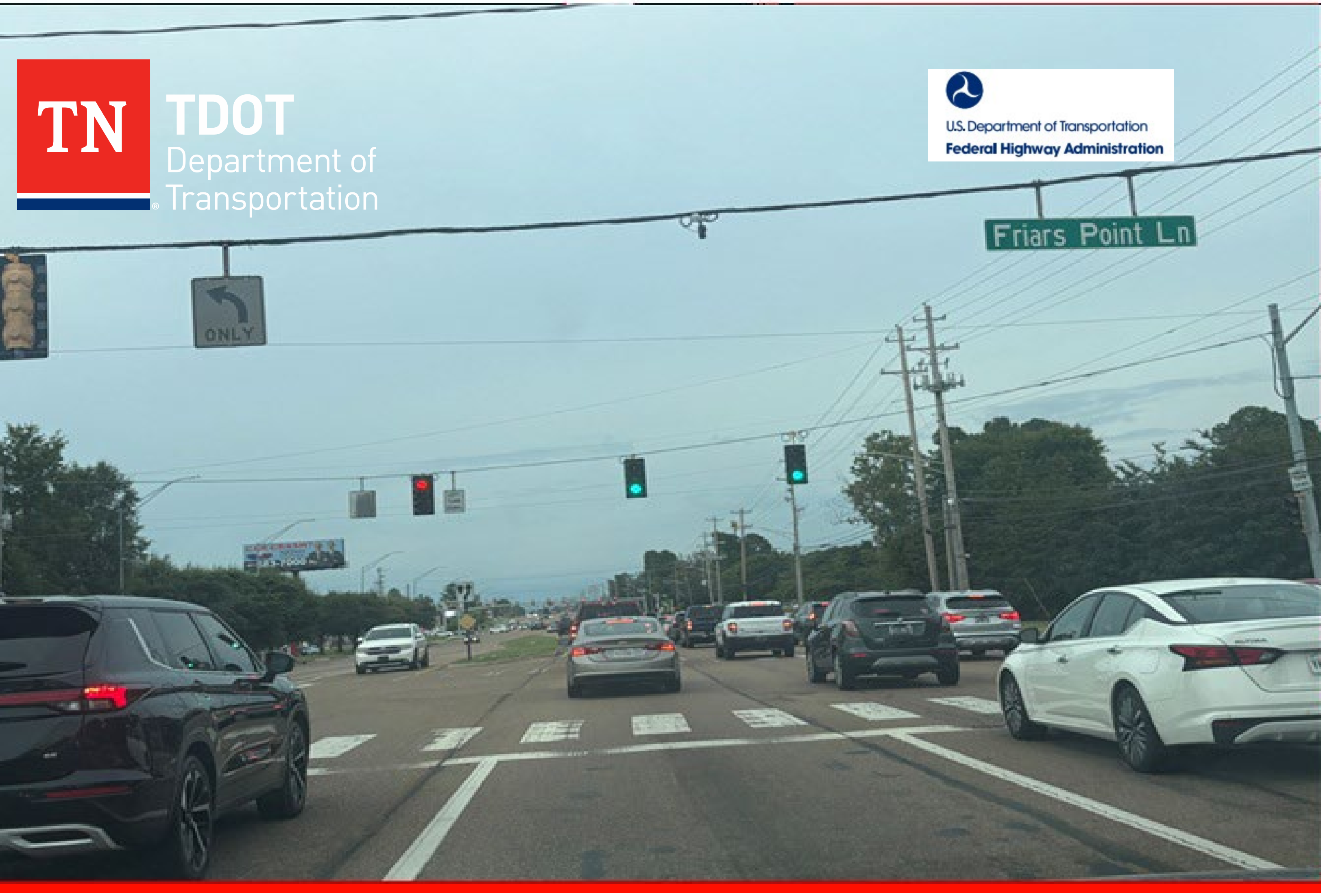

Applying Induced Travel Study in Urban Areas in Tennessee

Research Final Report from The University of Memphis | Angela Antipova, Sabya Mishra, Aman Agrawal, Jayanta Biswas. | July 31, 2026

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16. Abstract

There is a need to understand how transportation provision affects changes in travel including induced travel. Studies are especially needed in places where the increase in travel is substantial. Current research on induced travel in Tennessee has been largely lacking. Prior studies have often used the instrumental approach to isolate the effect of capacity enhancement on travel at the area-wide scale, thus, potentially masking the effect of additional capacity on a single road where improvements have been implemented. This project fills the identified research gaps. This study searches for and identifies instrumental variables at a disaggregate level to further examine the impact of changes in the transportation system on travel. This project operated at the level of individual facilities that experienced capacity enhancement such as road widening or constructing a new lane. The research conducted in this project has led to (1) obtaining local-based evidence of changes in travel after capacity enhancement implementation, (2) identifying drivers of induced travel, and (3) estimating the impact of adding road capacity on travel measured with vehicle miles traveled (VMT) via an instrumental variable (IV) approach at the facility level in Tennessee. Thus, transportation impact analyses will help planning agencies to better understand travel patterns and local transportation impacts of road capacity expansion in metro areas in Tennessee, assist with informed policy decision making, and develop regional and state transportation plans for regional and local transportation projects. The TDOT can use this research as evidence-based estimates of travel changes in response to adding road capacity. The TDOT and regional agencies will have a better understanding of impacts of induced travel from the road capacity expansion projects and to improve performance, environmental sustainability, and direct capital investment for transportation in Tennessee.

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Executive Summary

Road capacity expansion is commonly implemented to alleviate congestion. However, empirical evidence indicates that such expansion potentially has a countereffect of generating additional travel demand, offsetting expected benefits over time.

The main purpose of the project was to understand the impact of greater capacity on travel. Study sites in this project have been defined as the road segments that experienced road capacity enhancement such as road widening or constructing a new lane implemented between 2000-2024 in Tennessee. Road capacity was measured by lane-miles, and travel outcomes were represented by traffic flow and vehicle miles travelled (VMT).

The specific goals of this study were to (1) obtain local-based evidence of induced travel after road enhancement implementation, (2) identify drivers of induced travel, and (3) estimate the impact of adding road capacity on travel measured with vehicle miles traveled (VMT) via an instrumental variable (IV) approach at the facility level in Tennessee.

A comprehensive list of 87 roadway capacity expansion projects across Tennessee were evaluated over 20-year period spanning 10 years before and after expansion to analyze the effect of capacity upgradation. The study applied multi-method analytical framework, including before-after comparisons of traffic outcomes, regression-based estimation to assess causal effects, and a classification approach to identify the presence of induced demand. All analyses were conducted by disaggregating results across functional classes and speed regimes.

The findings indicate that capacity expansion is frequently associated with increases in traffic demand, particularly on higher-speed facilities. However, these effects are not uniform across the network. Within the same functional class, different speed regimes produce distinct outcomes, demonstrating that aggregated analysis can mask important variations in travel response. In urban arterials, higher-speed facilities exhibit stronger increases in traffic outcomes, while lower-speed facilities show limited or no change. In contrast, rural collectors show increases in travel demand even at lower speeds, suggesting that improved accessibility, rather than speed alone, drives demand growth in these contexts.

Overall, the results demonstrate that induced travel is not only present but also varies systematically with roadway characteristics and surrounding conditions. These patterns indicate that induced demand can be anticipated under specific conditions, reinforcing the need for more context-sensitive evaluation of capacity expansion projects.

Key Findings

The key findings of the project are as follows:

- Capacity expansion is associated with measurable increases in traffic demand, as before–after comparisons of capacity expansion projects and regression analyses show consistent increases in AADT and VMT, particularly on higher-capacity facilities.
- The magnitude and direction of induced demand vary by roadway context, with analysis across functional classes and speed regimes showing that aggregated evaluations mask substantial variation in traffic response.

- Higher-speed urban arterials exhibit the strongest increases in traffic outcomes, that indicates that facilities with greater capacity and accessibility tend to attract additional demand after expansion.
- In rural collectors, increases in traffic occur even at lower speeds, which suggests that improved accessibility rather than speed alone drives demand growth in these contexts.
- Induced demand can be systematically identified and categorized, with projects exhibiting distinct patterns ranging from no observable demand increase to clear evidence of post-expansion demand growth.
- Key determinants of induced demand include roadway type, baseline operating conditions, and surrounding activity intensity, indicating that demand response is driven by identifiable structural factors rather than random variation.

