
% reduction in VMT in the region	0.5%	0.5%
reduction in VMT in the region	0.079	535,428,331
reduction in gallons of gasoline used in the region	**0.003**	21,484,389
reduction in GHG emissions (lbs. CO2e) in the region	**0.062**	422,678,172
Ridership benefits	*Per capita per day*	*Annual for total regional population*
% reduction in VMT in the region	0.3%	0.3%
reduction in VMT in the region	0.047	321,256,999
reduction in gallons of gasoline used in the region	**0.002**	12,890,633
reduction in GHG emissions (lbs. CO2e) in the region	**0.037**	253,606,903

Figure 16. Table of benefits for analyses of regional projects.

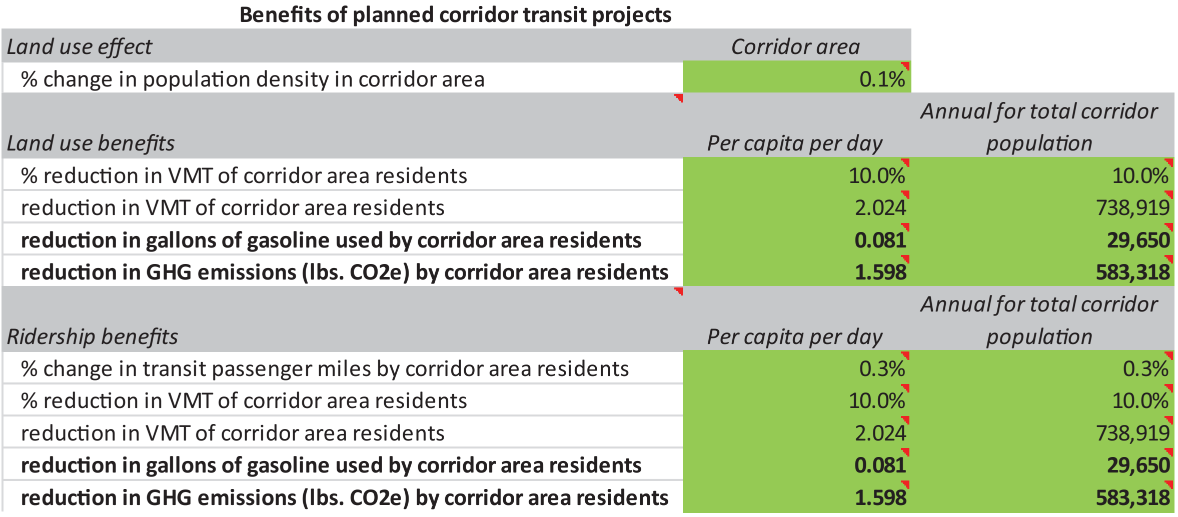
6.4.2 Corridor Analysis

Figure 17 shows the table of benefits for analyses of corridor transportation projects. The numbers shown in the table are placeholders provided to illustrate the structure of the calculator's outputs, rather than actual analysis results.

In addition to the benefits discussed above, the calculator also estimates the percentage change in population density and transit ridership along the corridor. The change in population density does not account for projected growth or other planned land use changes in the station area but represents an estimate of the effect that new transit will have on density, all other factors being equal. As discussed above, ridership estimates are not meant to be a substitute for in-depth ridership forecasts that transportation agencies routinely use to analyze new projects.

6.4.3 Station Area Analysis

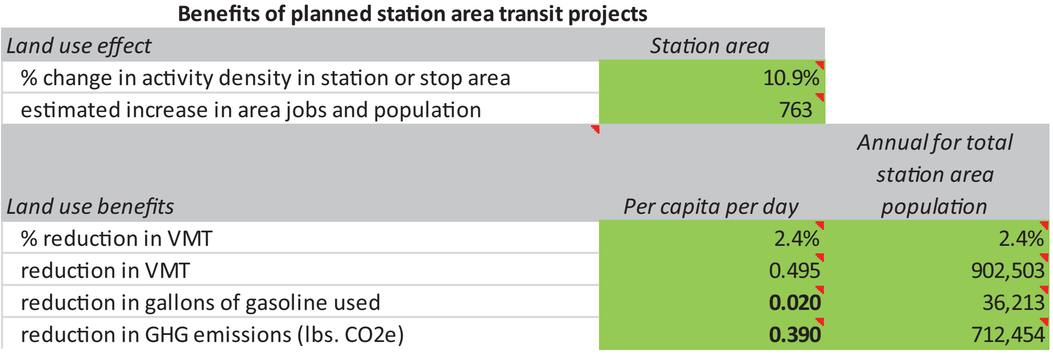
Figure 18 shows the table of benefits for analyses of station area transportation projects. The numbers shown in the table are placeholders provided to illustrate the structure of the calculator's outputs, rather than actual analysis results.



Benefits of planned corridor transit projects

Land use effect	*Corridor area*	
% change in population density in corridor area	0.1%	
Land use benefits	*Per capita per day*	*Annual for total corridor population*
% reduction in VMT of corridor area residents	10.0%	10.0%
reduction in VMT of corridor area residents	2.024	738,919
reduction in gallons of gasoline used by corridor area residents	**0.081**	**29,650**
reduction in GHG emissions (lbs. CO2e) by corridor area residents	**1.598**	**583,318**
Ridership benefits	*Per capita per day*	*Annual for total corridor population*
% change in transit passenger miles by corridor area residents	0.3%	0.3%
% reduction in VMT of corridor area residents	10.0%	10.0%
reduction in VMT of corridor area residents	2.024	738,919
reduction in gallons of gasoline used by corridor area residents	**0.081**	**29,650**
reduction in GHG emissions (lbs. CO2e) by corridor area residents	**1.598**	**583,318**

Figure 17. Table of benefits for analyses of corridor projects.



Benefits of planned station area transit projects

Land use effect	*Station area*	
% change in activity density in station or stop area	10.9%	
estimated increase in area jobs and population	763	
Land use benefits	*Per capita per day*	*Annual for total station area population*
% reduction in VMT	2.4%	2.4%
reduction in VMT	0.495	902,503
reduction in gallons of gasoline used	**0.020**	36,213
reduction in GHG emissions (lbs. CO2e)	**0.390**	712,454

Figure 18. Table of benefits for analyses of station area projects.

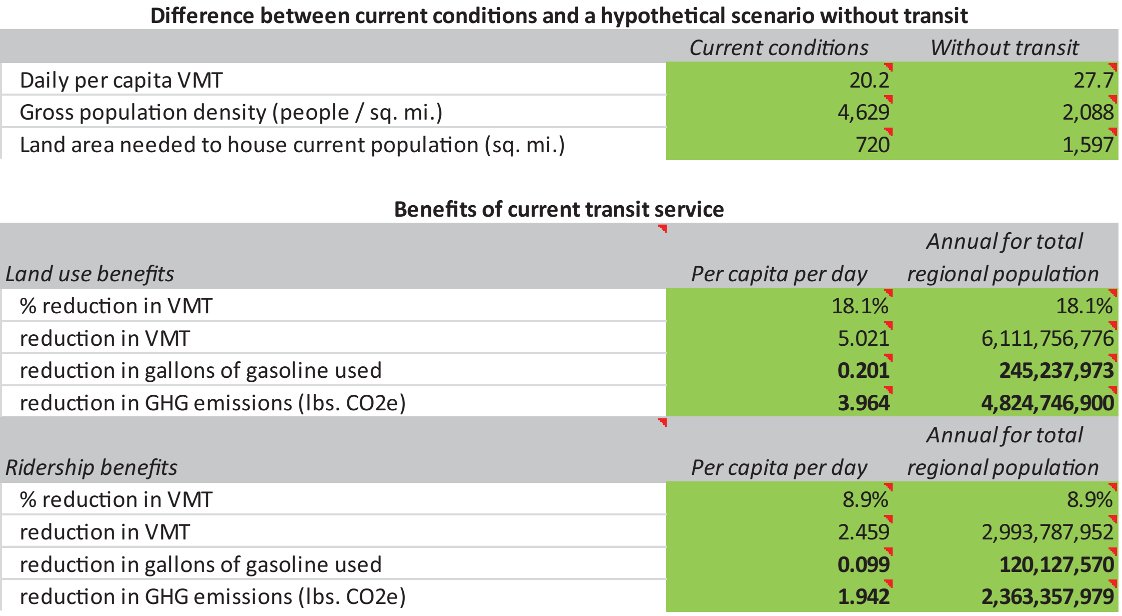
The calculator only estimates benefits due to the land use effect, not those due to the ridership effect. This is because the calculator does not collect sufficient information to estimate baseline ridership at the station area level.

In addition to the benefits discussed above, the calculator also estimates the percentage change in population density and the overall increase in jobs and population in the station area. These estimates do not account for projected growth or other planned land use changes in the station area, but represent an estimate of the effect that new transit will have on density and growth, all other factors being equal.

6.4.4 Benefits of Current Transit Service

Figure 19 shows the table of benefits for analyses of current transit service. The numbers shown in the table are placeholders provided to illustrate the structure of the calculator's outputs, rather than actual analysis results.

The benefits of current transit service are calculated against a hypothetical scenario where the region does not have any transit service. In addition to the benefits discussed above, the calculator compares current VMT, population density, and land consumption for current conditions with transit service to this hypothetical no-transit scenario.



Difference between current conditions and a hypothetical scenario without transit

	Current conditions	*Without transit*
Daily per capita VMT	20.2	27.7
Gross population density (people / sq. mi.)	4,629	2,088
Land area needed to house current population (sq. mi.)	720	1,597

Benefits of current transit service

Land use benefits	*Per capita per day*	*Annual for total regional population*
% reduction in VMT	18.1%	18.1%
reduction in VMT	5.021	6,111,756,776
reduction in gallons of gasoline used	**0.201**	**245,237,973**
reduction in GHG emissions (lbs. CO2e)	**3.964**	**4,824,746,900**
Ridership benefits	*Per capita per day*	*Annual for total regional population*
% reduction in VMT	8.9%	8.9%
reduction in VMT	2.459	2,993,787,952
reduction in gallons of gasoline used	**0.099**	**120,127,570**
reduction in GHG emissions (lbs. CO2e)	**1.942**	**2,363,357,979**

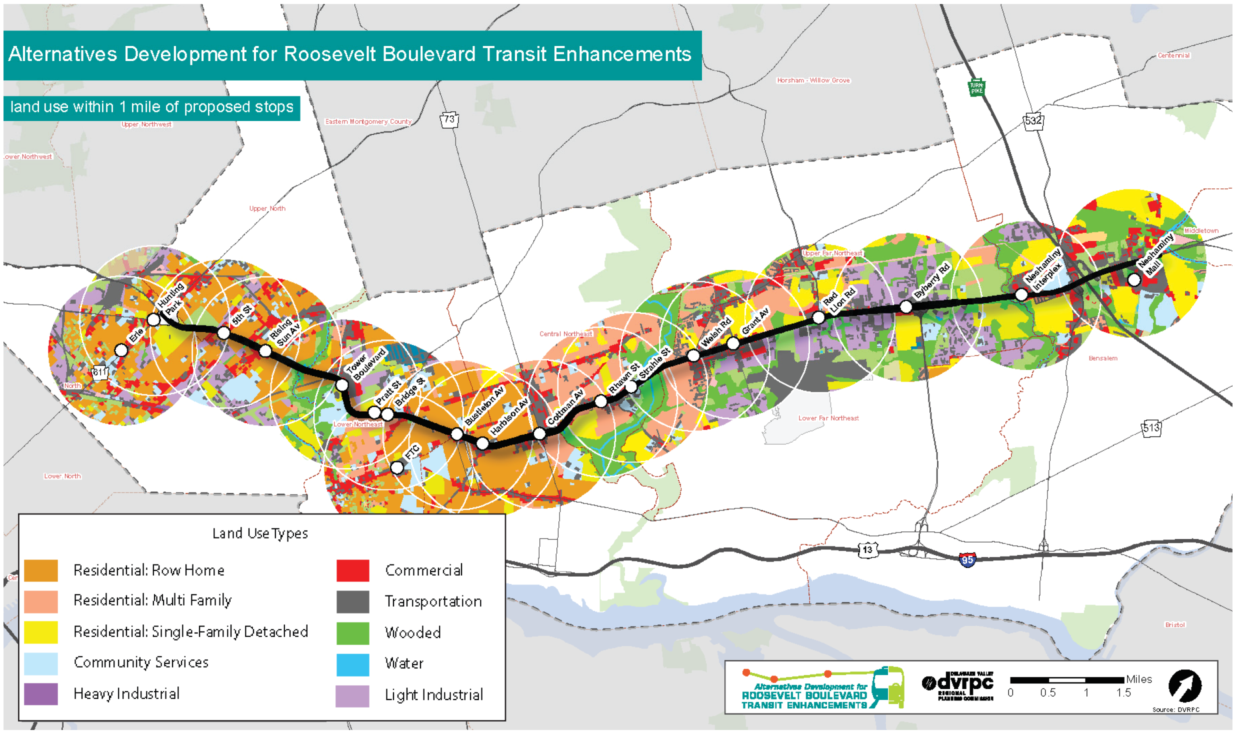
Figure 19. Table of benefits for analyses of current transit service.

6.5 Case Study: Delaware Valley Regional Planning Commission

Delaware Valley Regional Planning Commission (DVRPC) used the calculator to estimate land use effects for an ongoing study, "Alternatives Development for Roosevelt Boulevard Transit Enhancements." The goal of the study is to develop and screen a range of financially feasible alternatives for improved transit along Roosevelt Boulevard that would better meet the needs of neighborhood residents and longer-distance commuters from areas surrounding Philadelphia. DVRPC is in the process of developing a near-term "Better Bus" (or "BRT light") alternative, which will add frequent bus service along partially exclusive rights-of-way with wide station spacing and supportive treatments such as transit signal priority, before eventually developing an exclusive right-of-way BRT. The 15-mile corridor under consideration runs along the wide right-of-way from near Center City Philadelphia in the southwest to Bucks County, Pennsylvania, in the northeast. The proposed route would serve neighborhood residents and longer-distance commuters from surrounding areas. The Roosevelt Boulevard right-of-way ranges from 12 to 14 lanes at major intersections, and the corridor has a significant number of established bus routes and riders.

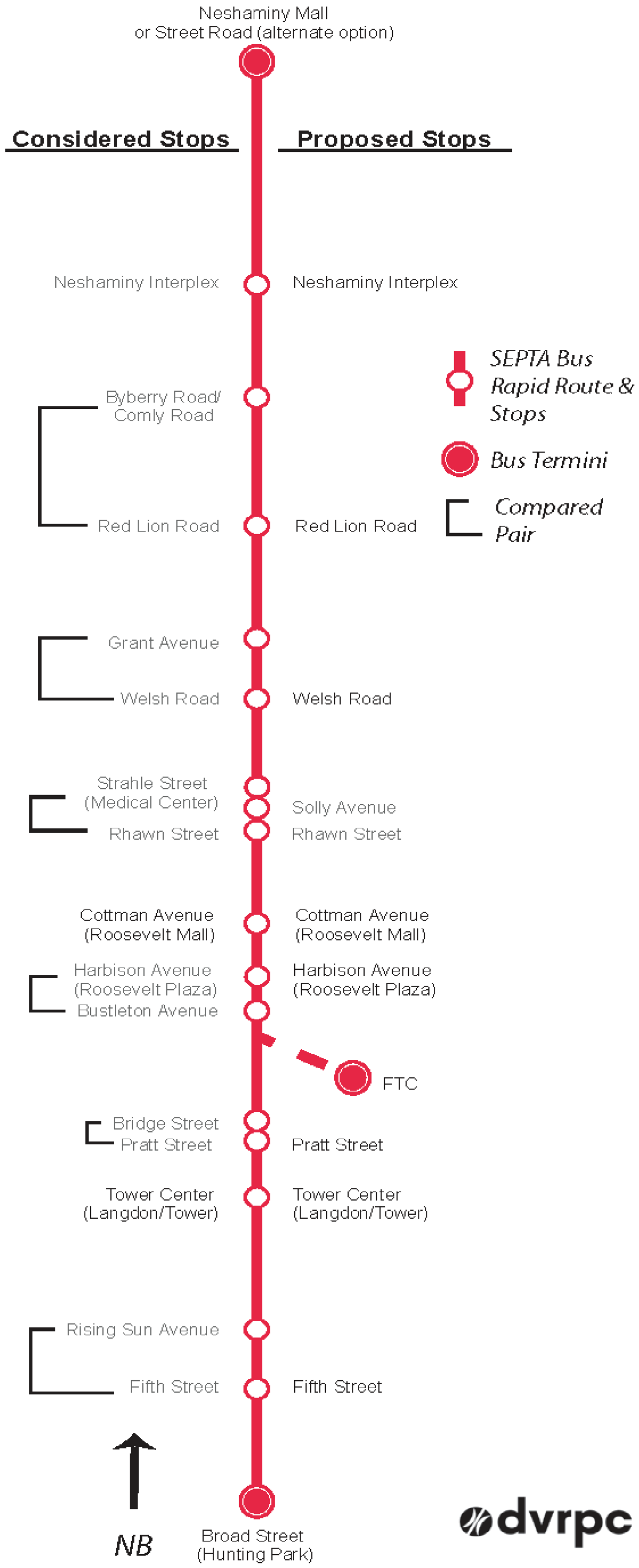
Outputs from the Land Use Benefit Calculator were used, along with a series of other performance measures, to compare alternative candidate stop locations and develop a recommended set of stops for the Better Bus alternative. DVRPC used the station area module of the calculator to examine 18 potential station locations, which include four possible route termini. Additionally, DVRPC used the corridor module to analyze the corridor encompassing all of the potential stations. Figure 20 shows the 15-mile corridor under consideration and the land use patterns within 1 mile of each stop.

To reduce travel time on the new route, DVRPC examined 15 potential stop locations in order to propose 10 stops. Pairs of neighboring stations were compared to select one of the pair to eliminate. The pairs were compared on a number of performance indicators, including the increase in area jobs and population estimated by the calculator. Figure 21 shows the stops under consideration on the left and stops proposed by the study team on the right.



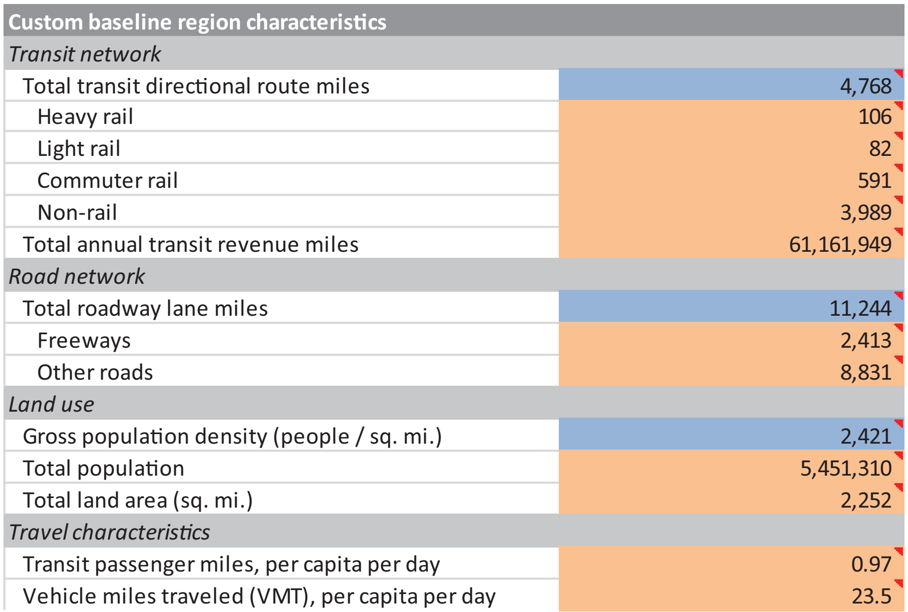
Source: DVRPC, "Alternatives Development for Roosevelt Boulevard Transit Enhancements."

Figure 20. Land use within 1 mile of proposed bus stops, Roosevelt Boulevard development.



Source: DVRPC

Figure 21. Proposed bus stops in Roosevelt Boulevard project.



Custom baseline region characteristics	
Transit network	
Total transit directional route miles	4,768
Heavy rail	106
Light rail	82
Commuter rail	591
Non-rail	3,989
Total annual transit revenue miles	61,161,949
Road network	
Total roadway lane miles	11,244
Freeways	2,413
Other roads	8,831
Land use	
Gross population density (people / sq. mi.)	2,421
Total population	5,451,310
Total land area (sq. mi.)	2,252
Travel characteristics	
Transit passenger miles, per capita per day	0.97
Vehicle miles traveled (VMT), per capita per day	23.5

Figure 22. Baseline data for Philadelphia urbanized area.

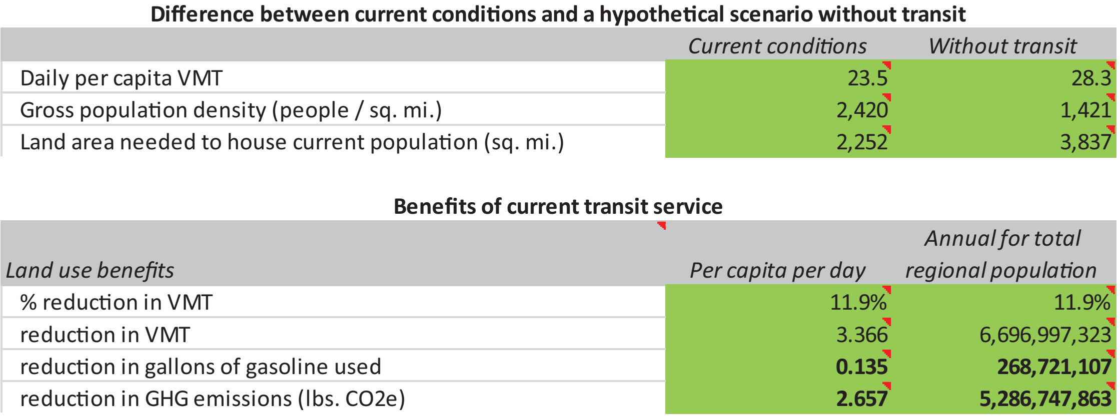
6.5.1 Baseline Region

DVRPC selected the Philadelphia urbanized area for its baseline region. As seen in Figure 20, the bus corridor under consideration covers a diverse range of land use types, representative of the larger region.

Figure 22 shows the baseline transportation network and travel characteristics for the Philadelphia urbanized area, based on 2010 data. The area has approximately 4,000 directional route miles of non-rail transit; this represents over 80% of the 4,768 total transit miles in the region. The population density was roughly 2,400 people per square mile, and daily VMT per capita was 23.5.

6.5.2 Benefits of the Current Transit System

Figure 23 shows the benefits from the current transit system in the greater Philadelphia area. The calculator estimates that without transit, average VMT per capita would be approximately



Difference between current conditions and a hypothetical scenario without transit

	Current conditions	*Without transit*
Daily per capita VMT	23.5	28.3
Gross population density (people / sq. mi.)	2,420	1,421
Land area needed to house current population (sq. mi.)	2,252	3,837

Benefits of current transit service

Land use benefits	*Per capita per day*	*Annual for total regional population*
% reduction in VMT	11.9%	11.9%
reduction in VMT	3.366	6,696,997,323
reduction in gallons of gasoline used	**0.135**	**268,721,107**
reduction in GHG emissions (lbs. CO2e)	**2.657**	**5,286,747,863**

Figure 23. Benefits of the current transit system in the Philadelphia area.

5 miles higher than the current average of 23.5 miles per day per person. The land use benefits from current transit are estimated to have cut over 3 miles per capita per day. This translates into a total reduction of roughly 270 million gallons of gasoline and 5.3 billion pounds of CO_2e emissions per year from land use benefits of current transit.

6.5.3 Corridor Analysis of Land Use Benefits

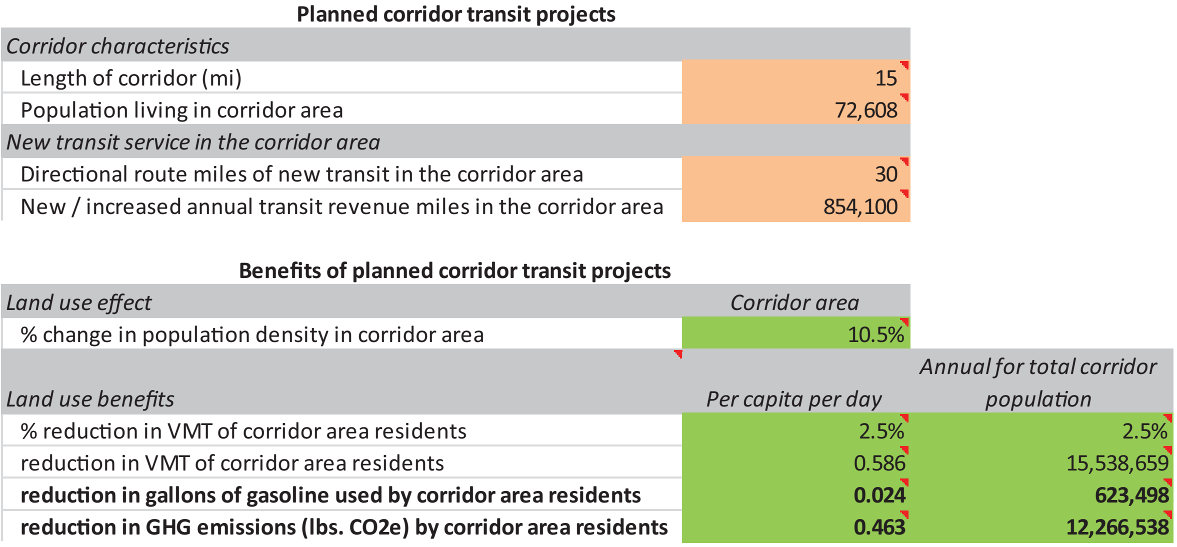
DVRPC analyzed the total benefits of the Roosevelt Boulevard corridor using the corridor module of the calculator in addition to analyzing each bus stop individually (see Section 6.5.4). Figure 24 summarizes the corridor-level benefits from the proposed Better Bus project along Roosevelt Boulevard. These benefits are calculated based on new transit service frequency of 78 vehicles per day along the corridor. The calculator estimates a 10.5% increase in population density in the corridor and a 2.5% reduction in VMT due to land use effects. Assuming the corridor area has the same population density as the Philadelphia region (approximately 2,400 residents per square mile), the VMT reduction in the area translates into a reduction of 620,000 gallons of gasoline and over 12 million pounds of CO_2e emissions per year by the corridor area residents.

6.5.4 Station Area Analysis of Land Use Benefits

DVRPC used the station area module of the calculator to analyze the 18 potential bus stop locations under consideration in the project. With no new rail stations proposed, job accessibility was the primary input and driver of station area results.

While DVRPC plans to model job accessibility along the proposed Better Bus corridor using its regional travel demand model, no model runs had been conducted at the time of this analysis. As a result, DVRPC made assumptions about changes in job accessibility based on preliminary estimates of travel time savings along the corridor:

- A 5% increase in job accessibility was assumed for areas that already had rapid transit (rail) connections to greater Center City, based on enhanced access to other employment locations in the BRT corridor.
- If no other rapid transit is currently available, a 25% increase in job accessibility was assumed because of the 25% decrease in transit travel times for people to get to Center City and University City, the primary job hubs relevant to the project.



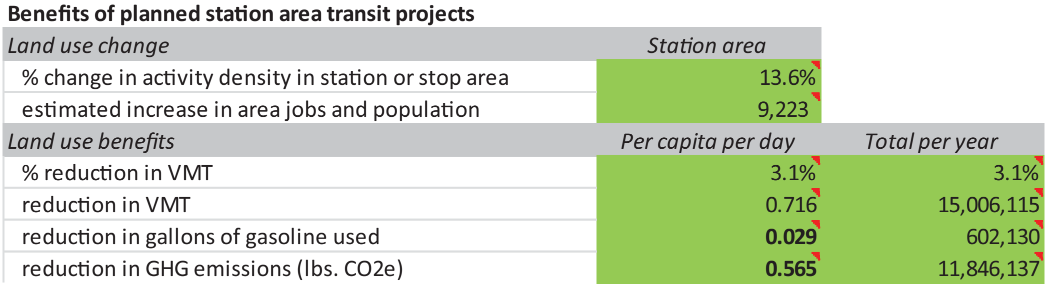
Planned corridor transit projects

Corridor characteristics	
Length of corridor (mi)	15
Population living in corridor area	72,608
New transit service in the corridor area	
Directional route miles of new transit in the corridor area	30
New / increased annual transit revenue miles in the corridor area	854,100

Benefits of planned corridor transit projects

Land use effect	*Corridor area*	
% change in population density in corridor area	10.5%	
Land use benefits	*Per capita per day*	*Annual for total corridor population*
% reduction in VMT of corridor area residents	2.5%	2.5%
reduction in VMT of corridor area residents	0.586	15,538,659
reduction in gallons of gasoline used by corridor area residents	**0.024**	**623,498**
reduction in GHG emissions (lbs. CO2e) by corridor area residents	**0.463**	**12,266,538**

Figure 24. Benefits of Better Bus Roosevelt Boulevard corridor.



Benefits of planned station area transit projects

Land use change	*Station area*	
% change in activity density in station or stop area	13.6%	
estimated increase in area jobs and population	9,223	
Land use benefits	*Per capita per day*	*Total per year*
% reduction in VMT	3.1%	3.1%
reduction in VMT	0.716	15,006,115
reduction in gallons of gasoline used	**0.029**	602,130
reduction in GHG emissions (lbs. CO2e)	**0.565**	11,846,137

Figure 25. Benefits of Cottman Avenue transit stop.

Figure 25 shows the estimated benefits of including a Better Bus stop at one of the proposed stop locations, Cottman Avenue. The station area analysis estimates an increase of over 9,000 residents and workers—a 13.6% increase over the baseline—within 1 mile of the stop over the long term. This increased density reduces VMT by 3.1%, or over 15 million vehicle miles traveled per year for the 57,000 residents in the stop area. The resulting environmental benefits are over 600,000 gallons of gasoline saved and nearly 12 million pounds of CO_2e reduced per year.

6.6 Case Study: Utah Transit Authority—Frontlines 2015 Rail Plan

The Utah Transit Authority (UTA) used the calculator to estimate the land use effects of its Frontlines 2015 rail plan for the greater Salt Lake City Area. Frontlines 2015 added 50 directional miles of light rail in four extension projects to the 39 miles that were already operational in 2010. All projects in the Frontlines 2015 plan were completed between 2011 and 2013. UTA used the calculator to estimate the long-term land use benefits that are expected from the expansion. Figure 26 shows light-rail improvements included in Frontlines 2015.

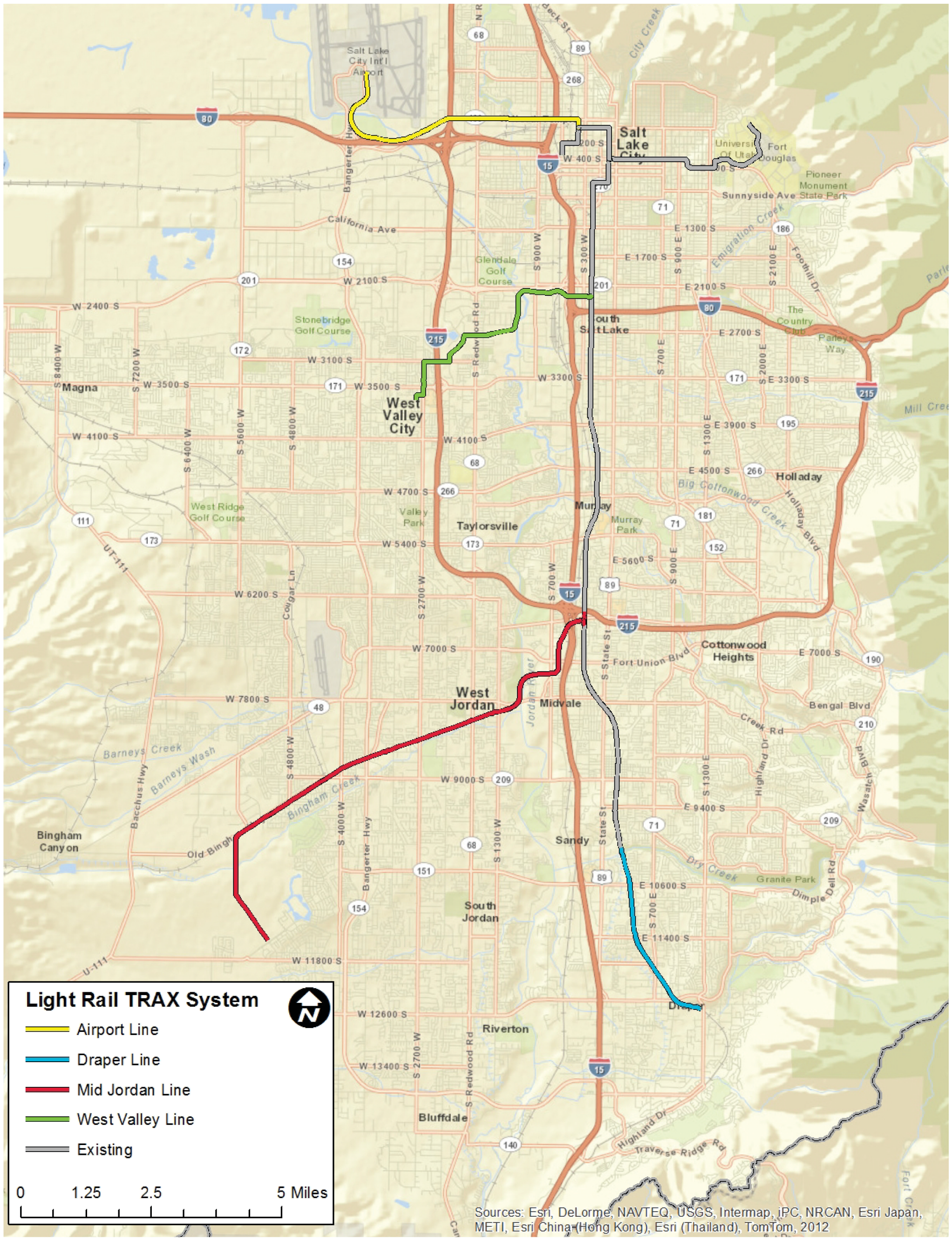
6.6.1 Baseline Region

UTA used the Salt Lake City, Utah, urbanized area as its baseline region. Because UTA's transit service area covers multiple urbanized areas (including Provo), UTA is a candidate for defining a custom region in the calculator (see information on defining custom regions in Section 6.1.3). Because UTA only analyzed new transit projects that fall within the Salt Lake City urbanized area, it was reasonable to use the default region as the baseline. Therefore, UTA declined to enter data to define a custom region.

Figure 27 shows the baseline data for the Salt Lake City urbanized area. In addition to the 39 directional miles of light rail, in 2010 the Salt Lake City region had 88 directional miles of commuter rail and more than 2,000 directional miles of bus routes for a total of nearly 2,300 directional route miles of transit. Population density in the region was approximately 3,000 people per square mile and daily per capita VMT was approximately 21.

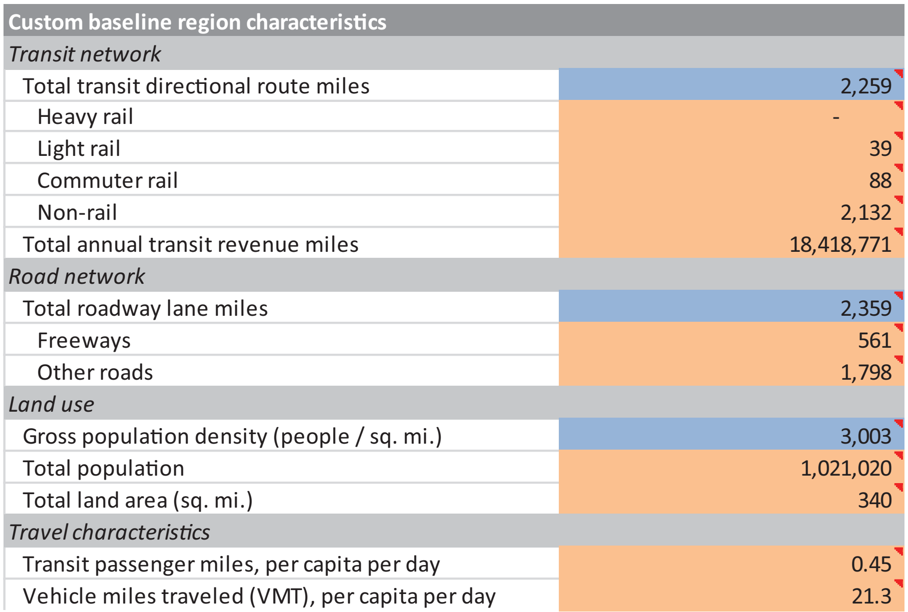
6.6.2 Benefits of the Current Transit System

Figure 28 shows the benefits of the current transit system in Salt Lake City. Daily VMT per capita would be 26 if the region had no transit. The land use benefits of transit alone reduce VMT by 4 per capita per day and gallons of gasoline consumed by 0.2 per capita per day. Total annual land use benefits of transit are savings of 59 million gallons of gasoline and 1.1 billion pounds of CO_2e emissions reduced.



Source: Utah Transit Authority

Figure 26. UTA's Frontlines 2015 rail plan.



Custom baseline region characteristics	
Transit network	
Total transit directional route miles	2,259
Heavy rail	-
Light rail	39
Commuter rail	88
Non-rail	2,132
Total annual transit revenue miles	18,418,771
Road network	
Total roadway lane miles	2,359
Freeways	561
Other roads	1,798
Land use	
Gross population density (people / sq. mi.)	3,003
Total population	1,021,020
Total land area (sq. mi.)	340
Travel characteristics	
Transit passenger miles, per capita per day	0.45
Vehicle miles traveled (VMT), per capita per day	21.3

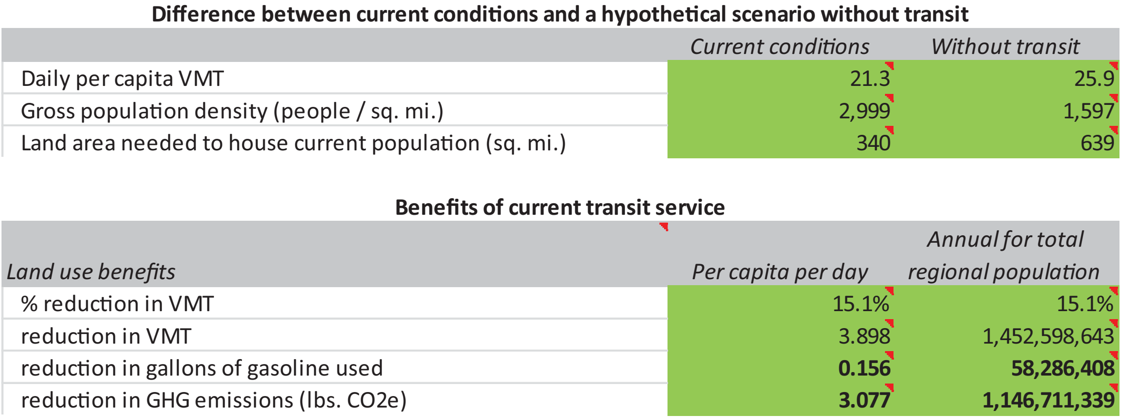
Figure 27. Baseline data for Salt Lake City urbanized area.

6.6.3 Regional Analysis of Land Use Benefits

Figure 29 shows the benefits of the Frontlines Rail Plan. The 50 new directional miles of light rail and 1.7 million new annual transit revenue miles in the Frontlines 2015 plan will reduce VMT per capita by 0.4% in the long term, resulting in savings of 1.3 million gallons of gasoline per year and 26 million pounds of CO_2e emissions reduced.

6.6.4 Corridor Analysis of Land Use Benefits

UTA also separately analyzed a single corridor in the Frontlines 2015 rail plan, the Mid-Jordan corridor. This 10.6-mile corridor serves the southwestern suburbs of Salt Lake City. Figure 30 shows the benefits of the new line to the surrounding area. The Mid-Jordan corridor is expected to increase in population density by 5% over the long term due to the new rail line and reduce VMT of area residents by 1.2%. Assuming the corridor area has average regional population density currently (about 3,000 residents per square mile), residents of the area will save 240,000 gallons of gasoline per year and will see a reduction of 4.7 million pounds of CO_2e emissions per year due to land use benefits.



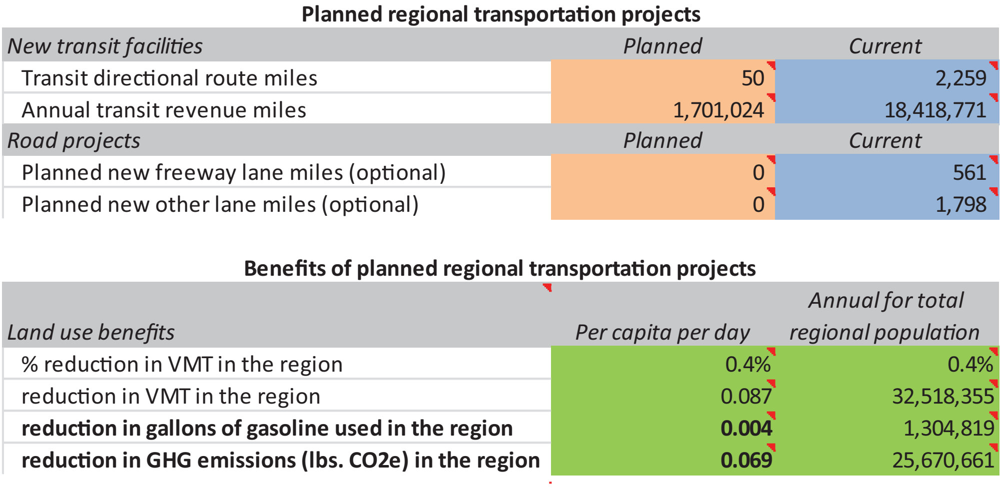
Difference between current conditions and a hypothetical scenario without transit

	Current conditions	*Without transit*
Daily per capita VMT	21.3	25.9
Gross population density (people / sq. mi.)	2,999	1,597
Land area needed to house current population (sq. mi.)	340	639

Benefits of current transit service

Land use benefits	*Per capita per day*	*Annual for total regional population*
% reduction in VMT	15.1%	15.1%
reduction in VMT	3.898	1,452,598,643
reduction in gallons of gasoline used	**0.156**	**58,286,408**
reduction in GHG emissions (lbs. CO2e)	**3.077**	**1,146,711,339**

Figure 28. Benefits of the current transit system in Salt Lake City.