Key Recommendations

Some of the key recommendations of this study are as follows:

- Agencies should include induced demand screening into project evaluation, as roadway characteristics such as functional class, speed regime, and surrounding activity levels can be used to identify projects where capacity expansion is likely to generate additional demand rather than relieve congestion.
- Alternate strategies to capacity expansion on high-speed urban arterials must be explored, since these facilities show the strongest increases in traffic demand and are more likely to experience demand rebound after expansion.
- Planners and policymakers should adopt site specific planning approaches, as the response to capacity expansion varies across roadway types, with rural collectors showing accessibility-driven growth and urban facilities exhibiting capacity-driven demand increases.
- Induced demand effects should be integrated into forecasting and planning models, as current approaches that do not account for demand feedback are likely to overestimate the long-term benefits of expansion projects.

Demand management and operational strategies in high-risk corridors should be prioritized, since induced demand is driven by identifiable structural factors and can be mitigated through targeted interventions rather than additional capacity.

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Glossary of Key Terms and Acronyms

AADT: Annual Average Daily Traffic

DDHV: Directional Design-Hour Volume

DVMT: Daily Vehicle Miles Traveled

Comparison sites: Roads that did not undergo any capacity enhancement across Tennessee.

IV: Instrumental Variable

MRLC: Multi-Resolution Land Characteristics

NLCD: National Land Cover Dataset

2SLS: 2-Stage Least Squares

SOV: Single-occupant vehicle

Study sites: Road segments which experienced capacity enhancement 2000-2024 across Tennessee.

TN-TIMES: Tennessee Traffic Information Management and Evaluation System

VMT: Vehicle Miles Travelled

Chapter 1 Introduction

Roadway congestion is a huge public policy issue in the United States. In response, roadway capacity expansion is seen as a solution. As a result, highway vehicle travel in the U.S. cities increases proportionately to highways and includes induced travel (Duranton & Turner, 2011; K. Hymel, 2019). However, impact assessments of such projects often fail to account for the induced vehicle travel effect (Volker, 2022). Thus, the user benefits of capacity expansions are often overestimated (i.e., reduced traffic congestion) (Metz, 2021).

In Tennessee growing traffic congestion is quickly becoming more prominent. For instance, from 1993 to 2017 in Nashville, despite an almost equal growth in population and freeway lane-miles (101% and 107%), the congestion grew by 330% (TfA, 2020). The most significant national-level freight corridors cross the state are predicted to grow significantly in the future. Unprecedented growth worsened traffic conditions in western, central, and eastern Tennessee, especially severely in urban areas.

While impact assessments of adding road capacity projects represent a substantial effort by the research community, however, observed estimates vary considerably from study to study. Studies to understand how transport provision affects the changes in travel, including induced travel are especially needed in places where the increase in travel is substantial, such as in Tennessee where travel measured as vehicle miles travelled (VMT) per capita has been growing faster than in the United States (Figure 1-1). Further, transportation in Tennessee is dominated by drive-alone traffic: almost 75% of work-related travel involved a single-occupant vehicle (SOV) in 2024 – almost 6% higher than the national average (69%) (TABLE 1-1).

It is not clear how much the induced travel effect holds for the cities in Tennessee as current scholarship on the topic is lacking except a few studies that go back several decades (COMSIS Corporation, 1996; DeCorla-Souza et al., 1998) making this research on evidence-based estimates very timely.

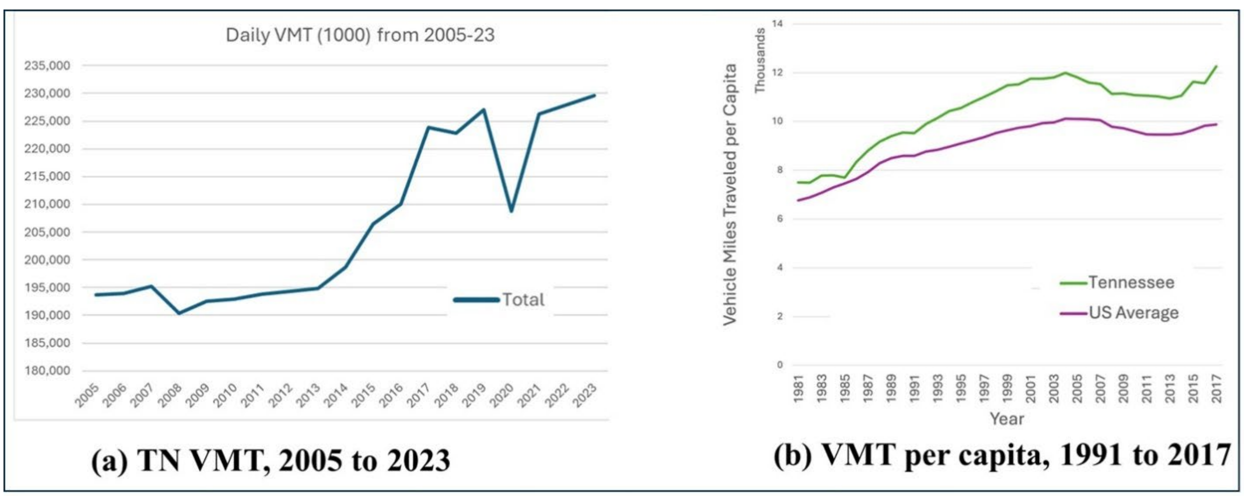

Figure 1-1 (a) VMT data from 2005 to 2023, (b) VMT per capita.

TABLE 1-1 COMMUTE BY MODE, TN AND USA, 2024

State	Mode	%, 2024	State	Mode	%, 2024
US	Drove alone	69.22	**Tennessee**	Drove alone	74.99
	Carpool	9.18		Carpool	9.30
	Worked at home	13.32		Worked at home	12.68
	Public transportation	3.69		Public transportation	0.45
	Taxi, motorcycle, or other	1.66		Taxi, motorcycle, or other	1.28
	Walked	2.45		Walked	1.20
	Bicycle	0.49		Bicycle	0.10

Prior research on induced travel has been largely inconclusive regarding the changes that might occur in response to new capacity. The instrumental approach has been often applied to isolate the effect of capacity enhancement on travel, with prior studies tending to apply instrumental variables (IVs) at the area-wide scale, thus, potentially masking the effect of additional capacity on a single road where improvements such as road widening or constructing a new lane have been implemented.

The study contributes to the current state of empirical knowledge in literature by describing challenges encountered in the search for appropriate instrumental variables for an induced travel study. Tennessee is used as a case study where travel has been greatly increasing compared with the US-average indicated by both total VMT and per capita data. In this study, we first search for factors that may potentially influence road capacity (lane-miles), second, we evaluate various instruments for relevance, third, we select valid instruments that are independent of unmeasured factors that could also affect the outcome (VMT), and finally, we apply them in the 2-stage least squares (2SLS) modelling of VMT.

This report first, describes changes in travel outcomes after implementation of road capacity enhancement in Tennessee between 2000-2024 across 87 study sites chosen for the Induced Travel study. We used a period of 10 years to analyze travel outcomes before and after project implementation. If a road experienced capacity improvement in 2000, the "before" period for the site was designated for 1990-1999, and the "after" period was designated for 2001-2010, respectively. Here, travel outcomes include peak-hour traffic flow, Annual Average Daily Traffic (AADT), peak-hour VMT, and daily VMT where these measures have been compared before and after the project completion. Second, this project identifies causal factors of induced travel. Third, it provides estimates of induced travel measured by vehicle miles travelled (VMT) in Tennessee. It achieves this by applying an instrumental variable (IV) approach at the facility level. Specifically, multiple IVs have been identified in modeling of VMT as a function of enhanced road capacity, itself estimated with various instruments to isolate the effect of capacity enhancement on VMT.

Chapter 2 Literature Review

Congestion has persistently plagued transportation operations and design. According to Schrank et al. (2021), the cost of congestion in 494 urban areas of the United States reached a staggering $101 billion. While expanding roadway capacity is often viewed as a remedy for this issue, it comes with an inherent drawback—induced travel. Induced travel refers to additional vehicle travel in response to the improvement in highway infrastructure to support higher speeds and LOS resulting in reduced travel time and cost of driving (K. Hymel, 2019a). This phenomenon of induced travel is shown in Figure 2-1. Studies on induced travel date back to the 1960s when researchers attempted to estimate the elasticity between roadway expansion and induced travel and found that highway capacity expansion benefits are transitory because, over time, traffic speeds reduce to their pre-expansion levels (Downs, 1962).