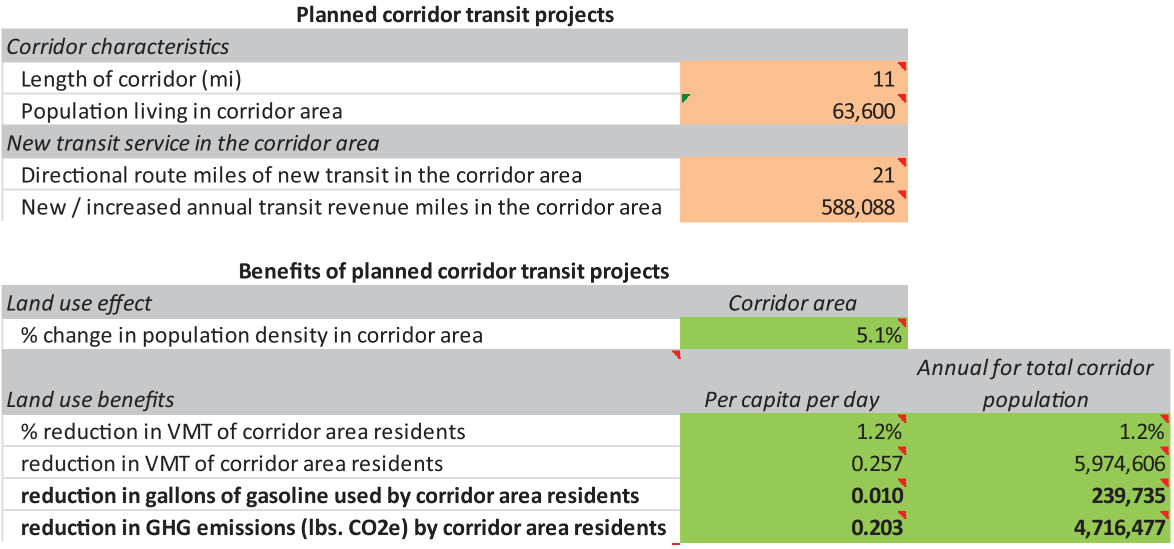
Planned regional transportation projects

New transit facilities	*Planned*	*Current*
Transit directional route miles	50	2,259
Annual transit revenue miles	1,701,024	18,418,771
Road projects	*Planned*	*Current*
Planned new freeway lane miles (optional)	0	561
Planned new other lane miles (optional)	0	1,798

Benefits of planned regional transportation projects

Land use benefits	*Per capita per day*	*Annual for total regional population*
% reduction in VMT in the region	0.4%	0.4%
reduction in VMT in the region	0.087	32,518,355
reduction in gallons of gasoline used in the region	**0.004**	1,304,819
reduction in GHG emissions (lbs. CO2e) in the region	**0.069**	25,670,661

Figure 29. Benefits of Frontlines 2015 rail plan.



Planned corridor transit projects

Corridor characteristics	
Length of corridor (mi)	11
Population living in corridor area	63,600
New transit service in the corridor area	
Directional route miles of new transit in the corridor area	21
New / increased annual transit revenue miles in the corridor area	588,088

Benefits of planned corridor transit projects

Land use effect	*Corridor area*
% change in population density in corridor area	5.1%

Land use benefits	*Per capita per day*	*Annual for total corridor population*
% reduction in VMT of corridor area residents	1.2%	1.2%
reduction in VMT of corridor area residents	0.257	5,974,606
reduction in gallons of gasoline used by corridor area residents	**0.010**	**239,735**
reduction in GHG emissions (lbs. CO2e) by corridor area residents	**0.203**	**4,716,477**

Figure 30. Benefits of Mid-Jordan corridor.

SECTION 7

Recommended Practice for Quantifying GHG Emissions from Transit

The land use benefits quantified in this study can be used to estimate displaced emissions from transit for the purposes of a GHG inventory. APTA's *Recommended Practice for Quantifying Greenhouse Gas Emissions from Transit* (2009) describes three categories of emissions displaced by transit and provides methodologies for their quantification:

- Avoided car trips through mode shift from private automobiles to transit (referred to as the ridership effect in this research).
- Congestion relief benefits through improved operating efficiency of private automobiles, including reduced idling and stop-and-go traffic.
- The land use multiplier, through transit enabling denser land use patterns that promote shorter trips, walking and cycling, and reduced car use and ownership.

The land use multiplier described in the APTA protocol is equivalent to the land use effect analyzed in this research in all but one aspect. The term "multiplier" was used in the APTA protocol because early estimation methods relied on stating the land use effects of transit in proportion to the ridership effects. For example, the APTA protocol recommends using a default national multiplier of 1.9 to estimate land use effects. This figure is multiplied by the total transit passenger miles traveled on a given transit system (with some adjustment for average occupancies of private vehicles traveling in the region).

Table 1 of this report demonstrates that there is no consistent ratio of ridership benefits to land use benefits. For the regions included in Table 1, the ratio ranges from 1:1 to 7:1. There has also been a substantial conclusion about what exact parameter the "multiplier" should be multiplied by. Accordingly, the research team recommends using the term "land use effect" or "land use benefit of transit" going forward.

7.1 Applying the Land Use Benefit in a GHG Inventory

The land use benefit of an existing transit system in terms of VMT, fuel use, and GHG emissions can be quantified using the calculator (available at www.TRB.org/main/blurbs/172110.aspx) produced as part of this research. Land use benefits are not proportional to ridership benefits, but rather are determined by two key variables:

- Transit route density.
- Transit revenue miles.

(See Appendices A and B for a description of the statistical models used to isolate these variables.)

The User Guide in Section 6 explains in detail how to quantify the land use benefit of existing transit by analyzing the benefits of the current transit system in the calculator. The sections that follow expand on that information with more specific detail about using the calculator for GHG quantification.

7.2 Quantifying the Land Use Benefit Using a Pre-Defined Region

Most regions can obtain an estimate of the land use benefit of public transportation in their area by using the calculator's pre-defined regions. It is not essential that the boundary of the pre-defined region (which corresponds to a federal-aid urbanized area) is an exact match for the boundary of the transit service area. Rather, it is most important that the two key variables described above (transit route density and transit revenue miles), as well as per capita VMT, are reasonably representative of the transit service area. Using a pre-defined region will provide a reasonable estimate of the per capita land use benefit in terms of VMT reduction under these circumstances.

To calculate total regional effects in terms of gallons of gasoline saved and CO_2e emissions reduced, users may want to supply their own values for the following:

- **Total regional population.** Verify that the population size of the pre-defined region is a reasonable fit for the transit service area in order to ensure that the total benefits in terms of gasoline consumption and GHG emissions are accurately estimated. If the fit is not reasonable, apply the per capita VMT reduction estimated by the calculator to a user-provided population total.
- **Average fleet fuel economy (mpg).** The calculator uses a single fuel economy assumption of 24.9 mpg for the national light-duty fleet, which is an average of the estimated on-road fleet fuel economy for 2013 to 2035, based on projections from the Department of Energy. Individual regions may want to customize this value using more specific data or projections.

Users can apply the VMT per capita reduction from the calculator to custom values for these variables (total regional population and average fleet fuel economy) in their own calculations outside of the calculator. References to standard GHG emission factors are available in the APTA protocol.

Transit agencies will note that the calculator quantifies the land use benefit of transit for an entire region, while many urban regions are served by more than one transit mode or provider. Regional land use patterns are a complex product of many historical factors, and transit agencies operating in the same region typically comprise an interdependent web of transit networks rather than a series of independent ones. When a rail system is served by feeder buses from another transit agency, there is a combined land use effect of the two. In light of these complex interdependencies, the calculator itself does not quantify land use benefits for separate transit agencies.

Transit agencies that wish to isolate the land use benefits of their service alone could do so in one of two ways:

1. If the transit agency truly operates independently in its own subregion within the pre-defined region included in the calculator, the land use benefits could be isolated by defining a custom region (see below and Section 6.1.3) limited to the transit service area.
2. If the transit agency operates within the same geography as other transit agencies, the regional land use benefits could be apportioned based on the agency's share of total regional route miles or revenue miles. Using route miles would favor agencies with broader geographical coverage while using revenue miles would favor agencies with higher levels of service. Using an average of the two methods is recommended.

7.3 Quantifying the Land Use Effect Using a Custom Region

If no pre-defined region is a reasonable fit for the transit service area of interest, the user can define a custom region. Section 6.1.3 in the user guide provides more information about defining a custom region. Reasons to define a custom region include the following:

- If the urbanized area most closely associated with your transit service area is not included in the calculator.
- If the urbanized area that best aligns with the user's transit service area is significantly smaller than the transit service area. If the transit service area covers multiple urbanized areas, the user should consider creating a custom region to include all relevant urbanized areas.
- If the urbanized area that best aligns with the user's transit service area is significantly larger than the transit service area. For megaregions such as New York and Los Angeles, a single urbanized area can encompass areas with dramatically different transportation and land use characteristics. In these cases, users may want to consider defining a custom area for the subregion of the urbanized area served by their agency.

Note that defining a custom region may require a substantial data collection effort.

SECTION 8

Future Research

Two different statistical models were used in this research to quantify the transportation-related GHG emissions and energy use related to land use changes that can be attributed to transit. Each model used a separate, detailed dataset and provided new evidence of the land use effect.

As with any research based on statistical analysis, this research is limited by the data that could be collected and analyzed. Some topics that stand out as areas for further data collection and research are discussed below.

Different approaches to measuring density should be explored. The urbanized area model used gross regional population density as the measure of urban form, in part because that data point is readily available for multiple urbanized areas. Using gross density in statistical models could understate the magnitude of the land use effect. Population-weighted densities are a better way to represent the variation in densities across large urban areas. Calculation of population-weighted densities would require a substantial data collection and processing effort, but the potential gains for the statistical modeling are large.

Land use planning factors need to be considered in a way that can better inform transit planning processes. Transit agencies are interested in using information on the land use benefits of transit to plan or prioritize transit investments in terms of specific transit modes, routes, and station locations. The amount of development that could be expected within specific timeframes, in response to specific investments, is of particular interest. In order to increase the utility of the land use research for planning purposes, more information is needed on the influence of real estate market factors and public support for compact development on rates of development. These factors have a substantial but unquantified effect on development patterns. Data collection on these topics is a challenge for several reasons. First, tracking detailed development patterns requires the use of parcel-level land data, which are complicated to collect and must be gathered region by region. Second, tracking trends over time requires gathering data for multiple different years. Third, real estate markets and political environments are highly complex and resist being categorized in ways that are discrete and measurable.

An innovative approach to considering these factors in terms of the land use effect is needed. Future work could incorporate more research on predicting the market development potential of particular corridors or neighborhoods or further develop the typologies of market strength and public support used in the ITDP study. Future research may also rely on more qualitative analysis, “LEED-style,” point-based rating systems, or ranges of uncertainty in prediction. In terms of quantifiable land use benefits, transit agencies could claim some credit for land use plans that they help to develop. Research on this topic would benefit from collaboration with land use planning agencies and the real estate industry.

The relationship of transit vehicle capacity to land use development should be explored further. There is an obvious relationship between land use densities and transit vehicle capacities, with higher capacity vehicles generally used in denser areas. While using higher capacity vehicles probably would not encourage densification in and of itself, transit agencies would benefit from more information about the relationships between vehicle capacity and land use patterns. Such a study could include case research on methods that transit agencies use to determine appropriate transit vehicle capacities or instances where development around transit coincided with an increase in transit vehicle capacities.

APPENDIX A

Key Results from Statistical Models

This appendix contains a technical summary of the statistical models used, including datasets, model forms, and specifications of the best-fit models developed. It will give the reader an in-depth understanding of the elasticities developed for application in the TCRP Project H-46 research. A description of the longitudinal analysis of development patterns in Portland is also included.

The level of detail here will be of interest to a general audience. For statisticians and modelers, further detail on the model design is provided in Appendix B: Statistical Models in Depth.

Model Comparison

At the highest level, two types of models using two entirely distinct datasets were constructed for this study:

- **Urbanized area models** were constructed to analyze land use and transportation "ecosystems" over a large number of urban areas. These models use variables that are quantified at the level of FHWA-defined urbanized areas. The models draw on aggregate data that describe the total or average travel, land use, socioeconomic, and transit characteristics of a given region. While these data do not provide specific information about individual travelers or fine-grained information about the areas surrounding transit stations, these data are readily available from national datasets, which enabled the research team to analyze relationships for the nation as a whole.
- **Neighborhood models** were constructed to compare land use and transportation ecosystems in transit-accessible and non-transit-accessible areas *within* individual cities. These models use variables that are quantified at a very fine-grained level: travel patterns and transit access for individual households, land use patterns for specific parcels, and urban design characteristics of neighborhoods. Because this type of data requires much more effort to collect, fewer urban areas are included.

Data availability and data quality are inherent constraints for any statistical modeling exercise. By using two entirely different datasets and modeling approaches, the research team was able to cross-validate results, a unique benefit of this study. The models have different ways of looking at key aspects of the land use effect of transit, as follows:

- **Density**—Development density is quantified as gross population density (total population/total land area) in the urbanized area model. In the neighborhood model, development density includes both population and employment and is calculated at a finer level—the ½-mile radius around each household.
- **Land use mix**—Land use mix is not considered in the urban area model. In the neighborhood model, land use mix is calculated in two ways: (1) the balance between jobs and population in the local area and (2) an entropy value that quantifies the representation of residential, office, retail, and institutional uses.

- **Urban design**—Urban design is not considered in the urban area model. In the neighborhood model, urban design is represented by the density of street intersections in the local area. Places with denser networks of streets are generally more pedestrian friendly.
- **Destination accessibility**—Destination accessibility is not considered in the urban area model. In the neighborhood model, access to regional destinations is quantified as the percentage of regional jobs accessible to each household within 20 minutes driving and within 30 minutes on transit.
- **Transit systems**—In the urban area model, transit systems are represented by four unique variables: total supply of light rail, total supply of heavy rail, route density of transit (route miles/land area), and transit frequency (total revenue miles/total route miles). Bus transit is included in the latter two variables. Each variable represents the entire transit system of an urban area. In the neighborhood model, transit access is characterized for individual households by two variables. One variable indicates whether the household has access to rail transit within ½ mile. A second variable, as described above under "destination accessibility," measures the percentage of regional jobs accessible to each household within 30 minutes on transit. This variable acts as a proxy for both the number of transit routes and the frequency and speed of transit available in a given neighborhood, since households with access to more and better transit service will generally be able to reach a larger number of jobs via transit.

Use of Models

Two important factors not included in the models are public support and the strength of the market for land development. As described in Section 4.6.1 of this report, previous research has discussed the importance of these factors to the land use effect (Cervero et al. 1995, ITDP 2013). Since these aspects of urban development are not captured in the datasets used in this study, the research team used contextual clues to interpret the importance of these variables to the model results.

The following subsections describe the urbanized area models and the neighborhood models in turn. The basic process for each began with data collection and verification. Next, the research team constructed a best-fit model for each dataset using statistical analysis software. The best-fit model is the series of equations that best explains the relationships between variables within the dataset, based on widely accepted statistical goodness-of-fit measures. Finally, the research team interpreted results from each model in terms of the land use effect of transit. This step includes adjusting assumptions about individual transit systems, using the model equations constructed, to see how the land use effect of transit is impacted.

Urban Area Model

The urban area model was constructed with a statistical technique called structural equation modeling (SEM), as described in Appendix B: Statistical Models in Depth. SEM was an ideal approach for this analysis because it allowed the research team to analyze how multiple variables both influence and are influenced by each other and to isolate the effects of a given causal pathway in the transportation and land use ecosystem.

Model Description

Figure 31 illustrates how an SEM model creates equations for multiple relationships (illustrated by multiple arrows) to examine the influence of transit and land use on VMT and distinguishes between different types of variables. Note that the model diagram for an actual SEM model is more complex, because the model may include multiple transit, land use, or control variables that influence each other.

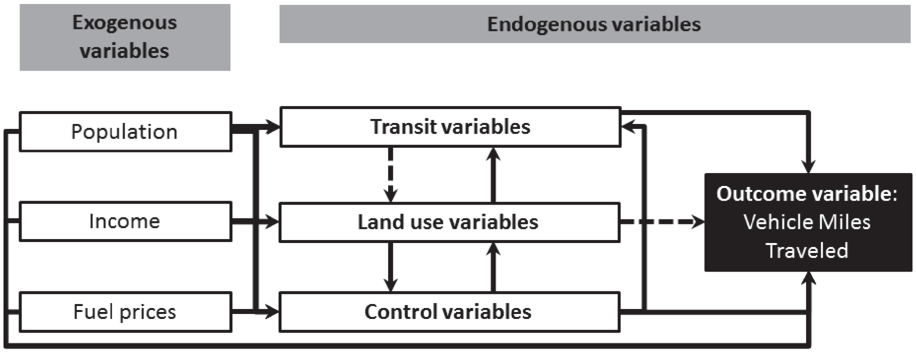


Figure 31. Example SEM model of the effects of transit and land use on VMT.

The primary purpose of the urbanized area model is to examine differences in travel behavior between urbanized regions that have experienced different levels and types of transit investment. The urbanized area models enabled the research team to answer the following research questions:

- What is the total land use effect of an urban area's existing transit system?
- What is the likely additional land use effect within the urban area of incremental improvements in the transit system?

Table 5 contains descriptions of variables and data sources of variables included in the final urban area model. The research team collected all variables for 315 urbanized areas for years

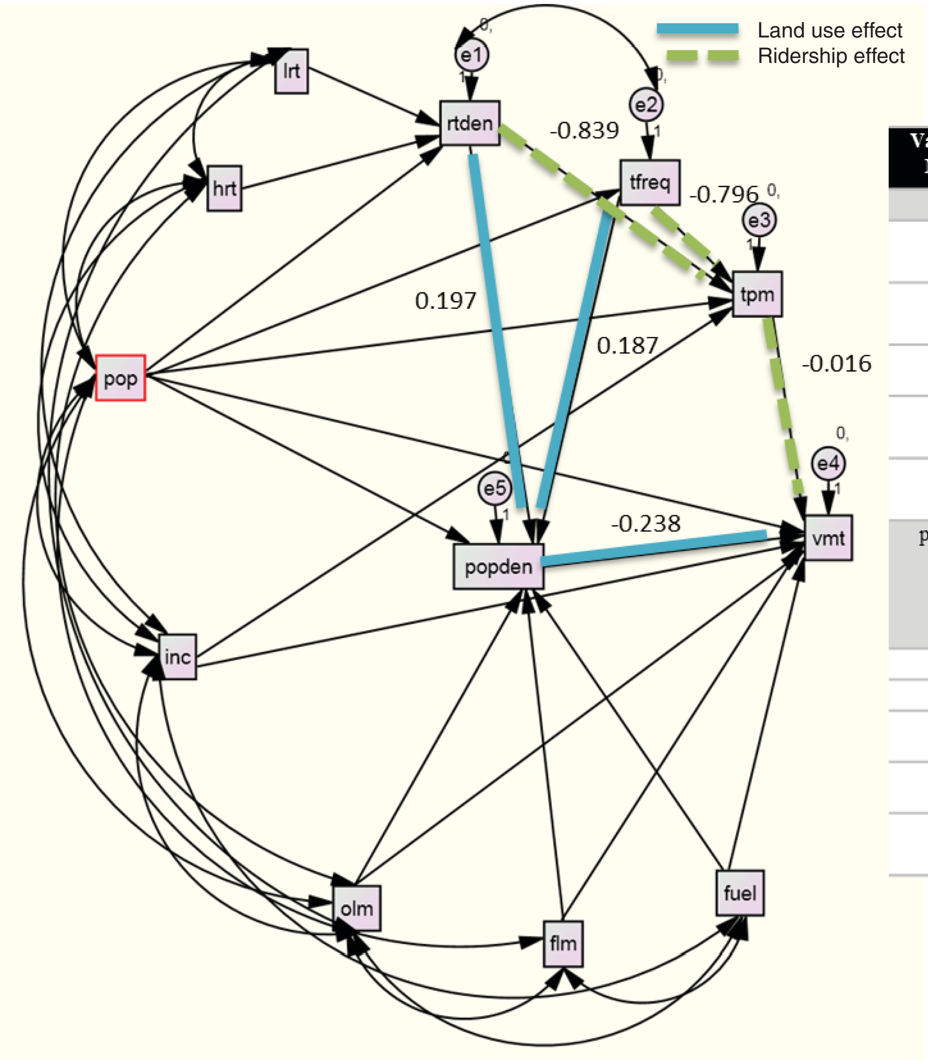
Table 5. Variables and data sources of variables included in the urban area model.

Category	Variable Name	Variable Definition	Source
Outcome variable	vmt	Daily VMT per capita	FHWA Highway Statistics
Transit variables	tfreq	Transit service frequency (annual revenue miles/route miles)	National Transit Database
	rtden	Transit route density per square mile (route miles/land area)	National Transit Database
	tpm	Annual transit passenger miles per capita	National Transit Database
	hrt	Directional route miles of heavy-rail lines per 100,000 population	National Transit Database
	lrt	Directional route miles of light-rail lines per 100,000 population	National Transit Database
Urban form variables	popden	Gross population density (in persons per square mile), excluding rural census tracts with fewer than 100 persons per square mile	U.S. Census
Control variables	pop	Population (in thousands)	U.S. Census
	inc	Annual per capita income	American Community Survey
	flm	Freeway lane miles per 1,000 population	FHWA Highway Statistics
	olm	Other street lane miles per 1,000 population	FHWA Highway Statistics & NAVTEQ
	fuel	Metropolitan average fuel price (in 1982 dollars)	Oil Price Information Service

2000 and 2010. Variables tested but not ultimately included were average transit fares and vehicle revenue miles, both derived from the National Transit Database. The latter is incorporated in the transit frequency variable.