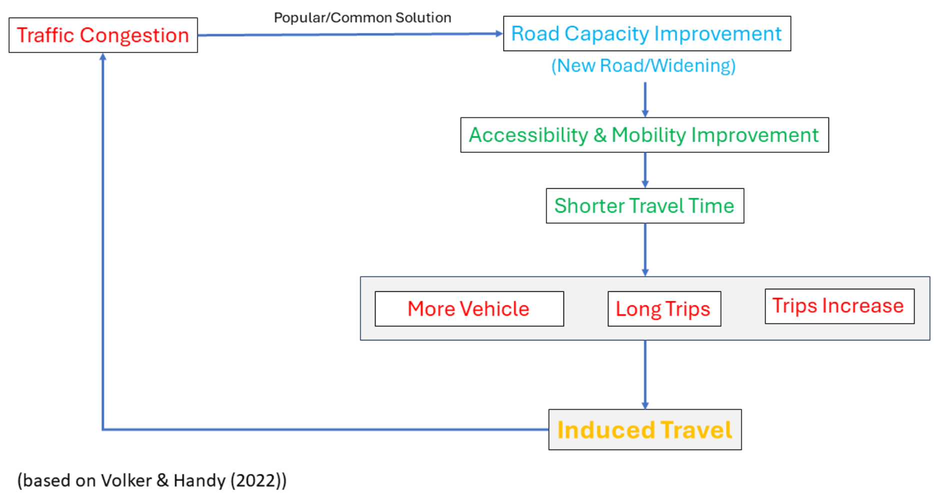

Figure 2-1 Roadway expansion and induced travel.

Induced travel can increase commercial or personal driving because of diversions from other roadways and shifts to single-occupant vehicles (SOV) from public transit or non-motorized transport (Milam et al., 2017).

2.1 Quantifying Travel Changes

Induced travel studies use various methods including elasticity-based econometric models, travel demand models, and corridor-specific case studies of travel growth and its causes, with VMT as a comprehensive measure.

Travel elasticity (demand) with respect to roadway capacity (supply) is the standard metric for measuring "induced travel", or how an increase in lane miles induces a corresponding increase in driving. This phenomenon of induced travel is shown in Figure 2-1.

2.2 Elasticity-based approach

The elasticity, also called sensitivity to change, of the demand with respect to supply is the percent change in demand resulting from a percent increase in supply. In the induced travel study, it is the change in the VMT due to the addition of lane miles. It is estimated through historical data on additional lane miles added and increased VMT using the following relationship:

$$Elasticity\ (from\ historical\ data) = \frac{\%\ Change\ in\ VMT}{\%\ Change\ in\ lane\ miles} \quad (1)$$

Induced travel is estimated with an equation:

$$Induced\ travel = \%\ Change\ in\ lane\ miles\ x\ Existing\ VMT\ x\ Elasticity \quad (2)$$

A generalized form of the equation of elasticity-based VMT equation (log-linear) is shown below:

$$\log(VMT) = a + \sum \beta log(X) + e \quad (3)$$

Where a = Constant term, b = Elasticity of induced travel, X = lane-miles), e = error term

The induced travel literature contains scores of studies in which the elasticity of VMT (induced travel) and added lane miles have been investigated. Past studies used this equation with modifications to account for different IVs, cross-sectional analysis, and time-series analysis. Literature uses time series analysis to capture the short-term (1 to 2 years) versus long-term (4 years or more) effects of roadway expansion on induced travel (Cervero & Hansen, 2002; Handy & Boarnet, 2014). The elasticity of VMT with respect to lane miles of 0.56 means a 5.6% increase in VMT in response to a 10% increase in lane miles (Cervero & Hansen, 2000). Overall, the VMT elasticity value varies depending on the location, time, and level of aggregation where the analysis is carried out.

Studies quantifying the effect of added lane miles on the induced travel often need to address the potential endogeneity bias occurring when the dependent and independent variables cause each other. The 2SLS approach is used when this issue occurs by using an IV that is highly correlated with the problematic endogenous variable (lane-mile) but uncorrelated with the error term of the main equation (VMT).

We addressed this issue in this project by first identifying potential instrumental variables, second, by testing these candidates for endogeneity, and finally, applying the selected instruments in induced travel modeling (see the section on instrumental variables in this report). The verification of the causal relationship is crucial because if capacity were to be expanded in an uncongested road, the likelihood of realizing the induced travel effect is very slim, an outcome, contrary to the estimation of induced studies. Noland & Cowart (2000) used the urbanized land area as the instrument variable for lane mile. The authors estimated the elasticity of VMT for freeways and arterial roads to be 0.284 for the short run and 0.904 for the long run.

Different statistical techniques such as the OLS model, the OLS model with fixed-effect variables, instrumental variables, and multiple methods have been used to assess the induced travel effects. OLS is the simplest regression technique, often used as a benchmark to estimate induced travel elasticity (Cervero & Hansen, 2002; Hansen & Huang, 1997; Hsu & Zhang, 2014). All studies support the finding that highway capacity expansion results in induced demand. The extent of induced travel with added lane miles varies across studies highlighting that travel demand management can be more effective than capacity expansion (Melo et al., 2012).

Overall, the results confirm that both methodological choice and spatial scale have a significant impact on elasticity estimates. Methods correcting for endogeneity tend to yield more conservative estimates, particularly at broader scales. At the same time, OLS and related models often produce higher elasticities that may overstate induced demand if model limitations are not addressed.

In facility-based studies, rather than the econometric model, microsimulation, or cost-benefit analysis are more commonly used methods to evaluate the impact of newly developed roads or the capacity expansion of an existing road before and after road improvement (Amin et al., 2017; Attab & Banyhussan, 2020; Seeherman & Skabardonis, 2016 in TABLE 2-1). Other studies that used induced travel elasticity developed an induced travel calculator for California, using uniform elasticity values (Ponnu et al., 2015; Volker et al., 2020).

TABLE 2-1 SELECTED SCHOLARLY RESEARCH ON EVALUATING INDUCED DEMAND

Study	Setting	Data	Facility Type	Variables		Method
				Demand	Supply	
Fulton et al. (2000)	Maryland; Virginia; North Carolina; Washington DC (220 Counties)	TS/CS	All state highways and many primary roads	VMT	New facility	OLS with FE FDM 2SLS
Noland & Cowart (2000)	Texas Metropolitan Area (70 urbanized areas)	TS/CS	Freeways & arterials	VMT per capita	New facility	OLS with FE 2SLS
Noland (2001)	50 US states	TS/CS	Interstate, freeway, arterial, and collector	VMT	New facility	OLS
Cervero & Hansen (2002)	34 California's urban counties	TS/CS	State facilities (freeway, arterial, and other major thoroughfares)	VMT	New facility	3SLS PDL
Cervero (2003)	24 California Freeway Projects	TS	Freeway (small to medium-sized suburban municipalities)	VMT	Widening	2SLS
Parthasarathi et al. (2003)	3 road projects in Twin Cities	TS	Interstate, trunk highway, and Hennepin County highway	VKT	New facility	Basic difference model
K. M. Hymel et al. (2010)	US State Level Data	TS/CS		VMT	New facility Capacity expansion	3SLS
Duranton & Turner (2011)	Metropolitan Statistical Area Data, United States	CS	Interstate highways and major roads	VKT	New facility	OLS 2SLS LIML

Study	Setting	Data	Facility Type	Variables		Method
				Demand	Supply	
Su (2011)	US State-level data	TS		VMT per capita	New facility	GMM
Zhao & He (2011)	China 31 Province	CS		VMT	New facility	OLS
Concas (2012)	50 US States	TS	Highway	VMT per capita	Capacity expansion	GMM OLS OLS with FE
González & Marrero (2012)	16 Spanish Region	TS	Entire network	VKT per capita	New facility	GMM
Næss et al. (2012)	Nordhavansvej link project, Norway		Link road	AADT	New facility	Cost-Benefit Analysis
Rentziou et al. (2012)	48 US States	TS	Interstate, principal arterial, minor arterial, collector	VMT	New facility	SURE
Shengchuan et al. (2012)	China 31 Province	TS		VKT	New facility	OLS
Hsu & Zhang (2014)	Japan	CS	National expressway	VKT	New facility	OLS with FE 2SLS (FE IV) LIML (FE IV)
Graham et al. (2014)	101 Major US Cities	TS	Freeway/Arterial	VMT	Capacity expansion	POLS POLS FE GMM
Ponnu et al. (2015)	NH-2 Delhi to Agra Highway, India		National Highway	VKT	Capacity expansion	Uniform elasticity value
Seeherman & Skabardonis (2016)	State route SR-24, California		Freeway	Daily Average Traffic	Capacity expansion	ANOVA
Amin et al. (2017)	Highway 25, Montreal		Highway	Peak hour traffic	New facility	Microsimulation

<table>
<tr><th rowspan="2">Study</th><th rowspan="2">Setting</th><th rowspan="2">Data</th><th rowspan="2">Facility Type</th><th colspan="2">Variables</th><th rowspan="2">Method</th></tr>
<tr><th>Demand</th><th>Supply</th></tr>
<tr><td rowspan="3">Hymel (2019)</td><td rowspan="3">US States & Dist. of Columbia</td><td rowspan="3">TS</td><td rowspan="3">Freeway & other limited-access roads</td><td rowspan="3">VMT</td><td rowspan="3">Capacity expansion</td><td>OLS</td></tr>
<tr><td>2SLS</td></tr>
<tr><td>GMM</td></tr>
<tr><td>Attab & Banyhussan (2020)</td><td>4 streets and 5 intersections in Baghdad</td><td></td><td>Street and intersection</td><td>Peak hour traffic</td><td>New facility</td><td>Microsimulation</td></tr>
<tr><td rowspan="4">Chen & Klaiber (2020)</td><td rowspan="4">103 Chinese cities</td><td rowspan="4">TS/CS</td><td rowspan="4">Urban roads (at least 3.5m wide)</td><td rowspan="4">VKT</td><td rowspan="4">New facility</td><td>OLS</td></tr>
<tr><td>OLS FE</td></tr>
<tr><td>2SLS</td></tr>
<tr><td>2SLS FE</td></tr>
<tr><td>Drabicki et al. (2020)</td><td>Suburban ring road, Kraków, Poland</td><td></td><td>Ring road</td><td>Traffic volume per hour</td><td>New facility</td><td>Macrosimulation & 4-stage model</td></tr>
<tr><td rowspan="2">Volker et al. (2020)</td><td rowspan="2">5 projects in California</td><td rowspan="2"></td><td>Interstate 405</td><td rowspan="2">VMT</td><td>Widening</td><td rowspan="2">Induced Travel Calculator</td></tr>
<tr><td>State route 1</td><td>New facility</td></tr>
<tr><td>Anderson et al. (2021)</td><td>4 highway projects in California</td><td>TS</td><td>4 Interstate and one state route</td><td>Traffic flow</td><td>New facility</td><td>OLS</td></tr>
<tr><td rowspan="3">Bucsky & Juhász (2022)</td><td rowspan="3">Road Bridges, Budapest, Hungary</td><td rowspan="3">TS</td><td rowspan="3">Bridge</td><td rowspan="3">ADT</td><td>Expansion</td><td rowspan="3">OLS</td></tr>
<tr><td>New facility</td></tr>
<tr><td>Restriction</td></tr>
<tr><td rowspan="2">Ossokina et al. (2023)</td><td rowspan="2">48 Highway Projects, Netherlands</td><td rowspan="2">TS</td><td rowspan="2">Highway</td><td rowspan="2">Log traffic flow</td><td rowspan="2">Widening</td><td>OLS</td></tr>
<tr><td>OLS with IV</td></tr>
<tr><td colspan="7">TS = Time Series; CS = cross section; LN = lane; IV = instrumental variables; FE = Fixed Effect; RE = Random Effect; FD = First Difference; OLS = ordinary least square; 2SLS= 2 stage least square; LN = lane; LIML= Limited information maximum likelihood; GMM= Generalized method of moments; SURE= Seemingly unrelated regression equation; ANOVA= analysis of variance; DSV = daily service volume; PDL= Polynomial Distributed Lag; FDM= First Difference Model</td></tr>
</table>

Chapter 3 Methodology: Comparison of travel outcomes after capacity enhancement and estimating travel impacts of adding road capacity

First, we set about obtaining local-based evidence of induced travel after road enhancement implementation. Travel outcomes have been compared before and after road capacity enhancement at study sites in Tennessee to find evidence (if any) of changes in travel. Travel outcomes included peak-hour traffic flows, AADT, peak-hour VMT, and daily VMT. Second, we identified drivers of induced travel. Third, we estimated the impact of adding road capacity on travel measured with vehicle miles traveled (VMT) via an instrumental variable (IV) approach at the facility level in Tennessee.

3.1 Data preparation

3.1.1 Study sites

The original sample consisted of 87 road segments which experienced capacity enhancement 2000-2024 (referred to as the *"study sites"*) (N=87), which have been used to identify local evidence of changes in travel after capacity enhancement for the induced travel study. The study site's shapefiles were provided by the Tennessee Department of Transportation (TDOT). Figure 3-1 visualizes the location of roads with their capacity enhanced during 2000-2024 in Tennessee. It provides a geographical context of the spatial distribution of the study sites. Each study site had their unique segment identification number, TN-TIMES identification number, project length, work type and project completion year, as well as a number of lanes (see Figure 3-2). The TN-TIMES identification number provided in the shapefiles' attribute table was used to extract travel characteristics of the road segments that experienced capacity enhancement during 2000-2024 from the TN-TIMES database maintained by the TDOT. After joining in ArcGIS Pro, the attribute table of study sites had information on the annual average daily traffic (AADT) before and after road improvement, which was used for calculations of peak-hour traffic flow before and after road improvement, and VMT before and after road improvement.

Then, we extracted travel outcomes from the TN_TIMES database for the pre- and post-enhancement periods as follows. To understand changes in travel outcomes (that is, changes in traffic flows measured as Annual Average Daily Traffic (AADT) (in vehicles per day, or veh/day), peak-hour flows, daily VMT and peak-hour VMT between the periods prior to and after enhancement), travel outcome data for 10-year periods of before and after project completion have been used for the comparison and travel outcome data have been respectively gathered. For example, for a study site with the segment ID =46 (its TN_TIMES ID= 91000026) completed in 2009, there are 10 observations for the 10-year periods of before the project completion in 2009 (covering a period of 1999-2008) and after its completion (covering a period of 2000-2020) (see Figure A-1 in Appendix A).

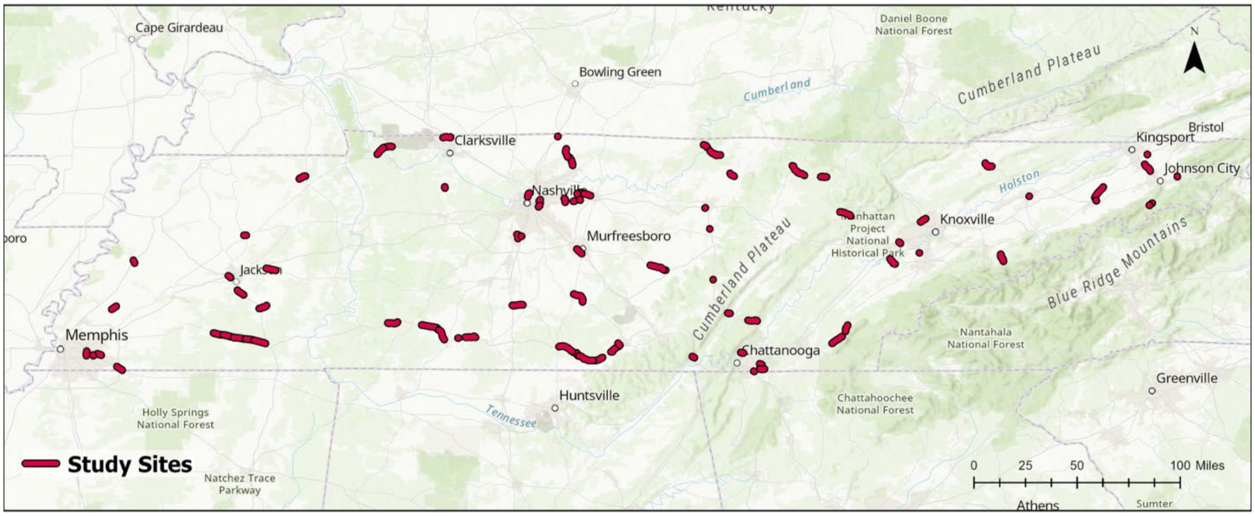

Figure 3-1 Location of roads with their capacity enhanced during 2000-2024 (referred to as the "study sites") in Tennessee.