Figure 32 shows the best-fit model that illustrates the relationships among the variables presented in Table 5. Causal pathways associated with the land use effect are highlighted with the solid blue line. Higher route densities and higher transit frequencies are associated with higher population density, and higher population density is in turn associated with lower VMT per capita. Causal pathways associated with the ridership effect of transit are highlighted with a dashed green line. Higher route densities and higher transit frequencies are also associated with higher transit passenger miles, which is in turn associated with lower VMT.

Other model forms were tested but ultimately rejected because they did not produce as good a fit with the model data. The research team also tested models using only a subset of urban areas to determine whether relationships among key variables were different in cities that have rail versus cities that do not and in urban areas of different sizes. These models were rejected for having sample sizes that were too small.



Variable Name	Variable Definition
vmt	daily VMT per capita
tfreq	Transit service frequency (annual revenue miles / route miles)
rtden	Transit route density per square mile (route miles / land area)
tpm	annual transit passenger miles per capita
hrt	directional route miles of heavy-rail lines per 100,000 population
lrt	directional route miles of light-rail lines per 100,000 population
popden	gross population density (in persons per square mile), excluding rural census tracts with fewer than 100 persons per square mile
pop	population (in thousands)
inc	annual per capita income
flm	freeway lane miles per 1,000 population
olm	other street lane miles per 1,000 population
fuel	metropolitan average fuel price (in 1982 dollars)

Figure 32. Best-fit model for the relationships among transit, land use, and VMT in urbanized areas.

Table 6. Land use effect elasticities derived from the urban area model.

Transit Variable	Land Use Effect (Elasticity of VMT)
Route Density	–0.0469
Transit Frequency	–0.0445

Results

Table 6 includes elasticity values for the key variable relationships making up the land use effect and the ridership effect. An elasticity represents the percentage change in one variable associated with a percentage change in another variable in the model. For example, the elasticity of VMT per capita with respect to population density is –0.238. This means that a 1% increase in population density is associated with a 0.24% decrease in VMT per capita. This result is consistent with the literature on the topic, given that other urban form variables that have an impact on VMT (land use mixing, urban design, and destination accessibility) are not accounted for in the model (Ewing et al. 2008). A 1% increase in transit passenger miles per capita is associated with a 0.02% decrease in VMT per capita. This result makes intuitive sense when one considers the scale of transit travel relative to car travel. Only 4% of all trips are made by transit in the United States. In contrast, 84% of trips are made by driving or riding as a passenger in a private vehicle.[14] The quantity of 1% of transit passenger miles is thus far smaller than 1% of VMT. The elasticity can be interpreted as indicating that roughly one out of every two or three trips made on transit replaces a car trip.

Table 6 shows the land use effects of the two transit variables or, in other words, the elasticity of VMT per capita with respect to the transit variables, following the land use effect pathways. The final values are derived by multiplying the elasticities along each pathway. The land use effect of a 1% increase in route density is a 0.047% decrease in VMT per capita. The land use effect of a 1% increase in transit frequency is nearly the same, a 0.045% decrease in VMT per capita.

The model presented shown in Figure 32 is based on "logged" versions of key variables, meaning that the natural log of each variable was the model input. This type of model best answers the question of how incremental improvements in transit systems will change the land use effect. To examine the land use effects of existing transit systems, a similar model was constructed using variables that were not log transformed. The specifics of that model are provided in Appendix B: Statistical Models in Depth.

The urban area model provides strong evidence of a land use effect of transit at the regional scale, based on the regional characteristics of more than 300 urban areas. Both expanding the transit network and increasing transit service frequencies are associated with higher overall gross regional densities and therefore with lower VMT per capita. However, densities can vary substantially within a region. In order to examine the land use effect of transit at a finer scale, models using more detailed datasets are required.

Neighborhood Model

A neighborhood model was constructed in order to examine the land use effect of transit at a finer scale. Whereas the urban area model was constructed by comparing whole regions to one another, the neighborhood model was constructed by comparing neighborhoods to one

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[14] 2009 NHTS. Includes all buses, trains, streetcar, and trolleys. Excludes taxicabs.

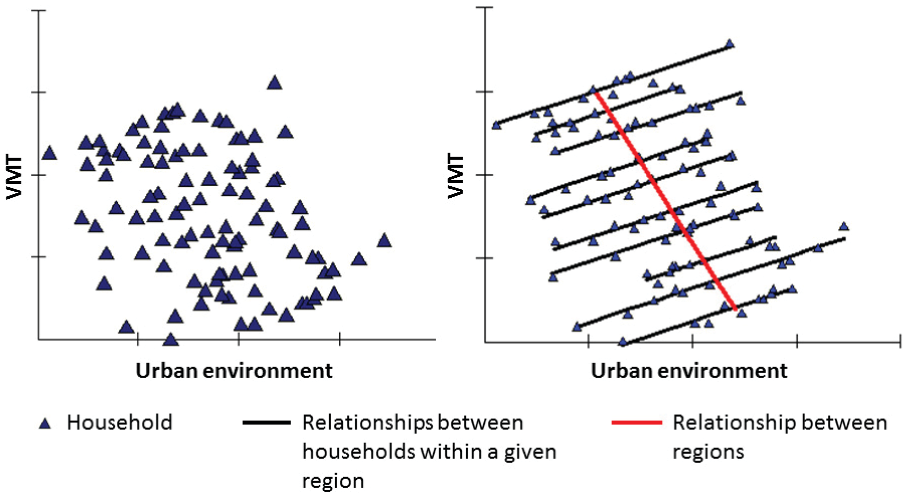
another, where neighborhoods are distinguished primarily by their level of access to transit. This modeling exercise required collecting highly detailed data on neighborhoods and households within a handful of cities.

Model Description

The statistical analysis technique used is called multilevel modeling (MLM) or hierarchical modeling (HM) and is explained in detail in Appendix B: Statistical Models in Depth. To construct the model, the research team needed to compare the land use patterns and transportation characteristics of neighborhoods with varying levels of transit service to one another. In order to compile a sufficient sample of neighborhoods, data from multiple cities had to be used. However, comparing a neighborhood in one city to a neighborhood in a different city introduces complications, since each city has its own unique regional transportation and land use characteristics that impact its neighborhoods. Neighborhoods located within the same region are more likely to have similar travel patterns. And a transit-oriented neighborhood in the Washington, D.C., area, which has an extensive regional transit system, may have higher transit ridership than the identical neighborhood would if it were located in greater Houston, which does not have such an extensive transit network. MLM allows the analyst to separately analyze sources of variation both between regions and within regions. In the case of this research, the research team was most interested in the sources of variation *within* regions, from neighborhood to neighborhood. Controlling for regional sources of variation makes it possible to use data from multiple regions to inform the comparison of neighborhoods to one another.

Figure 33 illustrates this relationship. Without MLM, there appears to be no relationship between the urban environment of a household and its VMT. With MLM, households are grouped into regions. In this hypothetical scenario, MLM reveals that different regions tend to have higher per capita VMT than others and that the relationship between urban environment and VMT at the neighborhood level is in fact relatively constant, as shown by the identical slopes of the black lines representing regions.

The neighborhood model augments the results of the urbanized area model described in the previous section in several key ways. It incorporates local variations in land use patterns and



Source: Adapted from "Introduction to Multilevel Modelling" (University of Bristol Centre for Multilevel Modelling 2011).

Figure 33. Example illustration of how MLM applies to the neighborhood level model.

travel patterns and includes both population and employment densities. The neighborhood model also explicitly considers more land use characteristics: land use mixing, pedestrian environment, and job accessibility. As a direct result of these advantages, the data collection burden for an individual region in the neighborhood model is orders of magnitude higher than that for an individual region in the urbanized area model.

For this research, data for the neighborhood model were collected from nine regions. To be incorporated in the modeling exercise, each region required a household travel survey and, from the same year as that survey, parcel-level land use data, a detailed model of the transit network, and travel time skims from the regional travel demand model. The research team was able to gather data from nine regions (listed in Table 7). The regions are diverse in their travel and land use characteristics. Average daily household VMT ranges from 21 in Boston and Eugene to 40 in Sacramento. The average activity density in the ½-mile area surrounding each household ranges from a low of 2,500 in Kansas City to a high of 23,000 in Boston.

Table 8 provides the full list of variables used in the neighborhood model.

Using the neighborhood dataset, the research team constructed a series of interrelated models to explain the relationship among transit access, land uses, and travel patterns at the neighborhood level. One model explains the impact that transit service has on local densities. Other models explain the relationship that local densities and urban form have on travel patterns. Linking these models together allowed the research team to quantify the land use benefits of transit. A complete description of the model specifications is provided in Appendix B: Statistical Models in Depth.

The conceptual framework used in the neighborhood model is very similar to that of the urbanized area model, although the specific variables used are different. Figure 34 illustrates the model theory. Causal pathways associated with the land use effect are highlighted with a solid blue line. Rail access and higher employment accessibility by transit are associated with higher population density, and higher population density is in turn associated with lower VMT per capita. Causal pathways associated with the ridership effect of transit are highlighted with the dashed green line. Rail access and higher employment accessibility by transit are also associated with higher transit passenger miles, which is in turn associated with lower VMT. Other

Table 7. Travel and land use characteristics of cities used to derive the neighborhood model.*

	Average Daily Household VMT	Average Activity Density (Jobs + Population per Square Mile)
Austin	37	8,678
Boston	21	22,966
Eugene	21	5,009
Houston	39	5,549
Kansas City	27	2,451
Portland	27	4,364
Sacramento	40	7,321
Salt Lake City	23	7,637
Seattle	30	8,745

*Averages are for the metropolitan-planning-organization-designated modeling region

Table 8. Category, definition, and scale of variables included in the neighborhood level model.

Category	Symbol	Definition	Level
Primary outcome variable	vmt	Household daily VMT	Household
Intermediate outcome variables	ttrips	Household daily transit trips	Household
	actden	Activity density within 1/2 mile (sum of population and employment divided by gross land area in square miles)	Household
Exogenous transit variables	emp30t	Proportion of regional employment accessible within 30-minute travel time via transit (in-vehicle time only)	Household
	rail	Rail station within 1/2 mile (dummy variable; yes=1, no=0)	Household
Exogenous built environmental variables	jobpop	Job-population balance within 1/2 mile of a household (index ranging from 0, where only jobs or residents are present within 1/4 mile, to 1, where there is one job per five residents)	Household
	entropy	Land use mix within 1/2 mile of a household (entropy index based on net acreage in different land use categories that ranges from 0, where all developed land is in one use, to 1, where developed land is evenly divided among uses)	Household
	intden	Intersection density within 1/2 mile of a household (number of intersections divided by gross land area in square miles)	Household
	int4way	Percentage of four-way intersections with 1/2 mile of a household (four-way intersections or intersections where more than four streets meet divided by total intersections)	Household
	emp20a	Percentage of regional employment accessible within a 20-minute travel time via automobile	Household
	emp30a	Percentage of regional employment accessible within a 30-minute travel time via automobile	Household
Household control variables	hhsize	Number of household members	Household
	employed	Number of household members employed	Household
	income	Household income (in 1,000s of 2012 dollars)	Household
Regional control variables	rpop	Total regional population (in 1,000s)	Regional
	remp	Total regional employment (in 1,000s)	Regional
	ract	Total regional activity (sum of population and employment in 1,000s)	Regional
	rind	Regional compactness index (index measuring compactness vs. sprawl based on a combination of four factors that measure density, land use mix, degree of centering, and street accessibility); higher values signify great compactness[a]	Regional

[a] For more information on the regional sprawl index and how it is calculated, see *Measuring Sprawl and Its Impact* (Ewing, Pendall, and Chen 2002).

"D" variables[15] including intersection densities, job-population balance, and land use mixing have measurable effects on both activity densities and transit ridership.

Results

Table 9 provides the elasticities of VMT with respect to urban form variables often studied in the literature, as determined by the best-fit neighborhood model. A 1% increase in activity

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[15] Density, diversity of land uses, design, destination accessibility, and distance to transit. See Footnote 4 or Ewing and Cervero (2010) for more information.

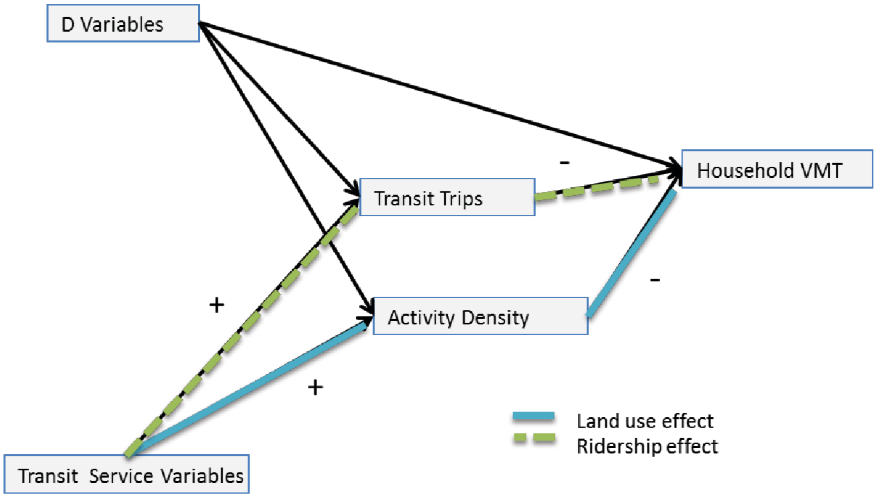

Figure 34. Conceptual model for the relationships among transit, land use, and VMT in neighborhoods.

density is associated with a 0.11% decrease in VMT. This value is somewhat higher than typical values from the literature, but lower than the elasticity of VMT with respect to population density found in the urbanized area model. The latter discrepancy makes sense, given that other "D" variables are controlled for in the neighborhood model that are not controlled for in the urbanized area model. Since "D" variables such as population or employment density, land use mixing, and intersection density are often correlated, we would expect the elasticity of population or employment density to be higher when other "D" variables are not explicitly incorporated into a model. Thus, the elasticities of VMT with respect to density from the urban area and neighborhood models are roughly consistent.

The elasticities of the two land use mixing variables, job-population balance and entropy, are in the range of –0.03 to –0.04. The elasticities of the street network variables are in the range of –0.09 to –0.10. The elasticity of regional employment accessibility is –0.10.

Since higher activity densities are typically associated with denser street networks, better land use mixing, and better employment accessibility, it makes sense to use a higher elasticity of VMT with respect to density. In order to be consistent with the urban area model, an elasticity of –0.24 was used. This puts the effect of land use on VMT within the range of values used in the literature.

Table 9. Elasticities of VMT with respect to key urban form variables.

Urban Form Variable	Elasticity of VMT with respect to variable
Activity density (population and employment divided by land area)	–0.112
Job-population balance	–0.037
Entropy	–0.032
Intersection density	–0.102
Percentage of four-way intersections	–0.088
Percentage of regional employment accessible within 20 minutes by automobile	–0.104

Table 10. Land use effects derived from the neighborhood model.

Transit Variable	Land Use Effect (Activity Density Increase)	Land Use Effect (VMT Decrease)
Rail Station Accessible within ½ mile	9%	2%
Transit Employment Accessibility Increases by 50%	32%	8%

The best-fit neighborhood model finds two key transit variables that impact the land use effect: rail access and employment accessibility via transit. Both are intuitive components of the land use effect. Rail access is associated with higher activity densities, as can be observed in many urban areas where rail stations are surrounded by dense development. Transit employment accessibility measures the percentage of regional employment that is accessible within 30 minutes from the closest transit station (excluding access times). The best-fit model finds that activity densities tend to be higher in places that have better employment access. This phenomenon is born out in studies of newer transit-oriented developments, which find that proximity to downtown and other job markets has an important impact on the ability of transit station areas to attract development (CTOD 2011).

Table 10 shows land use effects of transit predicted by the neighborhood model. Adding a rail station to a neighborhood that does not currently have rail accessible within ½ mile is associated with a density increase of 9% and a drop in VMT due to the land use effect of 2%. Increasing transit employment accessibility by 50% (for example, increasing the percentage of regional jobs accessible within 30 minutes from 20% to 30%) is associated with a density increase of 32% and a drop in VMT due to the land use effect of 8%.

To validate these results, the research team applied the findings from the urbanized area model to evaluate the impact of adding a single rail station to a given urban area. For each urban area that currently has a rail system, the research team increased transit directional route mileage by 4. The research team made the following assumptions: rail stations are spaced 2 miles apart and thus the ratio of directional route miles to stations is 4:1; new service on the route would be equivalent to 60 trains per day in each direction (4 trains per hour for 10 hours and 2 trains per hour for 10 hours); and all density changes in the region as a result of the new transit service would occur within the immediate area of influence of the rail station, defined as a 1-mile catchment area around the rail station. On average, for all cities that currently have rail systems, the urbanized area model predicts a 17% increase in population density around the new rail station.[16]

This result provides a strong cross-validation of the urbanized area model and the neighborhood model, since it is expected that the urbanized area model captures broader regional density changes than the neighborhood model, which only captures density changes within 1 mile of a rail station. If *all* density changes due to the new rail station are confined within the 1-mile catchment, the amount of new population and number of jobs would be about double that usually seen within the 1-mile catchment (17%/9% = 1.9). This suggests that the immediate station area accounts for approximately half of the expected regional increase in population and jobs.

Longitudinal Analysis of a Portland Light-Rail Line

Similar to the urbanized area model discussed above, the main neighborhood model constructed is a cross-sectional model. That is, the model explains variation in land use patterns

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[16] This is the population-weighted average for all cities that currently have rail.

according to key transportation factors using a snapshot in time. The model is agnostic on the subject of the time it takes for development patterns to change in response to transit networks.

The datasets used in the neighborhood model provided an opportunity to conduct a parallel longitudinal analysis for a single city, Portland, where the research team was able to obtain datasets for two different years, 1994 and 2011. The 2 years of data reveal empirically observed changes in land use patterns over a 17-year period. Using models similar to those constructed in the cross-sectional analysis, the research team could study the relationship of changes in the transit network to changes in land use patterns.

A quasi-experimental pretest-posttest study design was used. This research design required the research team to select a specific corridor that received a transit investment between the pretest year (1994) and the posttest year (2011). A control corridor that had comparable land use, transportation, and demographic patterns in the pretest year was also selected. Changes observed in the transit investment corridor and the control corridor during the study period were then compared.

The research team selected the Westside LRT line (western portion of the Blue Line) as the transit investment corridor. The portion of interest starts west of downtown Portland and extends through Beaverton out to Hillsboro. The 15-mile section, with 17 stations, opened in 1998, after the first study year survey and well before the second. Much of the alignment is through land that was ripe for development or redevelopment. Station areas have had many years to densify and thereby affect travel behavior.

The control corridor is another corridor heading southwest from downtown Portland to Tigard and beyond. This is a highway corridor, in contrast to the treated corridor, running along the SW Pacific Highway and (for the first few miles) Interstate 5. This portion of the corridor is 12.5 miles long and has 14 interchanges or major intersections.

In order to capture sufficient households to generate statistically valid results, the research team analyzed households living within 2 miles of the new Blue Line stations and households living within 3 miles of the major intersections in the control corridor. Density changes were measured within a ½-mile radius of each household. The effective geography analyzed for each corridor was therefore a 2.5-mile catchment area. Further detail about the study corridors and the experimental techniques applied is provided in Appendix B: Statistical Models in Depth.

With the comparison highway corridor as a baseline, Portland's Westside LRT extension is associated with an increase in activity densities within the 2.5-mile catchment area of 24% and an increase in average daily transit trips per household of 60%. These changes correspond to a 6% household VMT reduction due to the land use effect and an additional 8% VMT reduction due to the ridership effect.

The research team validated these results in comparison to changes in density predicted by the urbanized area model. Adding 30 new directional route miles with service of approximately 60 trains per day in each direction to the Portland region is expected to increase total regional population density by 0.4%. If the population growth is confined to the 2.5-mile catchment area around the transit corridor, densities in the corridor area would increase by 6%. The observed increase in activity densities of 24% demonstrates the high degree of variation in the land use effect of individual transit investments. The 6% estimate from the urbanized area model represents an average response in land use patterns without regard to key determinants, including public support and land potential. The Westside LRT corridor identified for this test had both many sites ripe for redevelopment and one of the highest levels of government support for TOD of any city in the country. The result of these factors was an increase in densities four times that of the average seen in U.S. cities.

APPENDIX B

Statistical Models in Depth

This appendix provides full details of the statistical models used in this research. The level of detail provided here will be of interest to statisticians and modelers.

Cross-Sectional Analysis of Urbanized Area VMT for the Entire United States

Research Design

In this analysis, a cross-sectional model is estimated to capture the long-run relationships between transportation and land use at a point in time, 2010. Each urbanized area has had decades to arrive at quasi-equilibrium among land use patterns, road capacity, transit capacity, and VMT. This quasi-equilibrium is captured via SEM.