Label	Description	Data Sources
Segment_ID	Segment Identification Number	TDOT
TN_TIMES_I	TN Times Station Id	TDOT
PROJECT_LE	Project Length	TDOT
WORK_TYPE_	Work Type (e.g., Widen, Resurfacing or New Construction)	TDOT
COMPLETION_YEAR	Project Completion Year	TDOT
ROUTE_NUMB	Route Number	TDOT
NBR_LANES	Number of Lanes (TRIMS)	TDOT
PRE_LANES	Previous Lane Number	Google Earth
AADTBfr	AADT data before the road improvement	TN-TIMES
VMTBfr	VMT data before the road improvement	Calculated
FlowBfr	Peak-Hour Traffic flow data before the road improvement	Calculated
AADTAft	AADT data after the road improvement	TN-TIMES
VMTAft	VMT data after the road improvement	Calculated
FlowAft	Peak-hour traffic flow data after the road improvement	Calculated

Figure 3-2 Example of label descriptions for study sites in Tennessee.

3.1.2 Travel outcome measurements (peak-hour traffic flows, AADT, peak-hour VMT, and daily VMT)

In the analysis of comparison of travel outcomes, traffic flows were measured using Annual Average Daily Traffic (AADT). The AADT is the total vehicle volume at a site on a typical day of the year (Tsapakis et al., 2020). According to the Traffic Monitoring Guide (TMG) developed by the FHWA which is the main reference for transportation agencies on traffic data collection, processing, analysis, and reporting, AADT is the “total volume of vehicle traffic of a highway or road for a year divided by 365 days” (FHWA, 2016).

The Average Daily Traffic (ADT) counts and the AADT estimates are used by highway agencies to provide information for individual corridor, traffic control studies, and other projects; develop policies, safety, meet federal reporting requirements, and supply broad knowledge of roadway use.

First, AADTs have been adjusted for peak-hour volume and peak-hour directional distribution. Passenger car traffic patterns vary over hours of the day. The morning and evening peak periods have the highest passenger car volumes in urban areas, and those in rural areas usually increase slowly until the evening before decreasing (Tsapakis et al., 2020). The unadjusted AADT values (as found in the TN-TIMES database) incorporate traffic volume from both directions. Therefore, during the peak hour flow calculation, we have utilized the directional percentage factor (d%). However, there is no data available for passenger car (FHWA class 1-3) and commercial vehicle (FHWA class 4 and above) proportions in TN-TIMES for the study period. (Note: For many stations, the values are provided for years starting 2021, where commercial vehicles tend to constitute 3-4% of the total volume). AADT does not capture the variations of traffic including those over different time periods during the day (Huntsinger, 2022). AADT can be converted to an equivalent directional design hourly volume (DDHV) in the major direction by multiplying it by both the K-factor and the D-factor (FHWA, 2018). Thus, to compare traffic flows during the peak hour period, the estimated annual average daily traffic (AADT) values as provided in the TN-TIMES database have been adjusted for peak-hour volume and peak-hour directional distribution and Directional Design-Hour Volume (DDHV) calculated.

Directional Design-Hour Volume (DDHV) is the proportion of AADT in the peak-hour (design hour) in the predominant direction of traffic flow (FHWA, 2018). DDHV (its unit is vph) is one-direction volume computed by multiplying AADT by K-factor and D-factor (US DOT. FHWA, 2018) using an equation:

$$DDVH = AADT\ x\ K\ x\ D \quad (4)$$

Where: K = the proportion of AADT occurring in the peak hour, i.e., the K-factor.

D = peak-hour volume proportion in the major direction, i.e., the D-factor

2. Then we computed Vehicle Miles Traveled (VMT) and Daily vehicle miles traveled (DVMT).

VMT refers to the total miles traveled by vehicles in a certain area (e.g., a route, a functional road classification, or geographic area) during one year (US DOT. FHWA, 2018). VMT is used for monitoring travel demand as well as analysis of a facility’s performance on emissions, safety, and mobility (FHWA, 2018). Daily vehicle miles traveled (DVMT) is defined as total miles travelled by vehicles in one day.

VMT is calculated by multiplying the AADT value for each section of road by 365 and by the section length (in miles) and summing all sections to obtain VMT for a complete route as:

$$VMT\ = AADT_{x} * Section\ length_{x}\ (miles) * number\ of\ days\ in\ a\ year \quad (5)$$

Where:

AADTx = AADT for section x, Section length, x = Length of section x in miles

By using data on traffic counts (measured in AADT, veh/day) and section length (miles), both infrastructure performance measures, DVMT (in veh-miles) and VMT (in veh-miles) = DVMT*365, have been computed for study sites.

3.1.3 Study site distribution by functional class and speed

Next, we distinguished all study sites by functional classification. All study sites are classified by their functional class into the following 10 classes: 1 (Rural Principal Arterial - Interstate, routes designated as Interstate Highways), 2 (Principal Arterial – Other, Non - Interstate principal arterials), 6 (Rural Minor Arterial), 7 (Rural Major Collector), 8 (Rural Minor Collector), 11 (Urban Principal Arterial – Interstate, Routes designated as Interstate Highways), 12 (Urban Principal Arterial - Other Freeways and Expressways: Non - Interstate principal arterials), 14 Urban Principal Arterial - Other (no control of access), 16 (Urban Minor Arterial), and 17 (Urban Collector) (shown in Figure 3-3). Figure 3-3 shows the location of all study sites in TN by their functional class showing each class in a different color.

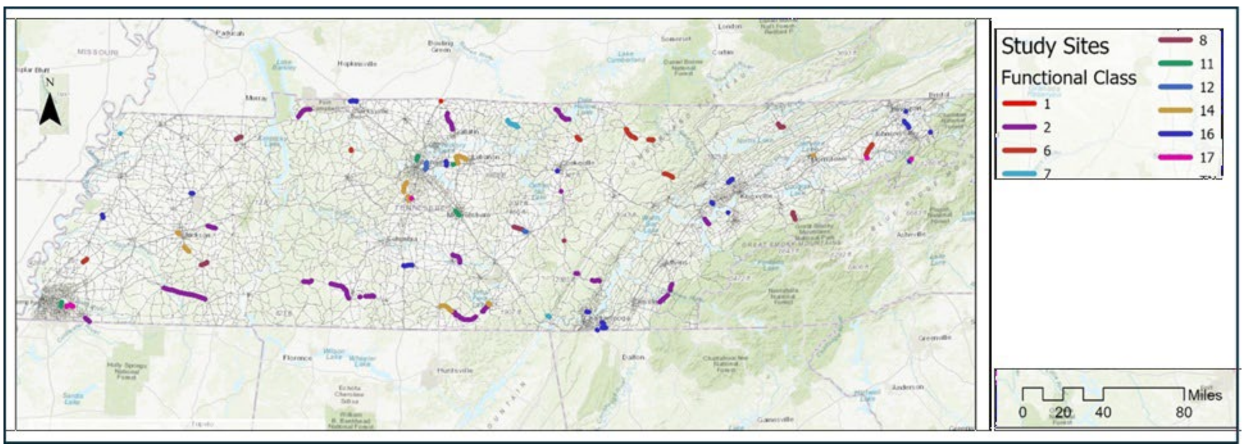

Figure 3-3 Study sites by their functional class.

Since travel outcomes have been obtained for every study site over the 10-year period (over 10 years each of before and after periods preceding and following capacity improvement), each study site has at least 10-years' worth data falling into one of ten functional classes.

As Figure 3-4 reports, there are 10 observations of the functional class 1 (corresponding to the 10-year long travel outcomes data of a single study site), 290 observations of a functional class 2 (corresponding to 29 study sites), 70 observations of a functional class 6, 30 observations of a functional class 7, 60 observations of a functional class 8, 40 observations of a functional class 11, 40 observations of a functional class 12, 110 observations of a functional class 14, 110 observations of a functional class 14, 170 observations of a functional class 16, and 50 observations of a functional class 17 (870 observations in total of all functional class corresponding to 87 study sites identified for the analysis over 10 years of observation). Mostly (66% of 870 observations) for all study sites) fall into the functional classes 2, 16, and 14, at over 33%, almost 20%, and almost 13%, respectively. Thus, 1/3 of all study sites' observations are rural non - Interstate principal arterials and another 1/3 of all study sites' observations are urban principal and minor arterials (Figure 3-4).

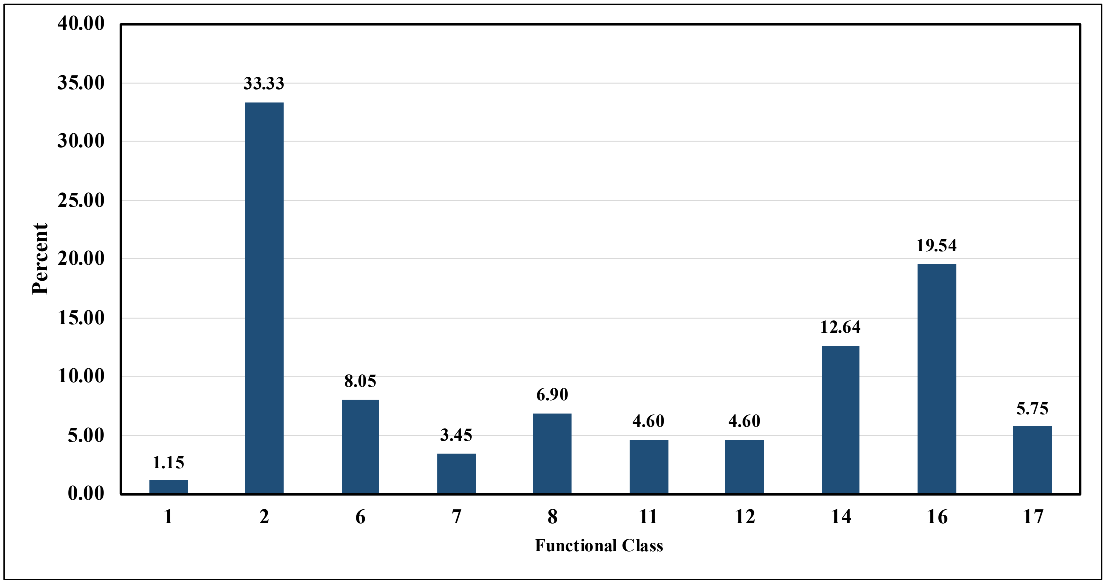

Figure 3-4 Study sites by their functional class.

Next, we distinguished all study sites by speed limit. The speed limits for the study sites of all functional classes range between 25mi/hr and 70mi/hr. Figure 3-5 presents the speed distribution for the study sites of all functional classes, shown as a count (frequency) and a percent, respectively. The speed limit of 55mi/hr is the most common at 31%, followed by the speeds of 45mi/hr and 40mi/hr, respectively at 18.4% and 10.3%.

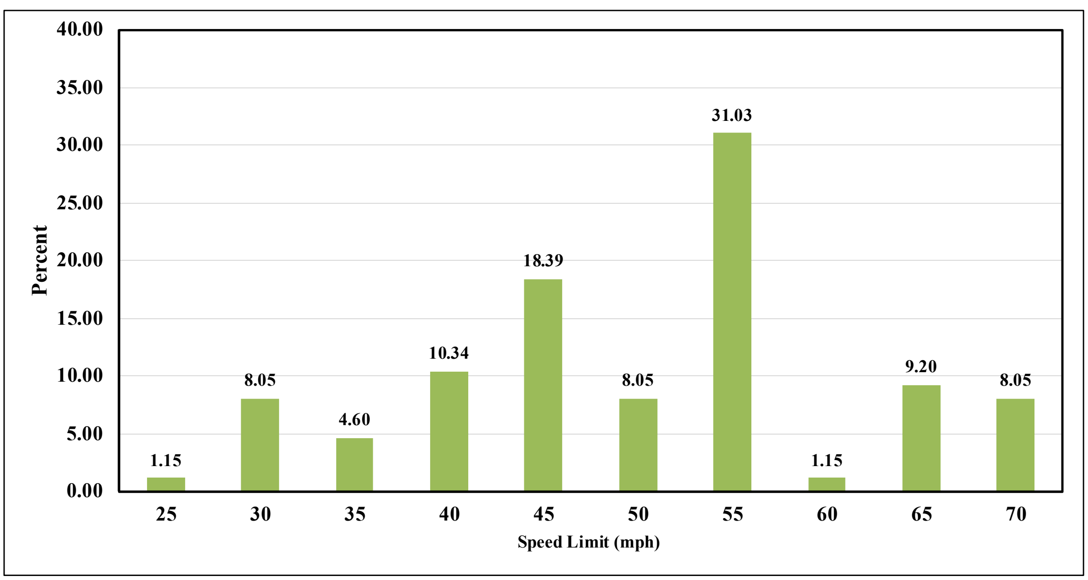

Figure 3-5 Study sites by their speed distribution.

3.1.4 Designation of "before" and "after" periods for travel outcomes

Travel outcomes data (peak-hour traffic flow coded as "Flow", AADT, Peak-hour VMT coded as "VMTPk", and daily VMT) have been obtained for each study site for the 10-year period before any road capacity improvement (coded as "FlowBfr", "AADTBfr", "VMTBfr", "VMTPkBfr"), and for the 10-year period after the road capacity improvement (coded as "FlowAft" , "AADTAft", “VMTAft”, “VMTPkAft”), resulting in the sample of 870 (87 x 10=870) observations for each period, respectively. Some study sites had missing data for a few years in the period before the project completion or after, resulting in unequal (unbalanced) samples on some occasions. Study sites’ travel outcomes data for “before” and “after” periods were compared to determine whether significant changes occurred in travel outcomes following enhancement of road capacity. Due to the presence of missing data, a t-test assuming unequal variance has been applied for a comparison of travel outcomes (described in a greater detail in the subsection titled “Statistical analysis of travel outcomes of 10 years before and 10 years after road capacity improvement” below). Since capacity enhancement took place during 2000-2024, the comparison analysis covered the period of 1990-2024 (as the pre- and post-improvement data have been used).

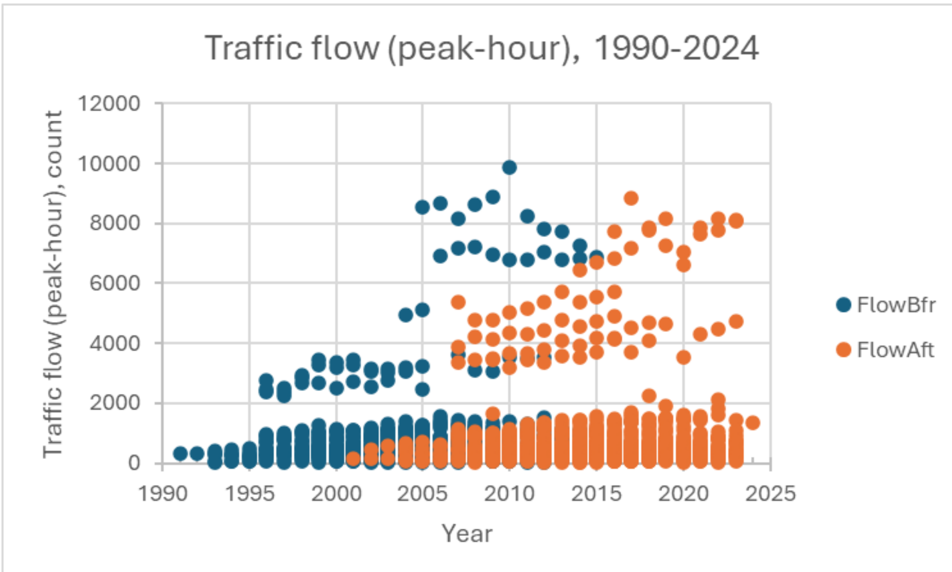

Figure 3-6 Peak-hour traffic flow, study sites of all functional classes (N=870) and all speeds, 1990-2024.

Figure 3-6 provides a visual presentation of all peak-hour traffic flows, for the period of 1990-2024 for roads of all functional classes (N=870) and all speeds. This scatterplot shows peak-hour traffic flows for the period before capacity enhancement in a dark blue color (coded as “FlowBfr”) and peak-hour traffic flows for the period after capacity enhancement in a red color (coded as “FlowAft”).

3.2 Statistical analysis: Comparison of travel outcomes (peak-hour traffic flows, AADT, peak-hour VMT, and daily VMT) for the 10-year period before and 10-year period after road capacity improvement

Next, we ran a statistical analysis of travel outcomes for the 10-year period before and 10-year period after road capacity improvement. Specifically, a statistical analysis of difference in means in traffic flows (AADT values, both unadjusted and adjusted for peak hour flow and directionality), DVMT, VMT at study sites has been implemented. Traffic flows measured using

AADT values, both unadjusted and adjusted for peak hour flow and directionality as described above), as well as DVMT and VMT were compared for before and after capacity enhancement.

Travel outcomes included the following measures: peak-hour traffic flow coded as “Flow”, annual average daily traffic (AADT), peak-hour vehicle miles travelled (VMT) coded as “VMTPk”, and daily VMT. The research question is whether greater road capacity changes travel outcomes. Specifically, whether the implementation of road capacity enhancement increases peak-hour traffic flow, AADT, peak-hour VMT, and daily VMT.