Method of Analysis

SEM is a statistical technique for evaluating complex hypotheses involving multiple, interacting variables (Grace 2006). The estimation of SEM models involves solving a set of equations. There is an equation for each "response" or "endogenous" variable in the transit system. Endogenous variables are affected by other variables and may also affect other variables. Variables that are solely predictors of other variables are termed "influences" or "exogenous" variables. They may be correlated with one another but are determined outside the transit system.

Typically, solution procedures for SEM models focus on observed versus model-implied correlations in the data. The unstandardized correlations or co-variances are the raw material for the analyses. Models are automatically compared to a "saturated" model (one that allows all variables to inter-correlate), and this comparison allows the analysis to discover missing pathways and, thereby, reject inconsistent models.

Data

Growing Cooler (Ewing et al. 2008) used data from the Texas A&M Transportation Institute (TTI) Urban Mobility database to estimate VMT models. In this research, data were instead gathered from several different primary sources. This was due to three critical shortcomings of the current TTI database, which contains 2010 data and was released in 2011:

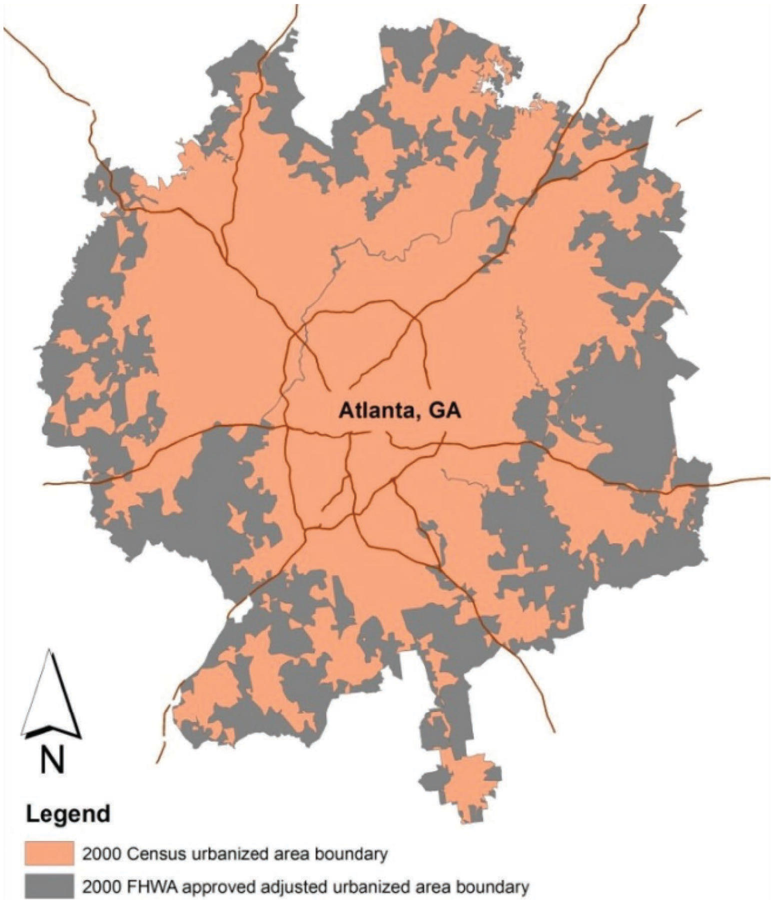
- **Small sample size.** The 2010 TTI database contains data for 101 large urbanized areas. This relatively small sample limits the statistical power of the analysis and the ability to discern significant relationships. It also makes it difficult to generalize results to smaller urbanized areas.
- **No land use variables.** Previous versions of the TTI database contained one land use variable, the gross density of each urbanized area, but this measure has been dropped from more recent

versions. The lack of land use variables makes it impossible to use the current TTI data alone to examine the land use effects of transit on VMT.

- **Discrepancies with official databases.** The TTI database contains estimates of transit passenger miles that differ from the official figures in the National Transit Database. The reason is unclear, but these discrepancies raised the question of whether the TTI database would be appropriate for use in this research.

The research team gathered data from several primary sources for the cross-sectional analysis. For the sake of consistency, the boundaries used to compute explanatory variables had to be the same as the boundaries used to estimate the dependent variable, VMT per capita from FHWA Highway Statistics.

The Highway Statistics definition of urbanized area is different from the Census definition. According to FHWA, "the boundaries of the area shall encompass the entire urbanized area as designated by the U.S. Bureau of the Census plus that adjacent geographical area as agreed upon by local officials in cooperation with the State." Cervero and Murakami (2010) used the Census boundaries for their analysis and deleted urbanized areas from the sample if the Census and FHWA boundaries were hugely different. The research team for this project (TCRP Project H-46) chose not to make such approximations or lose many cases, and therefore set out to find FHWA-adjusted boundaries for urbanized areas in a geospatial shapefile format, which could then be used to conduct spatial analyses in geographical information systems (GIS) (see Figure 35).



Source: Metropolitan Research Center, University of Utah

Figure 35. 2000 Census and FHWA-adjusted urbanized area boundaries for Atlanta.

Based on FHWA advice, the research team contacted individual state department of transportation offices for their shapefiles. From this effort, shapefiles for all 50 states and 443 urbanized areas were obtained. The individual state files were then combined into one national shapefile by using the "merge" function in GIS. Many of the urbanized areas cross state boundaries, resulting in more than one polygon for each urbanized area. So, the "dissolve" function in GIS was used to integrate those polygons into one for each urbanized area.

Several spatial "joins" were conducted in GIS to capture data from other sources. For example, the "centroid" function was used to join 2010 census tracts to FHWA-adjusted urbanized areas. Values of per capita income for census tracts were aggregated to obtain urbanized area averages (weighted by population).

Variables

The variables in the research models are defined in Table 11. The variables fall into three general classes:

- **Outcome variable, VMT per capita.**
- **Exogenous explanatory variables.** The exogenous variables, population and per capita income, are determined by regional competitiveness. The real fuel price is determined by

Table 11. Variables included in the urbanized area model.

Variable	Definition	Source	Mean	Standard Deviation
Dependent variable				
vmt	Natural log of daily VMT per capita	FHWA Highway Statistics	3.09	0.25
Exogenous variables				
pop	Natural log of population (in thousands)	U.S. Census	12.45	1.16
inc	Natural log of income per capita	American Community Survey	10.13	0.19
fuel	Natural log of metropolitan average fuel price	Oil Price Information Service	1.03	0.06
flm	Natural log of freeway lane miles per 1,000 population	FHWA Highway Statistics	−0.46	0.53
olm	Natural log of other lane miles per 1,000 population	FHWA Highway Statistics NAVTEQ	0.91	0.32
hrt	Directional route miles of heavy-rail lines per 100,000 population*	National Transit Database	0.04	0.23
lrt	Directional route miles of light-rail lines per 100,000 population*	National Transit Database	0.09	0.33
Endogenous variables				
popden	Natural log of gross population density	U.S. Census	7.33	0.44
rtden	Natural log of transit route density per square mile	National Transit Database	0.67	0.82
tfreq	Natural log of transit service frequency	National Transit Database	8.51	0.59
tpm	Natural log of annual transit passenger miles per capita	National Transit Database	3.76	1.12

* 1 was added to values so that urbanized areas with no rail mileage would have a zero value when log transformed.

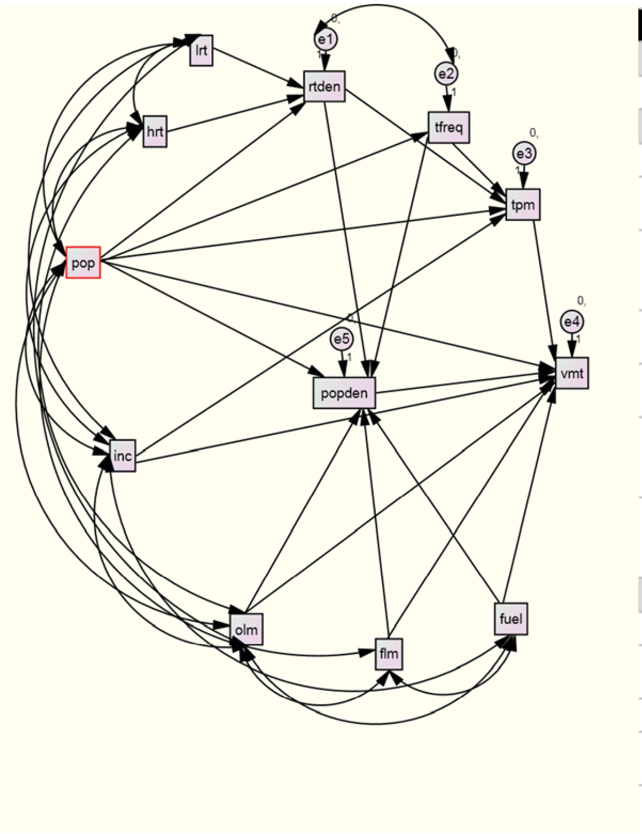
federal and state tax policies and regional location relative to ports of entry and refining capacity. Variables representing highway capacity and rail system capacity were also treated as exogenous, as they are the result of long-lived policy decisions to invest in highways or transit.

- **Endogenous explanatory variables.** The endogenous variables are a function of exogenous variables and are, in addition, related to one another. They depend on real estate market forces and regional and policy decisions: whether to increase transit revenue service and/or whether to zone for higher densities.

All variables were transformed by taking natural logarithms. The use of logarithms has two advantages. First, it makes relationships among the variables more nearly linear and reduces the influence of outliers (such as New York and Los Angeles). Second, it allowed the research team to interpret parameter estimates as elasticities, which summarize relationships in an understandable and transferable form.

Model

The SEM model was estimated with the software package Amos (version 7.0, SPSS 2007) and maximum likelihood procedures. The path diagram in Figure 36 is copied directly from Amos. Causal pathways are represented by uni-directional straight arrows. Correlations are represented by curved bi-directional arrows (to simplify the already complex causal diagram, some correlations are omitted). By convention, circles represent error terms in the model, of which there is one for each endogenous (response) variable.



Variable	Definition
Dependent variable	
vmt	Daily VMT per capita
Exogenous variables	
pop000	Population (in thousands)
inc000	Income per capita (in thousands)
fuel	Average fuel price metropolitan average fuel price
flm	Freeway lane miles per 1,000 population
olm	Other lane miles per 1,000 population
hrt	Directional route miles of heavy-rail lines per 100,000 population
lrt	Directional route miles of light-rail lines per 100,000 population
Endogenous variables	
popden	Gross population density
rtden	Transit route density per square mile
tfreq	Transit service frequency
tpm	Annual transit passenger miles per capita

Figure 36. Causal path diagram explaining VMT per capita for urbanized areas.

Most of the causal paths shown in the path diagram are statistically significant (have nonzero values). The exceptions are a few paths that are theoretically significant, although not statistically significant.

The main goodness-of-fit measure used to choose among models was the chi-square statistic. Probability statements about an SEM model are reversed from those associated with null hypotheses. Probability values (p-values) used in statistics are measures of the degree to which the data are unexpected, given the hypothesis being tested. In null hypothesis testing, a finding of a p-value <0.05 indicates that the null hypothesis can be rejected because the data are very unlikely to come from a random process. In SEM, a model with a small chi-square and large p-value (>0.05) was sought because that indicates that the data are not unlikely given that model (that is, the data are consistent with the model).

Results

The VMT model in Figure 36 has a chi-square of 26.5 with 22 model degrees of freedom and a p-value of 0.23. The low chi-square relative to model degrees of freedom and a high (>0.05) p-value are indicators of a good model fit.

The regression coefficients in Table 12 give the predicted effects of individual variables, all other things being equal. These are the direct effects of one variable on another. They do not

Table 12. Path coefficient estimates (regression coefficients) and associated statistics for direct effects in the 2010 VMT per capita model (see Figure 36).

			Coefficient	Standard Error	Critical Ratio	P-Value
tfreq	<---	pop	0.235	0.025	9.234	<0.001
rtden	<---	lrt	0.495	0.131	3.787	<0.001
rtden	<---	hrt	0.355	0.187	1.900	0.057
rtden	<---	pop	–0.103	0.042	–2.463	0.014
popden	<---	olm	–0.552	0.047	–11.748	<0.001
popden	<---	rtden	0.197	0.017	11.528	<0.001
tpm	<---	pop	0.141	0.041	3.440	<0.001
tpm	<---	tfreq	0.796	0.077	10.406	<0.001
popden	<---	tfreq	0.187	0.023	8.035	<0.001
tpm	<---	rtden	0.839	0.049	17.124	<0.001
popden	<---	flm	–0.108	0.020	–5.383	<0.001
tpm	<---	inc	0.902	0.208	4.345	<0.001
popden	<---	pop	0.066	0.011	5.849	<0.001
popden	<---	fuel	0.733	0.236	3.111	0.002
vmt	<---	fuel	–0.448	0.238	–1.883	0.060
vmt	<---	popden	–0.238	0.043	–5.577	<0.001
vmt	<---	olm	0.040	0.051	0.784	0.433
vmt	<---	flm	0.133	0.021	6.412	<0.001
vmt	<---	inc	0.304	0.062	4.889	<0.001
vmt	<---	tpm	–0.016	0.011	–1.427	0.154
vmt	<---	pop	0.078	0.012	6.635	<0.001

Table 13. Direct, indirect, and total effects of variables on VMT per capita in the cross-sectional model for 2010 (see Figure 36).

	Direct	Indirect	Total
pop	0.078	–0.025	0.052
inc	0.304	–0.015	0.289
fuel	–0.448	–0.175	–0.623
hrt	0	–0.021	–0.021
lrt	0	–0.03	–0.03
flm	0.133	0.026	0.159
olm	0.04	0.131	0.172
popden	–0.238	0	–0.238
rtden	0	–0.06	–0.06
tfreq	0	–0.057	–0.057
tpm	–0.016	0	–0.016

account for the indirect effects through other endogenous variables. Also of interest are the total effects of different variables on VMT per capita, accounting for both direct and indirect pathways (see Table 13).

A number of key factors affect VMT and in some cases urban area density:

- **Population growth** is a driver of VMT growth. As urbanized areas grow, destinations tend to become farther apart (for example, the suburbs are farther from the central business district). Therefore, the direct effect of population size on VMT per capita is positive and significant due to the simple fact of their size. At the same time, as urbanized areas grow, they become denser and shift away from a singular focus on-road capacity to meet travel demands toward a balance of roads and transit.
- **Income.** Another exogenous driver of VMT growth is income. As per capita income rises, people travel more by private vehicle, reflecting the general wealth of the community. The direct effect of per capita income on VMT per capita is positive and highly significant. Income has an indirect effect as well, through transit passenger miles per capita. Surprisingly, the effect of income on transit use is positive; hence the indirect effect on VMT is negative. Wealthier communities may provide more transit service, and higher income residents in large regions such as New York may use transit to commute in from the suburbs.
- **Freeway capacity.** Controlling for other influences, areas with more freeway capacity are significantly less dense and have significantly higher VMT per capita. Areas with more highway capacity in arterials, collectors, and local streets are also significantly less dense (which affects VMT per capita indirectly), but the direct effect of other highway capacity on VMT per capita is not significant. From the standpoint of induced traffic, other roadways are more benign than freeways.
- **Transit** has an effect opposite to that of highways. Areas with more service coverage and more service frequency have higher development densities, which lead to lower VMT per capita. They also have more transit passenger miles per capita, which lead to lower VMT per capita. The causal path through transit passenger miles constitutes the ridership effect of transit on

VMT. The causal path through development density constitutes the land use effect of transit on VMT.

- **The two rail variables, HRT and LRT** directional route miles per capita, are positively associated with route coverage, and through that variable, increase transit passenger miles per capita and reduce VMT per capita. Surprisingly, neither HRT route mileage nor LRT route mileage has a direct effect on the development density of urbanized areas. One possible explanation for the failure of rail to raise densities is the oft-cited potential of rail extensions into the suburbs to cause sprawl, as long-distance commuters park and then ride into the city.
- **The real fuel price** is negatively associated with VMT per capita, both directly and indirectly through an effect on development densities. The direct price elasticity, around –0.45, is what one would expect from the literature (the long-run elasticity being much greater than the short-run elasticity). There are persistent regional variations in real fuel prices, and these appear to affect both urban form and VMT per capita.
- **Urbanized area density** is negatively related to VMT per capita. The elasticity, –0.24, suggests that every 1% rise in density is associated with a 0.24% decline in VMT per capita. With density serving as a proxy for all the "D" variables (density, diversity, design, and destination accessibility), the elasticity looks reasonable.

Simulation of VMT Per Capita in a No-Transit Scenario

The SEM models discussed above represent relationships using logarithmically transformed variables. Logged variables have the advantage of accounting for nonlinear relationships, reducing the influences of outlying data points, and producing regression coefficients that can be interpreted as arc elasticities (percentage changes in VMT with respect to a 1% change in an independent variable). These models are well suited to predicting the effect of incremental changes in one variable or another.

However, log models cannot answer the impacts that would occur in the extreme case of all transit service being eliminated. The log of zero is undefined (equal to negative infinity), so that transit variables in this scenario would be undefined.

Therefore, the research team estimated a new SEM model with linear variables that, in the case of the transit variables, could be zeroed out in a no-transit scenario. The study sample consists of 315 federal-aid urbanized areas that, in 2010, collectively housed 200 million Americans or nearly two-thirds of the U.S. population. Included are all large urbanized areas and most smaller urbanized areas. Some urbanized areas were lost for lack of complete datasets, particularly lack of fuel price data. Some urbanized areas were also lost for lack of complete transportation systems, including transit service and some freeway capacity.

Variables are defined in Table 14. The variable of ultimate interest is VMT per capita. Other endogenous variables are gross population density, transit route density, transit service frequency, and transit passenger miles per capita. Endogenous variables are variables that are influenced by other variables in the modeling transit system and that may influence other variables. The remaining variables, such as miles of light rail, lane miles of freeway per 1,000 population, and average fuel price, are exogenous. Exogenous variables are variables that influence other variables, but whose values are determined outside the transit system.

The model's path diagram (see Figure 37) is very similar to the path diagrams of the logarithmic models. Some causal links were added (straight single-headed arrows); several correlational arrows (curved two-headed arrows) were deleted from the diagram to make it appear less complex.

Table 14. Variables in the urbanized area model.

Variable	Definition	Source	Mean	Standard Deviation
Dependent variable				
vmt	Daily VMT per capita	FHWA Highway Statistics	22.7	5.5
Exogenous variables				
pop000	Population (in thousands)	U.S. Census	635.7	1,559.7
inc000	Income per capita (in thousands)	American Community Survey	25.5	5.1
fuel	Average fuel price metropolitan average fuel price	Oil Price Information Service	2.79	0.16
flm	Freeway lane miles per 1,000 population	FHWA Highway Statistics	0.72	0.38
olm	Other lane miles per 1,000 population	FHWA Highway Statistics NAVTEQ	2.60	0.80
hrt	Directional route miles of heavy-rail lines per 100,000 population	National Transit Database	0.085	0.545
lrt	Directional route miles of light-rail lines per 100,000 population	National Transit Database	0.193	0.785
Endogenous variables				
popden	Gross population density	U.S. Census	1,683.2	824.9
rtden	Transit route density per square mile	National Transit Database	2.82	3.21
tfreq	Transit service frequency	National Transit Database	5,831.4	3,315.1
tpm	Annual transit passenger miles per capita	National Transit Database	79.7	122.5

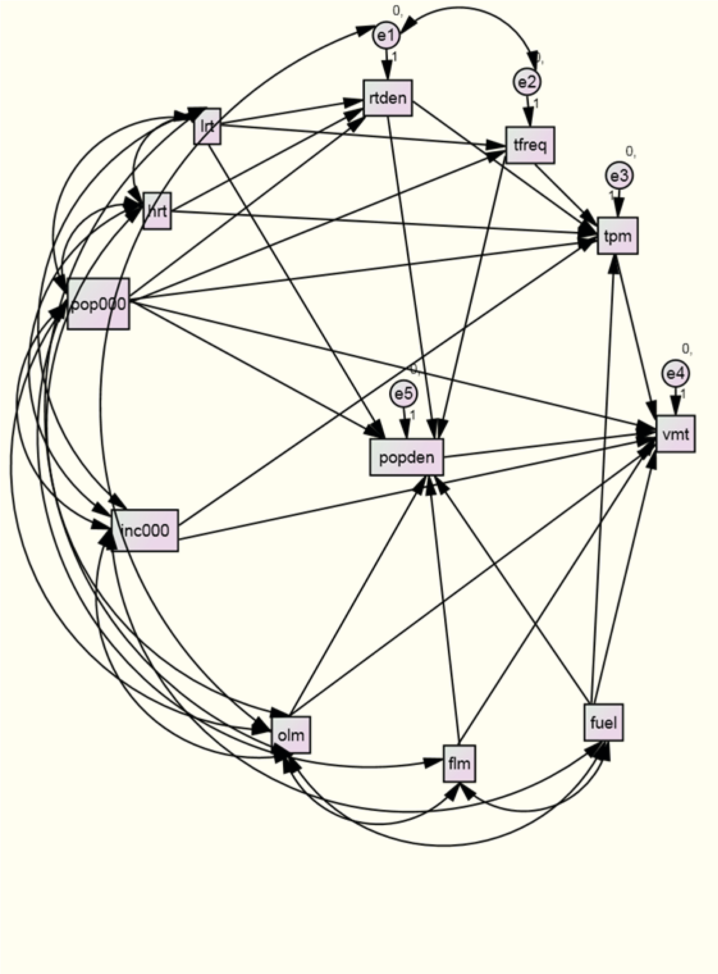
Regression coefficients for direct causal relationships and associated significance levels are shown in Table 15. The regression coefficients give the predicted effects of individual variables on one another, all other things being equal. These are the direct effects of one variable on another, not accounting for the indirect effects through other endogenous variables. The model has a chi-square of 15.0 with 18 model degrees of freedom and a p-value of 0.67. This indicates an extremely close fit between the model and the data.