The following hypotheses have been tested for each travel outcome:

1. H1: There were no changes in peak-hour traffic flow.
   H2: There were changes in peak-hour traffic flow.
2. H1: There were no changes in overall annual average daily traffic (AADT).
   H2: There were changes in AADT.
3. H1: There were no changes in peak-hour vehicle miles travelled (VMT).
   H2: There were changes in peak-hour VMT.
4. H1: There were no changes in daily VMT.
   H2: There were changes in daily VMT.

To answer whether there were changes in travel outcomes following road capacity enhancement, a t-test assuming unequal variance has been applied for the comparison of travel outcomes before and after the improvement.

For all 87 study sites studied over 1990-2024, there are 656 observations for the “before” period (N1=656) and 811 observations for the “after” period (N2=811). We tested if the hypothesized mean difference was 0. Table 3-1 reports the results of a two-sample t-Test assuming unequal variances for all observations, regardless of a functional class or a speed limit. Travel outcomes include peak-hour traffic flow coded as “FlowBfr” and “FlowAft” (to designate peak-hour traffic flow before and after the project completion, respectively) , AADT coded as “AADTBfr” and “AADTAft” (to designate AADT before and after the project completion, respectively), peak-hour VMT coded as “VMTPkBfr” and “VMTPkAft” (to designate peak-hour VMT before and after the project completion, respectively), and daily VMT coded “VMTBfr” and “VMTAft” (to designate VMT before and after the project completion, respectively). While there were increases across all travel outcomes, the changes were not significant when all observations have been used for in the analysis for a comparison.

Table 3-1 A Two-Sample t-Test Assuming Unequal Variances for travel outcomes (for all observations, regardless of a functional class or speed limit

Row Title	FlowBfr	FlowAft	AADTBfr	AADTAft		VMTBfr	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	881.2	903.9	15772.29	16202.27		33861.74	38607.01	2022.5	2095.5	881.2
Variance	1943983	1958958	5.7E+08	5.86E+08		3.56E+09	3.68E+09	11500113	9854593	1943983
N	656	811	656	811		680	811	656	811	656

df	1404		1409			1452		1352		1404
t Stat	-0.31		-0.34			-1.52		-0.42		-0.31
P(T<=t) 1-tail	0.38		0.37			0.06		0.34		0.38
t Critical 1-tail	1.65		1.65			1.65		1.65		1.65
P(T<=t) 2-tail	0.76		0.73			0.13		0.67		0.76
t Critical 2-tail	1.96		1.96			1.96		1.96		1.96

3.3 Statistical analysis of travel outcomes of 10 years before and 10 years after road capacity improvement by functional class.

As described above, the study sites in this study belong to the 10 different functional classes, while each functional class may have various speed limits (except for the functional classes 1 and 12 which have a single speed limit value each). Thus, analyzing travel outcomes without accounting for a functional class or a speed limit, may potentially mask any travel outcome change after capacity enhancement because of the existing variability in speeds even within a single functional class and other differences across different functional classes, thus, requiring a detailed analysis of travel outcomes separately for each functional class and the speed limit. (Note: travel data is not analyzed when there are no data for the “before” and/or after period).

Thus, we ran a statistical analysis of travel outcomes of 10 years before and 10 years after road capacity improvement by functional class applying the same two-sample t-test with unequal variances used in the section earlier. To determine whether travel outcomes changed significantly following road capacity improvement, changes in travel outcomes have been studied separately for each functional class and speed. Thus, the analysis was conducted at two levels. First, observations were grouped by functional class to examine class-level patterns across all speeds within the class. Second, each functional class was further divided by posted speed limit to examine variation within the same class. Appendix B reports the full set of test results and the number of observations in each subgroup for functional class groupings and Appendix C does that for functional class and speed limit combinations. The resulting patterns across subgroups are presented and discussed in Section 4.1.

3.3.1 Functional Class 1.

These are Rural Principal Arterials – Interstates. Routes are designated as Interstate Highways. Figure 3-7 provides a geographical context. It shows the location of the study site (functional class 1) (shown in a red color) and all study sites (shown in in the insert map), used in this study.

In this study, there are 18 observations in total including 10 observations of the study site (functional class 1) (a segment ID =91, TN-TIMES ID =83000133) corresponding to the “before” period (N1=10) and 8 observations for the same study site for the “after” period (N2=8). This functional class has a single speed of 70 miles/hr.

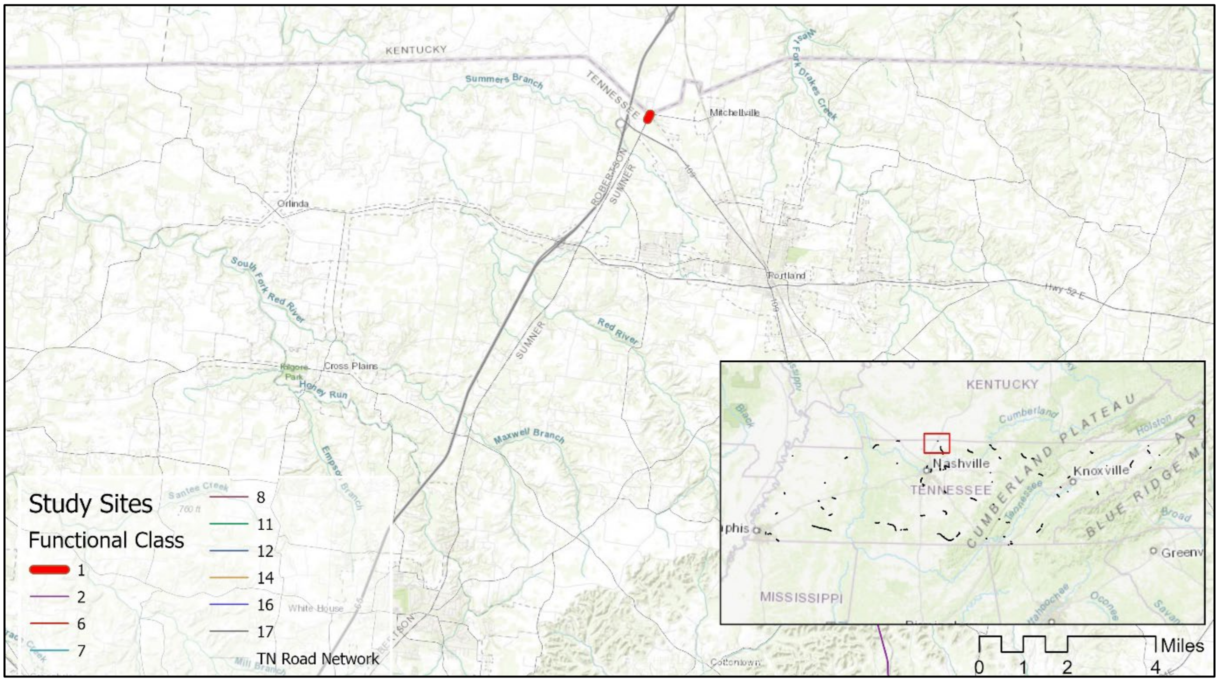

Figure 3-7 Study site (functional class 1).

TABLE B-0-1 in the Appendix B) presents the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes (peak-hour traffic flow coded as "Flow", AADT, Peak-hour VMT coded as "VMTPk", and daily VMT) for the functional Class1 with a speed limit of 70 mi/hr. Significant changes occurred in peak period traffic flow (greater FlowAft vs FlowBfr), daily traffic flow (greater AADTAft vs AADTBfr), daily VMT (VMTAft vs VMTBfr), and peak-period VMT (VMTPkAf vs VMTPkBfr). Both directional (1-tail) and non-directional (2-tail) t-tests reveal significance, providing evidence of a real effect of capacity enhancement, and not random variation. Small p-values shown by both 1-tail and 2-tail tests indicates strong evidence against the null hypothesis, leading to rejecting the null hypothesis while supporting the alternative hypothesis of the real effect of road capacity enhancement on travel outcomes. For the study sites of this functional class 1, with the speed limit of 70mi/hr, peak-period traffic flow increased by 28% on average (((620.08-484.43)/484.43)*100), daily traffic flow increased by 27.62% on average (((12046.63-9439.3)/ 9439.3)*100), peak-period VMT increased by 28.05% on average, and daily VMT increased by 27.62% on average.

3.3.2 Functional Class 2.

These are Rural Principal Arterials - Other: routes are designated as non - Interstate principal arterials. Figure 3-8 provides a geographical context. It shows the location of the study site (functional class 2) (shown in a red color in the map) as well as all study sites shown in a blue color used in this study.

TABLE B-0-2 (Appendix B) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 2 where all speeds are included (30 mi/hr, 45 mi/hr, 55 mi/hr, 60 mi/hr, 65 mi/hr, and 70 mi/hr). The data are represented by observations covering 10 years before (N1=186) and 10 years after project completion (N2=279) used in the statistical analysis. A t-test has been applied to all observations without accounting for various speed limits for comparison of means across the four measures on travel outcomes. Study sites with all speeds, had a significantly greater overall daily VMT occurring after capacity improvement (p-value =0.03) with an increase by 8.55% on average. There was an increase in AADT (with a borderline p-value=0.055), while no changes occurred in peak-hour traffic flow and peak-hour VMT.

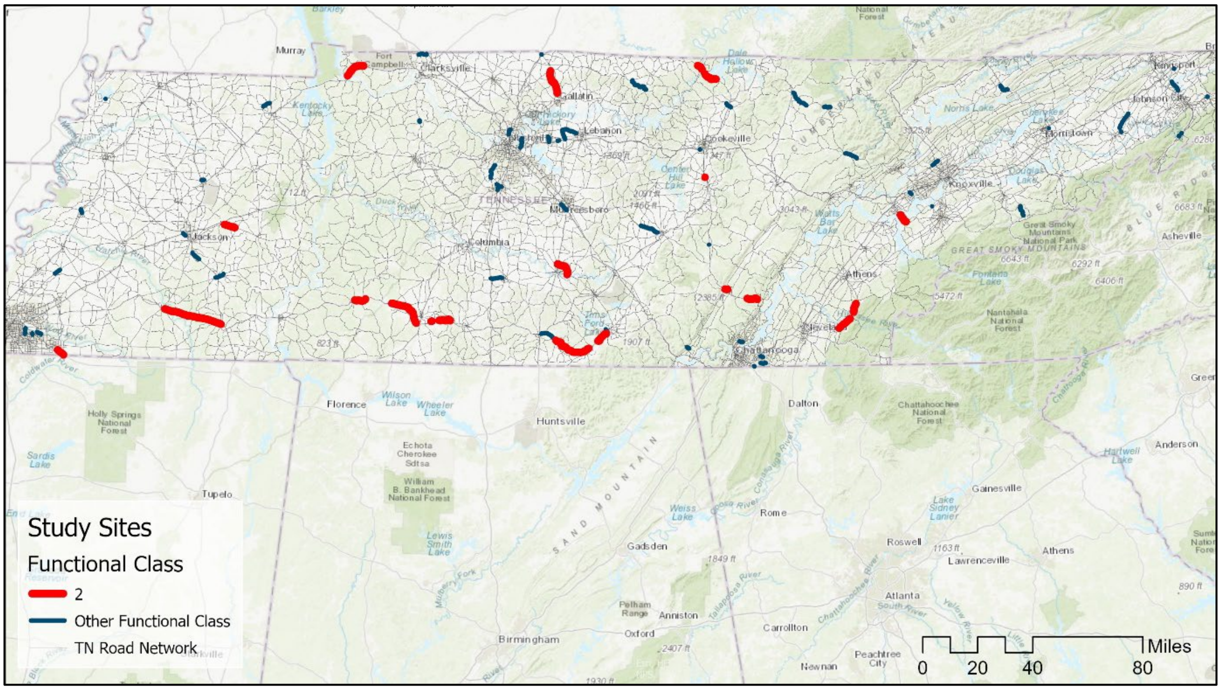

Figure 3-8 Study sites (functional class 2).

Speed limits for the study sites of this functional class include 30 mi/hr, 45 mi/hr, 55 mi/hr, 60 mi/hr, 65 mi/hr, and 70 mi/hr. Below is the description of the analysis of travel outcome changes due to capacity enhancement broken down by the speed limit within this functional class.

3.3.2.1 Functional Class 2: Speed Limit 30mi/hr.

Within the functional class 2, the speeds include the following limits: 30 mi/hr, 45 mi/hr, 55 mi/hr, 60 mi/hr, 65 mi/hr, and 70 mi/hr. Due to a great variability in speed limits within a single functional class, a comparison of travel outcomes has been implemented by various speed limit for the functional class 2. The results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes by functional class and by speed are reported in the Appendices section.

There are 20 observations (corresponding to a study site with a segment ID=46, and a TN_TIMES ID= 91000026) including 10 observations for the 10-year periods of before the project completion in 2009 (covering a period of 1999-2008) (N1=10) and 10 observations for the period after project completion (covering a period of 20010-2020) (N2=10).

TABLE C-0-1 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for Functional Class 2 with a speed of 30 mi/hr. For a functional class 2 with a speed of 30mi/hr, a reverse pattern has been observed when there were significant decreases across all measures of travel outcomes following the project completion. On average, peak-period flows and peak-period VMT decreased by 9.5%, and AADT and daily VMT dropped by 7.4%, after road capacity enhancement.

3.3.2.2 Functional Class 2: Speed Limit 45mi/hr.

For the study sites (functional class 2, speed limit of 45mi/hr), there are 50 observations covering 10 years before (N1=20) and 10 years after project completion (N2=30) used in the statistical analysis. A t-test has been applied to 50 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-2 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 2 with the speed limit of 45 mi/hr. There are significant decreases in peak-hour traffic flow (FlowAft vs FlowBfr) (p-value =0.009 for 1-tail test) and in AADT (AADTAft vs AADTBfr) (p-value =0.004 for 1-tail test) for the study sites of functional class 2 with the speed limit of 45 mi/hr. The 2-tail tests also show statistically significant decreases for these 2 travel outcomes. No significant changes have been found for the peak-hour VMT (VMTPkAft vs VMTPkBfr) and daily VMT (VMTAft vs VMTBfr) for the study sites of functional class 2 with the speed limit of 45 mi/hr.

3.3.2.3 Functional Class 2: Speed Limit 55mi/hr.

For the study sites (functional class 2, speed limit 55mi/hr), there are 124 observations covering 10 years before (N1=90) and 10 years after project completion (N2=134) used in the statistical analysis. A t-test has been applied to 134 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-3 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 2 with the speed limit of 55 mi/hr. There are no changes in peak-hour traffic flow (FlowAft vs FlowBfr) and AADT (AADTAft vs AADTBfr). However, there were significant changes in daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr). Daily VMT increased by 11.82% (((32534.1-29095.5)/29095.5)*100) and peak-hour VMT increased by 12.77% (((1723.3-1528.1)/ 1528.1)*100), on average.

3.3.2.4 Functional Class 2: Speed Limit 60mi/hr.

For the study sites (functional class 2, speed limit 60mi/hr), there are 18 observations for the study sites of the functional Class 2 with the speed limit of 60mi/hr covering 10 years before project completion (N1=8) and 10 years after project completion (N2=10) used in the statistical analysis. A t-test has been applied to 18 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-4 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 2 with the speed limit of 60 mi/hr. For the study sites of functional Class 2 with the speed limit of 60 mi/hr, there were statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 20.38% (((408.1-339)/339)*100), AADT (AADTAft vs AADTBfr) has experienced an increase by 26.42% (((8242.4-6519.6)/6519.6)*100), while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew by 20.38% (((693.8-576.3)/ 576.3)*100) and 26.43% (((14012-11083)/ 11083)*100), respectively.

3.3.2.4 Functional Class 2: Speed Limit 65mi/hr.

For the study sites (functional Class 2, speed 65mi/hr), there are 122 observations covering 10 years before (N1=58) and 10 years after project completion (N2=70) used in the statistical analysis. A t-test has been applied to 128 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-5 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 2 with the speed limit of 65 mi/hr. For the study sites of functional Class 2 with the limit of speed 65mi/hr, there were statistically significant increases in daily VMT (VMTAft vs VMTAft) (p-value =0.029), where daily VMT increased by 17.1% (((24374-20813.9/20813.9)*100) after the implementation of road capacity improvement. There were no statistically significant changes in peak-hour traffic flows, AADT, or peak-hour VMT after road capacity increased.

3.3.3. Functional Class 6: All Speed Limits.

These are Rural Minor Arterials: The Rural Minor Arterial Road System, together with the Principal Arterial System, form a rural network. Figure 3-9 provides a geographical context. It shows the location of the study sites (functional class 6) (shown in a red color) as well as all study sites shown in a blue color used in this study.