The two main transit service variables, transit service frequency (tfreq) and transit route density (rtden), affect VMT (vmt) directly through transit passenger miles (tpm) and indirectly through gross population density (popden). The resulting equations for vmt, tpm, popden are:

$$\text{vmt} = 28.87 - 6.105 * \text{fuel} - 0.002 * \text{popden} + 0.471 * \text{olm} + 4.564 * \text{flm} + 0.355 * \text{inc000} + 0.001 * \text{pop000} - 0.006 * \text{tpm}$$

$$\text{tpm} = -491.6 + 0.025 * \text{pop000} + 0.004 * \text{tfreq} + 4.198 * \text{rtden} + 4.134 * \text{inc000} + 59.882 * \text{hrt} + 146.800 * \text{fuel}$$

$$\text{popden} = -746.1 - 354.711 * \text{olm} + 55.895 * \text{rtden} + 0.046 * \text{tfreq} - 316.547 * \text{flm} + 0.108 * \text{pop000} + 1092.585 * \text{fuel} + 144.573 * \text{lrt}$$



Variable	Definition
Dependent variable	
vmt	Daily VMT per capita
Exogenous variables	
pop000	Population (in thousands)
inc000	Income per capita (in thousands)
fuel	Average fuel price metropolitan average fuel price
flm	Freeway lane miles per 1,000 population
olm	Other lane miles per 1,000 population
hrt	Directional route miles of heavy-rail lines per 100,000 population
lrt	Directional route miles of light-rail lines per 100,000 population
Endogenous variables	
popden	Gross population density
rtden	Transit route density per square mile
tfreq	Transit service frequency
tpm	Annual transit passenger miles per capita

Figure 37. Causal path diagram explaining VMT per capita for urbanized areas.

These equations allowed the research team to estimate how the absence of transit would affect VMT for the average urbanized area. Plugging mean values for the sample into the three equations, the research team estimated a mean vmt value of 22.19, a mean tpm of 79.5, and a mean popden of 1,675. These values apply to a status quo scenario. They are entirely comparable to the actual mean values for the sample, 22.7, 79.7, and 1,683, respectively. If tfreq, rtden, hrt, lrt, and hrt are zeroed out in a no-transit scenario, tpm falls from 79.5 to 39.3, popden falls from 1,675 to 1,221, and hence vmt rises from 22.19 to 23.36, a 5.3% rise. One could argue that despite the multivariate equation that says tpm would be 39.3 under this scenario, the actual value of tpm for the no-transit scenario would be zero. Plugging this value into the first equation, vmt would rise from 22.19 to 23.59, a 6.3% rise. The increase in vmt for the typical urbanized area was bounded between 5.3% and 6.3% if transit service were eliminated.

How much of the difference in vmt between the no-transit scenario and status quo is due to the ridership effect of transit through tpm, and how much is due to the land use effect through popden? Using predicted values of both mediating variables (39.3 and 1,221, respectively), the difference in vmt between scenarios is 1.17 vehicle miles per day. Of that, 22% is the ridership effect and 78% is the land use effect. Using the predicted value of popden (1,231) and the more plausible value of tpm (0), the difference in vmt between scenarios is 1.40 vehicle miles per day. Of that, 35% is the ridership effect and 65% is the land use effect.

Table 15. Path coefficient estimates (regression coefficients) and associated statistics for direct effects in the 2010 VMT per capita model (see Figure 37).

			Estimate	Standard Error	Critical Ratio	P-Value
tfreq	<---	pop000	.889	.108	8.223	<0.001
rtden	<---	lrt	.129	.214	.604	0.546
rtden	<---	hrt	.502	.333	1.506	0.132
rtden	<---	pop000	.000	.000	−1.106	0.269
tfreq	<---	lrt	750.004	213.148	3.519	<0.001
popden	<---	olm	−354.711	38.112	−9.307	<0.001
popden	<---	rtden	55.895	9.134	6.119	<0.001
tpm	<---	pop000	.025	.004	6.216	<0.001
tpm	<---	tfreq	.004	.002	2.415	0.016
popden	<---	tfreq	.046	.009	4.953	<0.001
tpm	<---	rtden	4.198	1.735	2.419	0.016
popden	<---	flm	−316.547	66.378	−4.769	<0.001
popden	<---	pop000	.108	.018	5.943	<0.001
popden	<---	fuel	1092.585	187.035	5.842	<0.001
tpm	<---	inc000	4.134	1.012	4.086	<0.001
popden	<---	lrt	144.573	32.719	4.419	<0.001
tpm	<---	hrt	59.882	10.287	5.821	<0.001
tpm	<---	fuel	146.800	34.614	4.241	<0.001
vmt	<---	fuel	−6.105	1.917	−3.185	0.001
vmt	<---	popden	−.002	.000	−3.139	0.002
vmt	<---	olm	.471	.421	1.119	0.263
vmt	<---	flm	4.564	.677	6.743	<0.001
vmt	<---	inc000	.355	.053	6.757	<0.001
vmt	<---	pop000	.001	.000	3.011	0.003
vmt	<---	tpm	−.006	.003	−2.332	0.02

Cross-Sectional Analysis of Household VMT in Nine Diverse Regions

This multivariate analysis pools household travel and built environment data from nine diverse regions of the United States. The model is distinct from many earlier studies for several important reasons:

- **Large, diverse database.** What most distinguishes this study from the many earlier studies of household travel behavior is the external validity (generalizability) that comes with such a large and diverse database. A study using data from cities such as Portland, Oregon, or Houston, Texas, could be challenged for relevance to other regions of the country, particularly when different dependent and independent variables are used in each study. Research that pools data from nine diverse regions and uses consistently defined built environmental variables to predict several consistently defined travel outcome variables should be ready for use in large metropolitan areas across the United States.
- **Multilevel modeling.** Another characteristic that distinguishes this study from earlier ones is the use of multilevel modeling (MLM). MLM overcomes the limitations of ordinary least

squares regression by accounting for the dependence of households in each region on the characteristics of that particular region, dependence that violates the independence assumption of ordinary least squares. MLM thereby produces more accurate coefficient and standard error estimates (Raudenbush and Bryk 2002). While MLM is just beginning to be used in planning studies, it has a rich history in education and public health research.

- **Two-stage "hurdle" models for two of the dependent variables.** A third characteristic that distinguishes this study from earlier studies is the estimation of two-stage "hurdle" models for two of the dependent variables, household VMT (vmt) and household transit trips (ttrips). The study dataset is "zero inflated," which means these two dependent variables have an excessive number of zero values that violate conventional distributional assumptions. The solution to this problem is to estimate so-called hurdle models (Greene 2012, pp. 443, 824–826). The research team is aware of no previous application of hurdle models to the planning field.

Data

The research team gathered and pooled data for nine metropolitan regions for the neighborhood-level analysis of the ridership and land use effects of transit on VMT. One region, Portland, Oregon, is represented twice in the combined dataset, once for 1994, early in the development of LRT, and then for 2011, after much LRT development, thereby permitting longitudinal comparisons. The early Portland dataset was dropped for purposes of cross-sectional analysis. The resulting dataset consists of 254,691 trips by 26,009 households in nine regions (see Table 16). The regions are diverse, with Boston and Portland at one end of the transit service continuum and Houston and Kansas City at the other.

All surveys provide XY coordinates for households and their trips. This allows travel to be modeled in terms of the precise built environment in which households reside and travel occurs. For individual trips, trip purpose, travel mode, travel time, and other variables are available from the survey dataset. Distance traveled on each trip was either supplied or computed with GIS from the XY coordinates. For travelers, individual age, employment status, driver's licensure, and other variables are available from the survey dataset. For households, household size, household income, vehicle ownership, and other variables are available from the survey dataset. This allowed the research team to control for sociodemographic influences on travel at the household level.

Additional geocoded household travel datasets have been acquired for Boston, Denver, Houston, Los Angeles, Minneapolis-St. Paul, Philadelphia, and San Antonio (see Table 17). The acquisition of a second database for Boston (1991 and 2011) allowed the research team to drop the early databases from the cross-sectional samples. In addition, having three regions (Boston,

Table 16. Combined dataset.

	Survey Date	Surveyed Households	Surveyed Trips
Austin	2005	1,446	14,196
Boston	1991	2,595	20,217
Eugene	2011	1,672	16,409
Houston	1995	1,954	19,417
Kansas City	2004	3,000	30,416
Portland	2011	4,500	46,854
Sacramento	2000	3,520	33,519
Salt Lake City	2012	3,516	38,595
Seattle	2006	3,896	35,068
Total		**26,099**	**254,691**

Table 17. New household travel datasets.

	Survey Year	Households	Trips
Boston	2011	7,661	103,124
Denver	2010	7,302	84,819
Houston	2009	5,807	79,393
Los Angeles	2000	16,939	190,169
Minneapolis-St. Paul	2010	10,363	79,232
Philadelphia	2000	4,217	47,071
San Antonio	2006	NA	NA

Houston, and Portland) with widely spaced travel surveys and with transit expansion in between the travel surveys, permitted longitudinal as well as cross-sectional analyses.

Other datasets have been collected for the same years as the travel surveys in order to estimate values of many “D” variables for ¼-, ½-, and 1-mile radius buffers around each household. These include a geocoded parcel land use layer, geocoded street and transit layers, and travel time skims, population, and employment by traffic analysis zone (TAZ) as supplied by the regions' metropolitan planning organizations.

Parcel-level assessor data in the survey area were acquired from each individual county to estimate the amount and type of each land use within the buffers. Parcel features were converted to centroid points, allowing parcel attributes to be joined to the buffer polygons. Roadway centerlines were used for collection of intersection points, where centerline intersections were counted and summarized. Transit stop geographic locations were collected from all operators serving the travel survey area. All stops were merged according to bus or rail categories. Bus and rail stop locations were joined to buffers for stop counts. Population density was determined by weighting census block group population estimates with residential parcel square footage for population density. Population density per square foot was then applied to residential parcels intersecting each buffer. Employment data were obtained at the TAZ level from metropolitan planning organizations and, along with interzonal travel times from metropolitan planning organizations, were used to compute employment accessible within 10-, 20-, and 30-minute automobile travel times and within 30-minute transit travel times. Employment for individual household buffers were generated by weighting the size of the TAZ in proportion to the buffer. The proportion was multiplied by the number of jobs in each intersecting TAZ.

Variables

To increase statistical power and external validity, household travel data from nine diverse regions were pooled. The data and model structure are hierarchical, with households nested within regions.

The variables extracted from these datasets and used in subsequent analyses fall into four categories (see Table 18). Three of the categories are specific to households. Each household has a different set of variable values. One of the categories is specific to regions. All households within a given region share these characteristics. Variables are the following:

- **VMT** (vmt), the household variable of ultimate interest. This is an outcome variable to be explained or predicted.
- **Transit trips (ttrips) and activity density** (actden—population plus employment divided by land area) in the ½-mile buffer around households. These are mediating variables on the causal pathway between household VMT and the exogenous variables. These are also outcome variables to be explained or predicted.

Table 18. Category, definition, and scale of variables proposed for inclusion in the neighborhood level model.

Category	Symbol	Definition	Level
Primary outcome variable	vmt	Household daily VMT	Household
Intermediate outcome variables	ttrips	Household daily transit trips	Household
	actden	Activity density within 1/2 mile (sum of population and employment divided by gross land area in square miles)	Household
Exogenous transit variables	emp30t	Proportion of regional employment accessible within 30-minute travel time via transit (in-vehicle time only)	Household
	rail	Rail station within 1/2 mile (dummy variable; yes=1, no=0)	Household
Exogenous built environmental variables	jobpop	Job-population balance within 1/2 mile of a household (index ranging from 0, where only jobs or residents are present within a 1/4 mile, to 1, where there is one job per five residents)	Household
	entropy	Land use mix within 1/2 mile of a household (entropy index based on net acreage in different land use categories that ranges from 0, where all developed land is in one use, to 1, where developed land is evenly divided among uses)	Household
	intden	Intersection density within a 1/2 mile of a household (number of intersections divided by gross land area in square miles)	Household
	int4way	Percentage of four-way intersections with 1/2 mile of a household (four-way intersections or intersections where more than four streets meet divided by total intersections)	Household
	emp10a	Percentage of regional employment accessible within a 10-minute travel time via automobile	Household
	emp20a	Percentage of regional employment accessible within a 20-minute travel time via automobile	Household
	emp30a	Percentage of regional employment accessible within a 30-minute travel time via automobile	Household
Household control variables	hhsize	Number of household members	Household
	employed	Number of household members employed	Household
	income	Household income (in 1,000s of 2012 dollars)	Household
Regional control variables	rpop	Total regional population (in 1,000s)	Regional
	remp	Total regional employment (in 1,000s)	Regional
	ract	Total regional activity (sum of population and employment in 1,000s)	Regional
	rind	Regional compactness index (index measuring compactness vs. sprawl based on a combination of four factors that measure density, land use mix, degree of centering, and street accessibility); higher values signify great compactness[a]	Regional

[a] For more information on the regional sprawl index and how it is calculated, see *Measuring Sprawl and Its Impact* (Ewing, Pendall, and Chen 2002).

- **Transit variables that measure the relative level and type of transit service at the neighborhood level.** These are the key independent variables in the research. They are the percentage of regional employment accessible within 30 minutes by transit from a household location (emp30t) and a dummy variable for the presence of a rail station within ½ mile of the household (rail).
- **Built environmental variables**, accounting for the land use diversity, street network design, and automobile accessibility to jobs at and around the household location.
- **Household control variables** accounting for the socioeconomics of households. There are three: household size, number of employed members, and household income.

- **Region size and urban form variables**, accounting for regional random effects shared by all households in a given region.

Statistical Methods

Nesting of households within regions creates dependence among observations, in this case the dependence of households within a given region. All households within a given region share the characteristics of the region. Regions such as Boston and Houston are likely to generate very different travel patterns irrespective of household and neighborhood characteristics. This dependence violates the independence assumption of ordinary least squares regression. Standard errors of regression coefficients based on ordinary least squares will consequently be underestimated. Moreover, ordinary least squares coefficient estimates will be inefficient.

One solution to the problem of nested data is MLM, also called hierarchical modeling (Raudenbush and Bryk 2002). The essence of MLM is to isolate the variance associated with each data level and then seek to explain as much of it as possible with available variables. The more explained variance, the better. MLM modeling is just beginning to be used in the planning field.

For this research, the research team began by partitioning variance between the household level (Level 1) and the region level (Level 2). Outcomes were then modeled in terms of variables specific to each level. Given the large sample of households, many household level variables were likely to prove significant, thereby reducing unexplained variance at Level 1. This was not the case at the regional level, with only nine regions. Variables such as regional population and density were unlikely to prove significant due to limited degrees of freedom. Still, there was significant variance in transportation outcomes from region to region, and MLM captures it in the random effects terms of the Level 2 equations.

The modeling task was further complicated by the large number of zero values for two of the three dependent variables. The vmt frequency distribution had an excessive number of zero values, specifically 1,878 of the 26,000 households with no VMT at all (see Figure 38). These were households that relied on alternative modes of transportation. The other variable—ttrips—had an excessive number of zero values too, in this case 21,934 households with no transit use at all (see Figure 42). Use of transit was the exception rather than the rule in the United States.

In the planning literature, the problem of zero inflation is often handled by adding one (1.0) to the value of a dependent variable and then log transforming the variable. The 1 becomes a 0 when transformed. This is not econometrically correct, however, since households with zero values may be qualitatively different than those with positive values. "In some settings, the zero outcome of the data-generating process is qualitatively different from the positive ones. The zero or nonzero values of the outcome is the result of a separate decision whether or not to 'participate' in the activity. On deciding to participate, the individual decides separately how much to, that is, how intensively [to participate]" (Greene 2012, p. 824).

The proper solution to the problem of zero inflation is to estimate two-stage "hurdle" models (Greene 2012, pp. 443, 824–826). The stage 1 models categorize households as either generating VMT or not, or generating transit trips or not. The stage 2 models estimate the amount of VMT generated for households with positive (nonzero) VMT and the number of transit trips generated for households with positive (nonzero) transit trips.

Setting aside for the moment the dependence of cases (which are handled with MLM) and zero inflation (which are handled with hurdle models), two of the three dependent variables—vmt and actden—were continuous but highly skewed to the left (see Figure 38 and Figure 40. The two were transformed by taking their natural logarithms (as in Figure 39 and Figure 41). With logarithmic transformations, these variables were very nearly normally distributed.

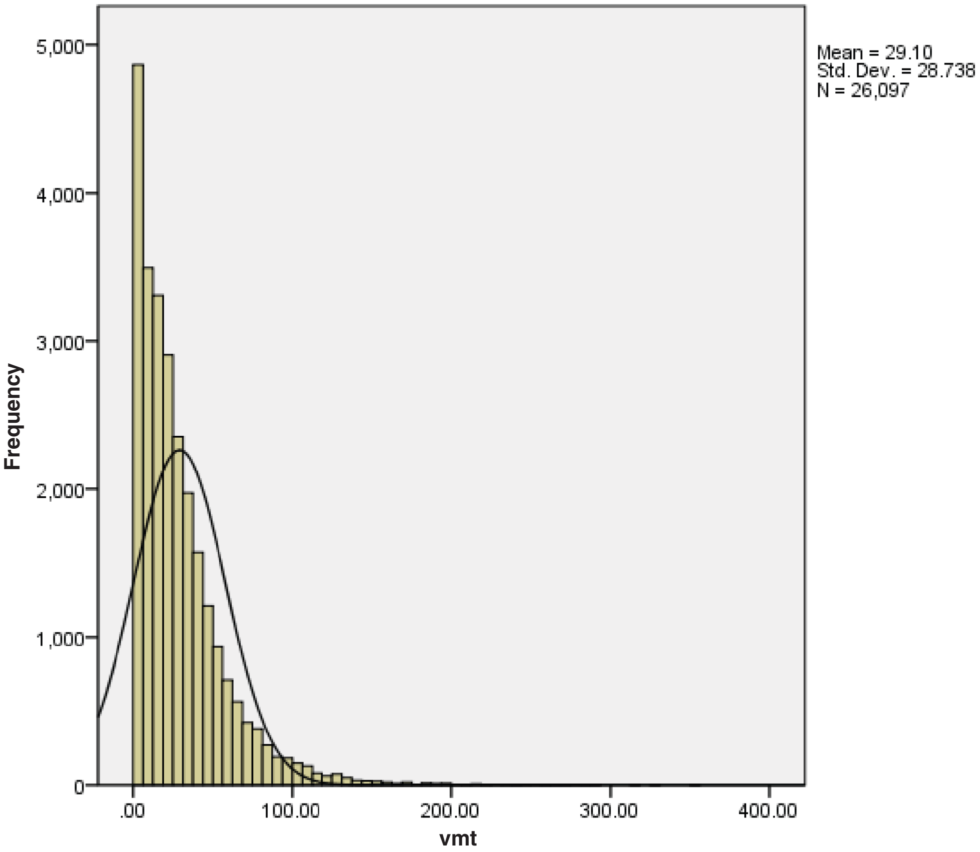


Figure 38. *Histogram of household VMT.*

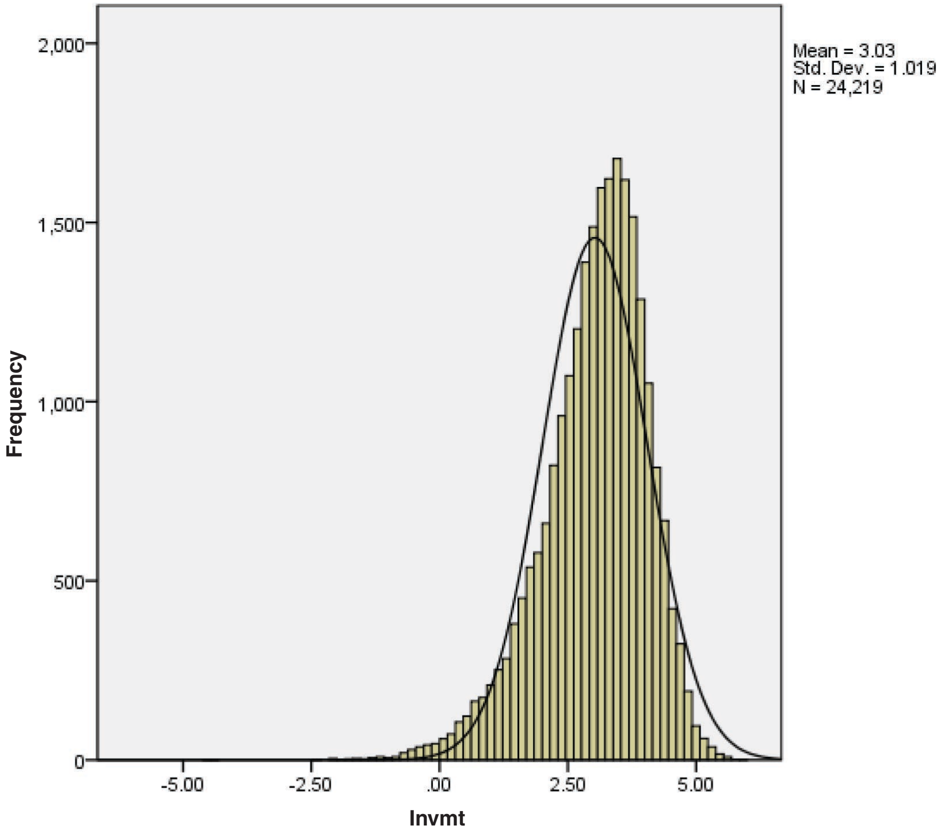


Figure 39. *Histogram of the natural logarithm of household VMT.*

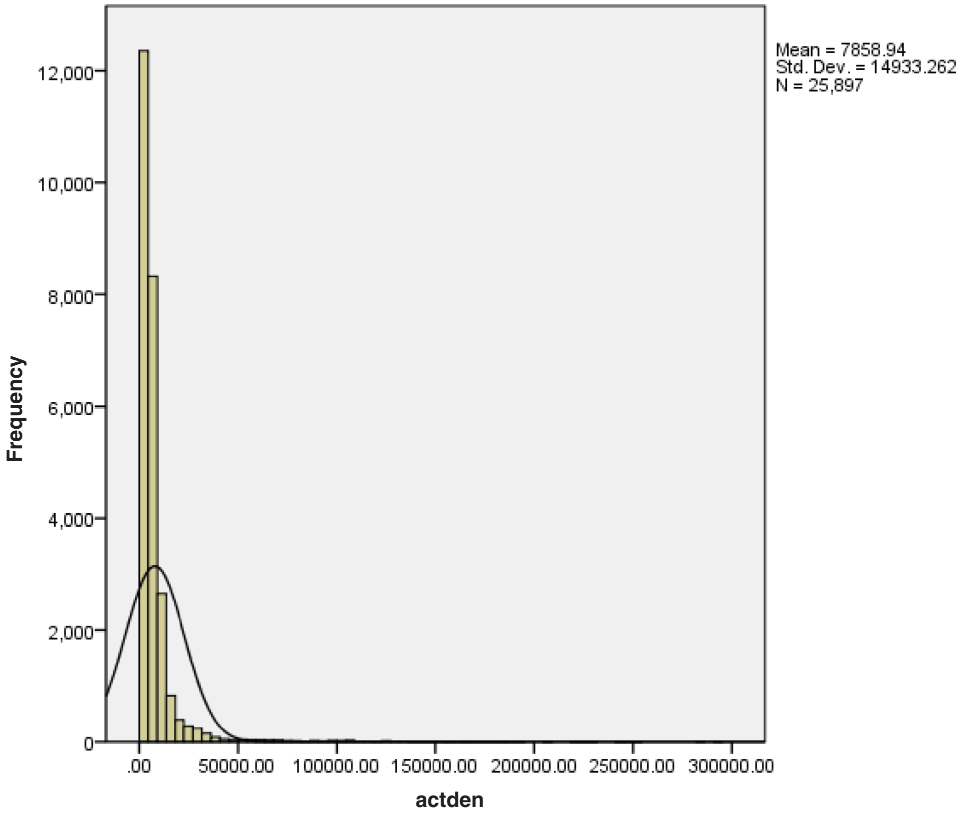


Figure 40. *Histogram of the household buffer activity density.*

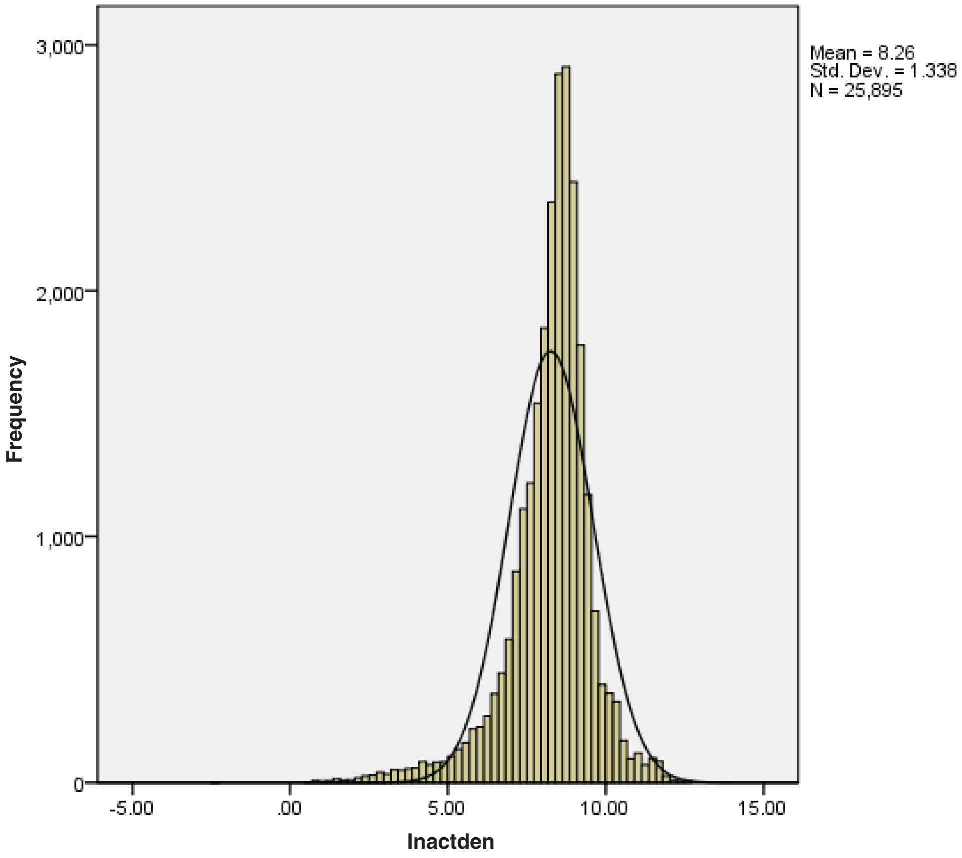


Figure 41. *Histogram of the natural logarithm of household buffer activity density.*

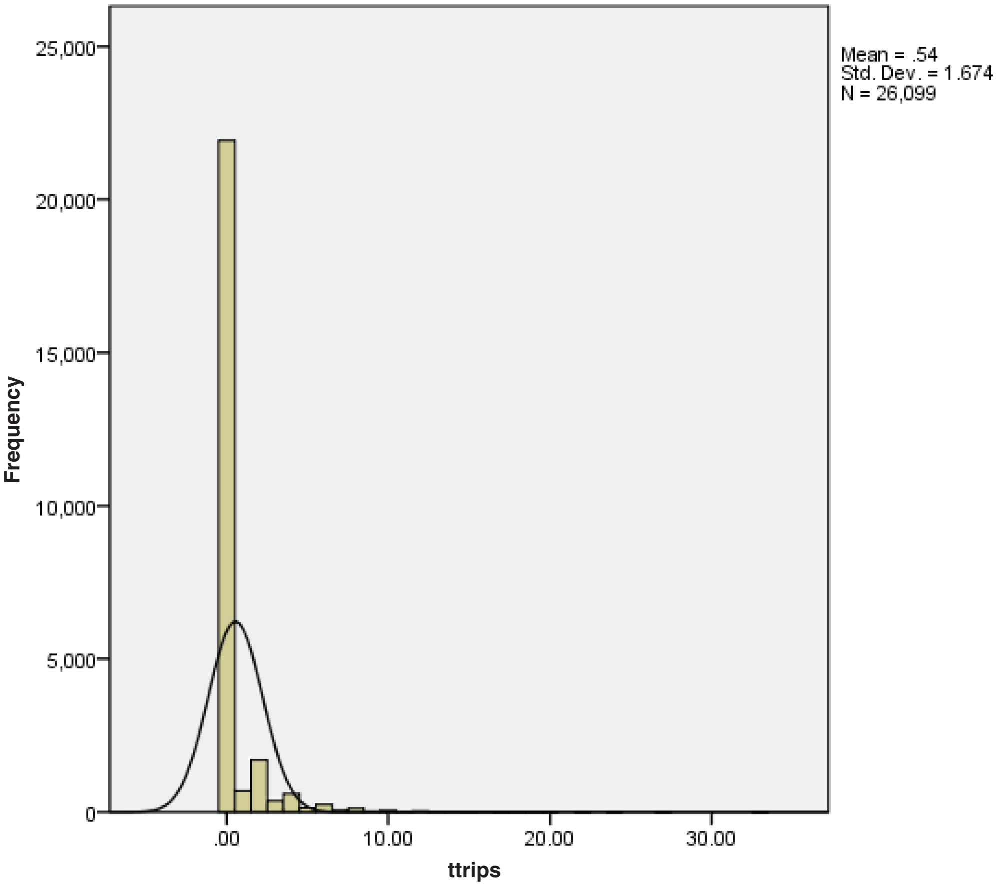


Figure 42. Histogram of household transit trip counts.

These dependent variables were modeled with Hierarchical Linear and Nonlinear Modeling software, HLM 6.08. For vmt, the research team first modeled the dichotomous outcome of a household having positive VMT or not, using hierarchical logistic regression. The team then modeled the continuous variable lnvmt using hierarchical linear regression. For actden, the process only involved one step since all values are positive; the team simply modeled the continuous variable lnactden using hierarchical linear regression.

The process of modeling the third dependent variable—ttrips—was somewhat trickier. This dependent variable was a count with many zero values (households making no transit trips—see Figure 42) and the rest with positive integer values whose frequency dropped off rapidly as the number increased (household making one or more transit trips—see Figure 43). Not only did the household's choice have to be first modeled between using transit or not, using hierarchical logistic regression, but then another type of hierarchical regression had to be used to model cases with positive values. Treating the positive values separately allowed them to be modeled with HLM 6.08.

Two basic methods of analysis were available when the dependent variable was a count with nonnegative integer values, many small values, and few large ones. The methods were Poisson regression and negative binomial regression, both fairly new to the planning field. These methods had mostly been used in crash studies because of the highly skewed nature of crash counts.[17]

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[17] For examples, see "Safe Urban Form: Revisiting the Relationship between Community Design and Traffic Safety" (Dumbaugh and Rae 2009) and "Does Street Network Design Affect Traffic Safety?" (Marshall and Garrick 2011).

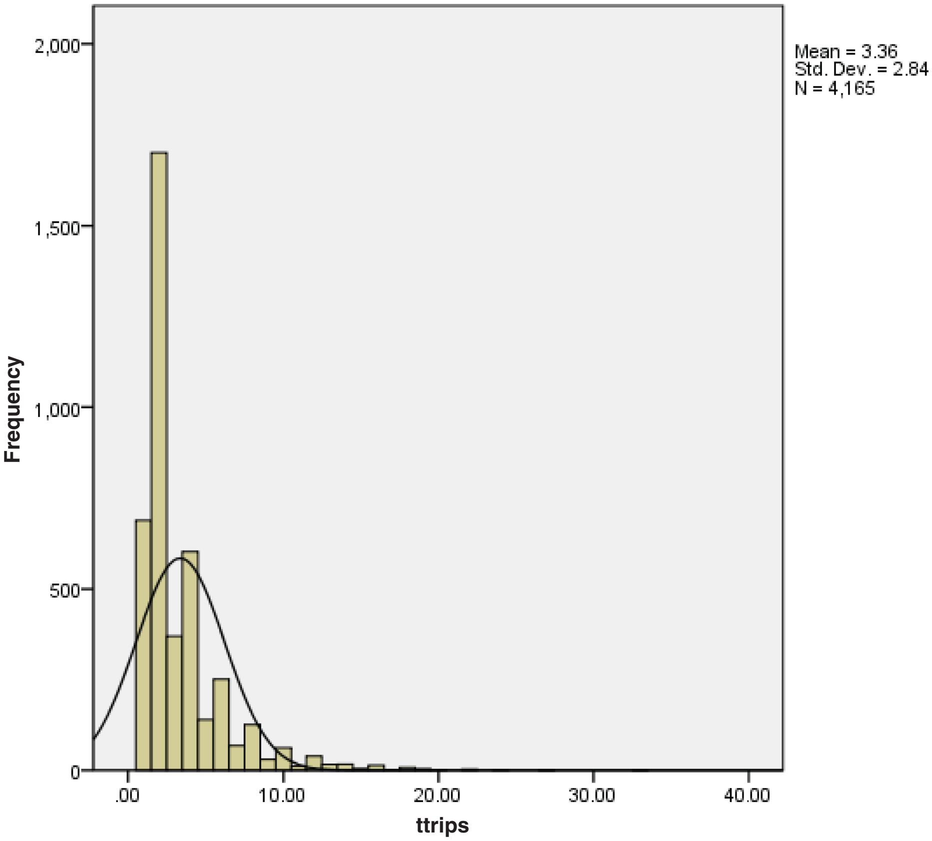

Figure 43. Histogram of transit trip counts for households making transit trips.

The two models—Poisson and negative binomial—differ in their assumptions about the distribution of the dependent variable. Poisson regression is the appropriate model form if the mean and the variance of the dependent variable are equal. Negative binomial regression is appropriate if the dependent variable is overdispersed, meaning that the variance of counts is greater than the mean. Because the negative binomial distribution contains an extra parameter, it is a robust alternative to the Poisson model (Hilbe 2011, p. 140).

Popular indicators of overdispersion are the Pearson and $\chi 2$ statistics divided by the degrees of freedom, so-called dispersion statistics. If these statistics are greater than 1.0, a model is said to be overdispersed (Hilbe 2011, pp. 88, 142). By these measures, the study had overdispersion of transit trip counts in the dataset, and the negative binomial model was more appropriate than the Poisson model.

Results

Modeled results for the three dependent variables are shown in Table 19 and Table 20 for vmt, Table 21 for actden, and Tables 22 and 23 for ttrips. The hurdle models required two tables each. Generalizing, Level 1 independent variables have the expected signs and are highly significant. Level 2 independent variables have the expected signs but, due to limited degrees of freedom, never reach conventional significance levels.

The best-fit model for the dichotomous variable, any VMT (1=yes, 0=no), is presented in Table 19. The likelihood of any VMT increases with household size, number of employed household members, and real household income. These sociodemographic variables are associated

Table 19. Best-fit logistic model for the any household VMT (1 = yes, 0 = no).

	Coefficient	Standard Error	T-Ratio	P-Value
constant	6.53	0.41	16.0	< 0.001
hhsize	0.506	0.039	13.0	< 0.001
employed	0.323	0.045	7.16	< 0.001
income	0.010	0.001	12.3	< 0.001
entropy	−0.974	0.130	−7.57	< 0.001
intden	−0.0010	0.0003	−3.08	0.003
int4way	−0.013	0.002	−6.15	< 0.001
emp20a	−0.010	0.004	−3.43	0.001
ttrips*	−0.326	0.014	−23.1	< 0.001
lnactden*	−0.478	0.048	−9.90	< 0.001
pseudo R2 0.21				

*Intermediate variables.

Table 20. Best-fit linear model for the natural logarithm of household VMT (for positive VMT).

	Coefficient	Standard Error	T-Ratio	P-Value
constant	3.54	0.09	41.2	< 0.001
hhsize	0.141	0.005	25.6	< 0.001
employed	0.230	0.008	27.5	< 0.001
income	0.0025	0.0002	16.5	< 0.001
jobpop	−0.063	0.025	−2.57	0.011
entropy	−0.083	0.026	−3.17	0.002
intden	−0.0006	0.0001	−6.45	< 0.001
int4way	−0.0032	0.0004	−8.61	< 0.001
emp20a	−0.0027	0.0004	−6.43	< 0.001
ttrips*	−0.063	0.004	−14.6	< 0.001
lnactden*	−0.112	0.008	−13.5	< 0.001
pseudo R2 0.22				

*Intermediate variables.

Table 21. Best-fit linear model for the natural logarithm of buffer activity density.

	Coefficient	Standard Error	T-Ratio	P-Value
constant	6.87	0.21	33.1	< 0.001
intden	0.0022	0.0001	1.89	0.058
int4way	0.0150	0.0014	10.7	< 0.001
emp30t*	0.0274	0.0064	4.31	< 0.001
rail*	0.0895	0.0175	5.12	< 0.001
pseudo R2 0.37				

*Exogenous transit variables.

Table 22. Best-fit logistic model for any transit trips (1 = yes, 0 = no).

	Coefficient	Standard Error	T-Ratio	P-Value
constant	–4.09	0.51	–8.04	< 0.001
hhsize	0.242	0.017	14.4	< 0.001
employed	0.183	0.027	6.73	< 0.001
income	–0.0044	0.0005	–8.99	< 0.001
jobpop	0.185	0.081	2.29	0.022
entropy	0.477	0.087	5.50	< 0.001
intden	0.0020	0.0002	7.89	0.003
int4way	0.0073	0.0012	6.14	< 0.001
emp30t*	0.0147	0.0018	8.18	< 0.001
rail*	0.0522	0.0143	3.65	< 0.001
pseudo R2 NA				

* Exogenous transit variables.

Table 23. Best-fit negative binomial model for household transit trips (for positive transit trips).

	Coefficient	Standard Error	T-Ratio	P-Value
constant	0.46	0.07	6.44	< 0.001
hhsize	0.148	0.027	5.39	< 0.001
jobpop	0.116	0.031	3.78	< 0.001
entropy	0.281	0.084	3.34	0.001
emp30t*	–0.00002	0.0006	–0.03	0.97
rail*	0.0092	0.0018	5.01	< 0.001
pseudo R2 0.16				

* Exogenous transit variables.

with increased likelihood of automobile use. The likelihood of any VMT declines with land use entropy within a ½-mile buffer around a household, with intersection density within the buffer, with the percentage of four-way intersections within the buffer, and with the percentage of regional employment accessible within a 20-minute drive time. Basically, those who live in highly accessible places (characterized by these "D" variables) are better able to make do without automobile trips. Most importantly, the likelihood of any VMT declines with the two mediating variables in this model: number of transit trips made by household members (ttrips) and activity density within ½ mile of households (lnactden).

For households with VMT, household VMT increases with the household size, number of employed household members, and real household income (see Table 20). VMT declines as the following "D" variables increase within ½ mile of households: job-population balance, land use entropy, intersection density, percentage of four-way intersections, and percentage of regional employment accessible within a 20-minute drive time. Those who live in highly accessible places (characterized by these types of "D" variables) generate less VMT than those in less accessible places. Most importantly, household VMT declines with the two mediating variables in this model: number of transit trips made by household members (ttrips) and activity density within ½ mile of households (lnactden).

The best-fit model for activity density is presented in Table 21. Activity density increases as intersection density and percentage of four-way intersections increase. A dense grid of streets can support more intense development than can a sparse hierarchy of streets. Activity density also increases with the two exogenous transit variables, percentage of regional employment accessible within 30 minutes by transit and presence of a rail station within ½ mile of a household. As economic theory suggests, better transit accessibility translates into higher density.

The best-fit model for the dichotomous variable, any transit trips (1=yes, 0=no), is presented in Table 22. The likelihood of a household having any transit trips increases with household size and number of employed members, and declines with household income. The likelihood also increases with job-population balance, land use entropy, intersection density, and percentage of four-way intersections within ½ mile of the household. These variables, plus activity density, virtually define transit-oriented development. Controlling for these variables, transit trips increase with the two transit service variables: percentage of regional employment accessible within 30 minutes by transit and presence of a rail station within ½ mile of a household. Consistent with the empirical literature, better transit accessibility translates into greater transit usage.

For households with transit trips, many variables that proved significant in other equations are not significant in this one (see Table 23). The number of household transit trips increases with household size, job-population balance within ½ of a household, and land use entropy within the same ½ mile. The number of household transit trips also increases with access to rail. However, the number of transit trips is not affected by the percentage of regional employment accessible by transit. This does not mean that employment accessibility has no effect on transit use, since it affects the likelihood of having any transit trips. It just means that those who use transit anyway do not make more transit trips as employment accessibility increases.

The study sample is much smaller when limited to households with transit trips (just over 4,000 vs. 26,000 for the full sample). But the sample is large enough to produce significant results if the associations among the variables are moderately strong. Apparently, variables such as household income cut both ways when it comes to transit use. There may be a propensity to substitute the automobile for transit among the higher income users, but at the same time, a propensity to consume more transit at higher income levels. The two effects may cancel each other out.

Transit's Land Use Effect

For transit accessibility to employment, the ridership effect of transit on VMT occurs through the causal pathway:

transit accessibility to employment –> transit trips –> ridership effect on VMT

The land use effect occurs through a different causal pathway:

transit accessibility to employment –> activity density –> land use effect on VMT

Likewise for rail access, the ridership effect of transit on VMT is:

rail access –> transit trips –> ridership effect on VMT

while the land use effect is:

rail access –> activity density –> land use effect on VMT

The equations estimated previously outputted natural logarithms, log odds, and expected values of variables. They were transformed to compute effect sizes. The simplest transformation was for activity density, whose natural logarithm was the dependent variable in Table 21. Values of the natural log computed with this equation were exponentiated:

activity density = exp (log of activity density)

The calculations were more complicated for transit trips. From the logistic equation in Table 22, the research team first computed the odds of any transit trips by exponentiating the log odds and then the probability of any transit trips with the formula for the probability in terms of the odds:

odds of any transit trips = exp (log odds any transit trips)

probability of any transit trips = odds of any transit trips/(1 + odds of any transit trips)

From the negative binomial equation in Table 23, the expected number of transit trips for households with any transit trips were also calculated by exponentiating:

number of transit trips (for households with transit trips)
= exp (log of expected number of transit trips)

The expected number of transit trips for all households was the product of the two:

number of transit trips (for all households) = probability of any transit trips
× number of transit trips (for households with transit trips)

A parallel set of calculations was applied to VMT. From the logistic equation in Table 23, the odds of any VMT were computed by exponentiating the log odds and then the probability of any VMT with the formula for probability in terms of odds:

odds of any VMT = exp (log odds any VMT)

probability of any VMT = odds of any VMT/(1 + odds of any VMT)

From the semi-logarithmic equation for households with any VMT, the expected VMT were computed, again, by exponentiating:

VMT (for households with VMT) = exp (log of VMT)

The expected VMT for all households was the product of the two.

VMT (for all households) = probability of any VMT × VMT (for households with VMT)

To estimate land use effects for the two exogenous transit variables, transit accessibility to employment (emp30t) and rail access (rail), base values of each endogenous variable were first calculated using average values of exogenous variables for the sample households, with this exception: the research team assumed no rail access in the base case (rail = 0). Values for the base case are shown in Table 24.

Table 24. Values of exogenous variables in the base case.

hhsize	2.23
employed	1.25
income	73.0
jobpop	0.59
entropy	0.39
intden	169.4
int4way	27.6
emp20a	38.5
emp30t	19.9
rail	0

For the base case, activity density was computed from the equation in Table 21; the number of household transit trips was computed from the equations in Table 22 and Table 23. Using resulting values of activity density and transit trips, household VMT was computed from the equations in Table 19 and Table 20.

For comparison with the base case, two scenarios were created that represented enhanced transit service at the neighborhood level. For the first scenario, the research team bumped up transit accessibility to employment by 10 percentage points from 19.9% to 29.9%, assuming the neighborhood had better access to employment via transit. For the second scenario, the team bumped up the rail access dummy variable from 0 to 1, assuming the neighborhood had rail access.

The team then went through the similar calculations as in the base case. First, activity density and transit trips were calculated with the equations in Tables 21, 22, and 23. Then, household VMT was computed three ways for each scenario from the equations in Tables 19 and 20.

In the first calculation, revised values of both activity density and transit trips were used to obtain an estimate of household VMT that included the ridership and land use effects of the scenario. In the second calculation, the revised value of transit trips and the base value of activity density were

Table 25. Results for a scenario with enhanced neighborhood access to employment (10 percentage point bump in transit accessibility to employment).

	Base Case	Scenario	Percentage Difference
Daily transit trips per household	0.218	0.249	+14.5%
Neighborhood activity density (population + employment per square miles)	3,645	4,794	+31.5%
Average daily VMT per household (ridership + land use effects)	20.08	19.35	−3.63%
Average daily VMT per household (ridership effect only)	20.08	20.03	−0.22%
Average daily VMT per household (land use effect only)	20.98	19.39	−3.40%

Table 26. Results for a scenario with enhanced neighborhood access to rail (from no rail within ½ mile to rail within ½ mile)

	Base Case	Scenario	Percentage Difference
Daily transit trips per household	0.218	0.231	+5.8%
Neighborhood activity density (population + employment per square miles)	3,645	4,794	+9.4%
Average daily VMT per household (ridership + land use effects)	20.08	19.35	−1.25%
Average daily VMT per household (ridership effect only)	20.08	20.03	−0.08%
Average daily VMT per household (land use effect only)	20.98	19.39	−1.15%

used to obtain an estimate of household VMT due to the ridership effect only. In the third calculation, the revised value of activity density and the base value of transit trips were used to obtain an estimate of household VMT due to the land use effect only. Finally, subtracting VMT for each scenario from VMT in the base case, the ridership and land use effects of the scenarios were obtained.

Results for the two scenarios are shown in Table 25 and Table 26.

Longitudinal Analysis of LRT Expansion in Portland, Oregon

Two of the 10 regional household travel databases in this study are for Portland, Oregon. One survey was conducted in 1994, the second in 2011. The 17-year separation between the dates of these two surveys allowed the research team to study the effect of transit investments on VMT in and around transit stations. With a bit of manipulation, ridership effects could be separated from land use effects.

This is a classic quasi-experimental study design referred to as a pretest-posttest (pre-intervention–post-intervention) design with a comparison group. The intervention is the construction of a new LRT line between the two survey years, which affects development patterns and travel behavior of households proximate to the new line. The comparison group consists of households in another transportation corridor not directly affected by the new line. It was assumed that changes in the treated group would have paralleled those in the comparison group in the absence of any intervention. Deviations from general trends were assumed to be due to the intervention itself—in this case, the opening of an LRT line.

Case Study Selection

This case study focuses on the Westside LRT line (western portion of the Blue Line). The portion of interest starts west of downtown Portland and extends through Beaverton out to Hillsboro. The 15-mile section, with 17 stations, opened in 1998, after the first household travel survey and well before the second. Much of the alignment is through land that was ripe for development or redevelopment. Station areas have had many years to densify and thereby affect travel behavior. This represents the best opportunity for a pre-intervention–post-intervention comparison.

The comparison group for this study is another corridor heading southwest from downtown Portland to Tigard and beyond. This is a highway corridor, in contrast to the treated corridor, running along the SW Pacific Highway and (for the first few miles) Interstate 5. This portion of the corridor is 12.5 miles long and has 14 interchanges or major intersections.

In a quasi-experimental study, the comparison group should be as similar as possible to the treated group. If the two groups were equivalent, this would be a true experiment. They can never be truly equivalent in planning practice, and a quasi-experiment is the best available for this study. The two corridors are similarly situated in the region and relative to downtown. In the next section, the study tests for rough equivalence of travel and other statistics before the intervention. The existence of big differences before the intervention would create statistical problems, most notably the likelihood of regression to the mean.

As for the other rail lines in Portland, the Eastside LRT line was completed in 1986, 8 years before the 1994 household travel survey. It had already had much of its ultimate impact on development patterns by the time of the survey. The Airport LRT Red Line, opened in 2001, mostly travels through land that is industrial (surrounding the airport). Only one station serves a residential neighborhood, and it is bounded by highways. The Downtown Streetcar also began service in 2001. Any reasonable buffer around its stations would encompass LRT stations as well, making it difficult to isolate the streetcar's effect on land use. The Interstate LRT Yellow Line, opened in 2004, may not exemplify the potential of rail to affect development patterns due to its alignment along the Interstate. Portland's fifth LRT line, the Green Line connecting downtown Portland to Clackamas County, was opened in 2009, too recently to have had much effect on development patterns in the corridor.

Data and Variables

This study uses geocoded household travel data from surveys conducted in 1994, 4 years before the opening of the Westside LRT line, and 2011, 13 years after the opening.

The 1994 survey was a 2-day travel survey. The research team selected the travel day with the largest number of trips for each household. Even so, it appears that trips were underreported on average, as households are less diligent about reporting trips over 2 days than 1 day. The 2011 survey was a 1-day survey that covered a larger sample of households.

This study also uses socioeconomic data for surveyed households, built environmental data for buffers around household locations, and transit service data for households and buffer areas.

Variables used in this study are defined in Table 27. Measures of household size, employment, VMT, and trip frequency refer only to household members who completed travel diaries. Data for other household members were not available.

Table 27. Variable definitions.

Variables	Definition	Explanation
Location	Household within 2 miles of a Westside LRT station or an SW Pacific Highway intersection	A 2-mile buffer was used to produce a large enough sample of households for statistical purposes
Household socioeconomic variables		
hhsize	Household size	Only includes household members who completed travel diaries
employed	Employed household members	Only includes household members who completed travel diaries
income	Household income in 1,000s of 2012 dollars	Income inflated by the personal consumption expenditure price index
vehicles	Household vehicles	Number of cars and other vehicles owned by household
Household built environmental variables		
actden	Activity density within the 2-mile buffer in 1,000s of persons per square mile	Population + employment divided by gross land area in square miles
jobpop	Job-population balance within the 2-mile buffer	Index ranging from 0, where only jobs or residents are present within 1/4 mile, to 1, where there is one job per five residents
entropy	Land use mix within the 2-mile buffer	Entropy index based on net acreage in different land use categories that ranges from 0, where all developed land is in one use, to 1, where developed land is evenly divided among uses
intden	Intersection density within the 2-mile buffer	Number of intersections divided by gross land area in square miles
int4way	Percentage of four-way intersections within the 2-mile buffer	four-way intersections or intersections where more than four streets meet divided by total intersections
emp10a	Percentage of regional employment accessible within a 10-minute travel time via automobile	Midday travel times
emp20a	Percentage of regional employment accessible within a 20-minute travel time via automobile	Midday travel times
emp30a	Percentage of regional employment accessible within a 30-minute travel time via automobile	Midday travel times
Household travel variables		
vmt	Average household VMT per day	Adjusted for average vehicle occupancy by household size from 2009 National Household Travel Survey
wtrips	Average number of household walk trips	Only includes household members who completed travel diaries
btrips	Average number of household bike trips	Only includes household members who completed travel diaries
ttrips	Average number of household transit trips	Only includes household members who completed travel diaries
atrips	Number of household automobile person trips	Only includes household members who completed travel diaries
trips	Number of household person trips by all modes	Only includes household members who completed travel diaries
adist	Average length of automobile trips	Only includes household members who completed travel diaries
n	Sample size	

All variables are defined and measured consistently for the two survey years. Household income is adjusted for consumer price inflation. Even adjusting for inflation, incomes rose substantially between 1994 and 2011 across the prosperous Portland region.

Importantly, the study team used a 2-mile network distance to define the study area around the transit stations on the Westside LRT line and around the intersections on the SW Pacific Highway. This relatively large buffer produces a large enough sample of households for statistical purposes. A 1-mile network buffer would have left a sample of only 40 households living in the transit corridor surveyed in 1994, and a ½-mile network buffer would have left only eight households. By using a larger buffer, the team is not suggesting that the effects of LRT on transit use and activity density are identical in the first ½ mile around stations and second ½ mile, or the first mile and the second mile. It is suggested, however, that average effects over a larger area can be used to define transit's impacts on VMT.

Statistical Methods

The analysis was conducted in two parts. The first part used independent samples difference-of-means tests to see if household travel and other variables differ between the LRT corridor and the comparison corridor, and between the first survey and the second survey. The research team looked for gross effects of the new LRT line on household travel and development patterns around the stations.

The second part of the analysis estimated a household VMT model in terms of household socioeconomic variables; built environmental variables for their surroundings; and the variables of greatest interest, household transit trips and activity density. Once estimated, the model could be used to predict the ridership effect of LRT on household VMT through increased transit usage and the land use effect of LRT on household VMT through increased activity density around stations.

Difference-of-Means Tests

The research team began with the results of difference-of-means tests. Table 28 permits a pre-intervention comparison of the Westside LRT corridor and the SW Pacific Highway corridor.

Table 28. Westside LRT corridor vs. SW Pacific Highway corridor in 1994.

Location	LRT	Control	T-Ratio	P-Value
hhsize	2.28	2.04	2.28	0.023
employed	1.25	1.16	1.18	0.24
income (1,000s)	60.2	60.1	0.05	0.96
vehicles	1.86	1.74	1.66	0.097
actden (1,000s)	5.29	6.26	–4.21	<0.001
vmt	23.1	21.9	1.50	0.13
wtrips	0.83	0.83	0.04	0.97
btrips	0.08	0.08	0.08	0.94
ttrips	0.16	0.27	–1.89	0.06
atrips	8.12	7.33	1.49	0.14
trips	9.78	9.02	1.28	0.20
adist	4.87	4.96	–0.31	0.76
n (varies but max)	194	440		

This may be the most important comparison of all, as large differences would introduce the likelihood of regression to the mean. In 1994, the two corridors were equivalent in most respects. There was no significant difference in mean number of employees per household; mean income per household; and mean frequencies of walk, bike, automobile, and total trip making. Also, most importantly, there was no significant difference in mean household VMT. Interestingly, activity density was significantly higher in the highway corridor, and transit trip frequency was marginally higher (approaching significance at the 0.05 level). Vehicle ownership was marginally lower in the highway corridor. By these measures, the highway corridor was actually more urbanized in 1994 than was the transit corridor.

By 2011, the introduction of LRT had changed the LRT corridor, and it now differed significantly from the highway corridor. Compare the 2011 values in Table 29 to the 1994 values in Table 28. Real household incomes had risen in both corridors, but not nearly as fast in the transit corridor. Vehicle ownership, which had been higher in the transit corridor, was now lower. Activity density, which had been lower in the transit corridor, was now significantly higher. The mean walk and transit trip rates rose in both corridors, but much faster in the transit corridor. Looking at relative numbers, it might be expected that the increase in walk trips had a greater impact on VMT than the increase in transit trips. Most importantly for this research, while the mean household VMT rose in both corridors, it rose much faster in the highway corridor. The rapid rise in household VMT mirrors the region as a whole. Hence the LRT corridor is bucking the trend. The difference in household VMT is entirely due to mode shifts in the LRT corridor, as the average automobile trip rates and lengths are not significantly different.

The final comparison is between household data for the transit corridor before and after the Westside LRT line opened (see Table 30). Average household income increased significantly between the years, which partially accounts for the higher overall trip rate and the longer average automobile trip length in 2011. Vehicle ownership actually declined in the transit corridor, bucking the regional trend. Activity density increased by almost 30%, as land near stations was rezoned, in many cases for transit-oriented development (dense mixed-use development). The increase in density was greater in the first mile around the transit stations than the second mile (a 2-mile buffer was used in this study to achieve a meaningful sample size). Walk and transit rates both increased dramatically after LRT, the former by 158% and the latter by 438%.

Table 29. Westside LRT corridor vs. SW Pacific Highway corridor in 2011.

Location	LRT	Control	T-Ratio	P-Value
hhsize	2.20	2.16	0.52	0.60
employed	1.27	1.39	−2.27	0.023
income (1,000s)	74.8	83.0	−2.96	0.003
vehicles	1.79	1.93	−2.19	0.029
actden (1,000s)	6.81	6.40	3.90	<0.001
vmt	24.7	29.0	−2.54	0.011
wtrips	2.14	1.36	3.78	<0.001
btrips	0.12	0.20	−1.40	0.16
ttrips	0.86	0.45	4.31	<0.001
atrips	7.65	8.33	−1.64	0.10
trips	11.10	10.51	1.20	0.23
adist	5.72	6.29	−1.39	0.17
n (varies but max)	502	489		

Table 30. Westside LRT corridor in 1994 vs. 2011.

Date	1994	2011	T-Ratio	P-Value
hhsize	2.28	2.20	–0.75	0.45
employed	1.25	1.27	0.38	0.70
income (1000s)	60.2	74.8	5.54	<0.001
vehicles	1.86	1.79	–0.95	0.34
actden (1000s)	5.29	6.81	8.93	<0.001
vmt	23.1	24.7	0.85	0.39
wtrips	0.83	2.14	6.41	<0.001
btrips	0.08	0.12	0.60	0.55
ttrips	0.16	0.86	7.63	<0.001
atrips	8.12	7.65	–0.80	0.42
trips	9.78	11.10	2.06	0.041
adist	4.87	5.72	2.47	0.014
n (varies but max)	194	502		

In absolute terms, the walk rate actually increased more than the transit rate (1.31 vs. 0.70 trips), suggesting that the indirect effect of transit investment through increased walking may be as large or larger than the ridership effect through increased transit use. Of course, it depends on the length of automobile trips that these two modes are replacing.

Generalizing from these three tables, household VMT increased in both corridors between 1994 and 2011, but much less so in the Westside LRT corridor than in the control highway corridor or the region as a whole. VMT increases across the region are probably related to rising incomes and increasing sprawl. The fact that VMT in the transit corridor did not rise as fast appears to be largely due to mode shifts from the automobile to transit and walking. But many variables were at play. These kinds of comparisons naturally suggest a multivariate analysis, as many variables contribute to household VMT, as seen in the next section.

Statistical Modeling

To predict the ridership and land use effects of the Westside LRT line on household VMT, the research team first estimated a linear regression model using Portland data for the entire region in 2011. The model was estimated for 2011 because the team wanted to know how changes in the LRT corridor between 1994 (pre-LRT) and 2011 (post-LRT) likely affected household VMT in 2011. Excluding households with missing values of one or more variables, there was a sample of 3,665 households.

The natural log of household VMT was taken to make the distribution of the dependent variable more normally distributed. The log transformation costs households with no VMT, about 9% of the sample. As these are the households most likely affected by the availability of LRT, the effect of LRT on VMT was necessarily underestimated.

The natural logs of other variables, specifically household size and household income, were taken to account for nonlinear relationships to VMT. This costs a few additional cases but improved the model fit.

The study had three buffer widths to choose from (¼, ½, and 1 mile); all three were tested. The research team opted for the smallest buffer to capture the most localized conditions and still

Table 31. Natural log of household VMT as a function of transit trips, activity density, and control variables.

	Coefficient	Standard Error	T-Statistic	P-Value
constant	1.20	0.25	4.75	< 0.001
lnhhsize	0.586	0.033	17.8	< 0.001
employed	0.132	0.022	5.90	< 0.001
lnincome	0.155	0.023	6.63	< 0.001
emp30a	–0.0023	0.0008	–2.91	0.004
intden	–0.00044	0.00015	–3.04	0.002
int4way	–0.0026	0.0007	–3.99	< 0.001
ttrips	–0.154	0.013	–11.8	< 0.001
actden	–0.022	0.006	–4.05	< 0.001

N = 3,665 R2 = 0.238

achieve a good model fit. A measure of regional accessibility—percentage of regional jobs accessible within 30 minutes by automobile—was used to control for regional location (as opposed to local conditions). Previous studies have found that regional accessibility is the most important determinant of VMT, more important than the local "D" variables (Ewing and Cervero 2001, Ewing and Cervero 2010).

The best-fit model is presented in Table 31. As expected, sociodemographic and built environmental control variables proved highly significant. The two variables of ultimate interest were also significant. The number of transit trips made by the household has the expected negative sign and is significant at the 0.001 level or beyond. Households that use transit drive less. Activity density also has a negative sign and is significant at the 0.001 level or beyond. Households living at higher densities drive less, independent of their transit use.

Effect of Transit on VMT

Next, the regression model was used to compute the ridership effect of greater transit use on household VMT in the transit corridor and the land use effect of greater activity density on household VMT in the transit corridor. Consistent with the quasi-experimental methodology, the team assumed a counterfactual, that in the absence of LRT, transit use and activity density in the transit corridor would have changed to just the same extent as in the highway corridor.

Between 1994 and 2011, the average number of transit trips per household in the LRT corridor rose from 0.16 to 0.86, an increase of 0.7 daily transit trips. During the same period, due to expanded transit service regionally, the average number of transit trips per household in the highway corridor rose from 0.27 to 0.44, an increase of 0.18 transit trips. Assuming transit use would have increased by this same amount in the absence of LRT, the net increase in the transit corridor attributable to LRT is 0.70–0.18 or 0.52 transit trips per household.

Likewise, between 1994 and 2011, the average activity density in the LRT corridor rose from 5.29 to 6.81 persons per square mile, expressed in 1,000s, for an increase of 1.25 persons per square mile, again in 1,000s. During the same period, due to general urbanization of the west side of Portland, the average activity density in the highway corridor rose from 6.26 to 6.40 persons per square mile (in 1,000s), for an increase of 0.14 thousand persons per square mile. Assuming activity density would have increased by this same amount in the absence of LRT, the net increase in the activity density attributable to LRT is 1.25–0.14, or 1.11 thousand persons per square mile.

Table 32. Descriptive statistics for variables in the household VMT model.

	N	Mean	Standard Deviation
lnvmt	458	2.84	1.05
lnhhsize	502	0.63	0.56
employed	539	1.27	0.85
lnincome	506	11.00	0.76
emp30a (1,000s)	539	66.5	17.8
inten	539	212.0	100.4
int4way	537	22.8	19.3
ttrips	502	0.86	1.81
actden (1,000s)	539	5.81	2.29

The net change in the average transit trip rate was then substituted into the VMT model to determine the ridership effect of the LRT line on VMT. Because household VMT was logged in the model, the effect of an increase in transit trips on household VMT depends on other variables in the VMT model. The average values of all other variables for the households in the LRT corridor were substituted into the VMT equation to see what the average effect on household VMT would be. Average variable values are listed in Table 32. A 0.52 increase in the number of transit trips reduces the predicted average VMT from 17.7 to 16.3 vehicle miles per household per day, a reduction of 1.4 VMT. A 1.1 thousand increase in activity density reduces the predicted average VMT from 17.7 to 17.3 vehicle miles per household per day, a reduction of 0.4 VMT.

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Acronyms and Initialisms

BRT	Bus rapid transit
CTOD	Center for Transit-Oriented Development
DVRPC	Delaware Valley Regional Planning Commission
GHG	Greenhouse gas
GIS	Geographical information systems
HM	Hierarchical modeling
HRT	Heavy-rail transit
ITDP	Institute for Transportation and Development Policy
LRT	Light-rail transit
MLM	Multilevel modeling
NHTS	National Household Travel Survey
SEM	Structural equation modeling
TAZ	Traffic analysis zone
TOD	Transit-oriented development
TTI	Texas A&M Transportation Institute
UTA	Utah Transit Authority
VMT	Vehicle miles traveled

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation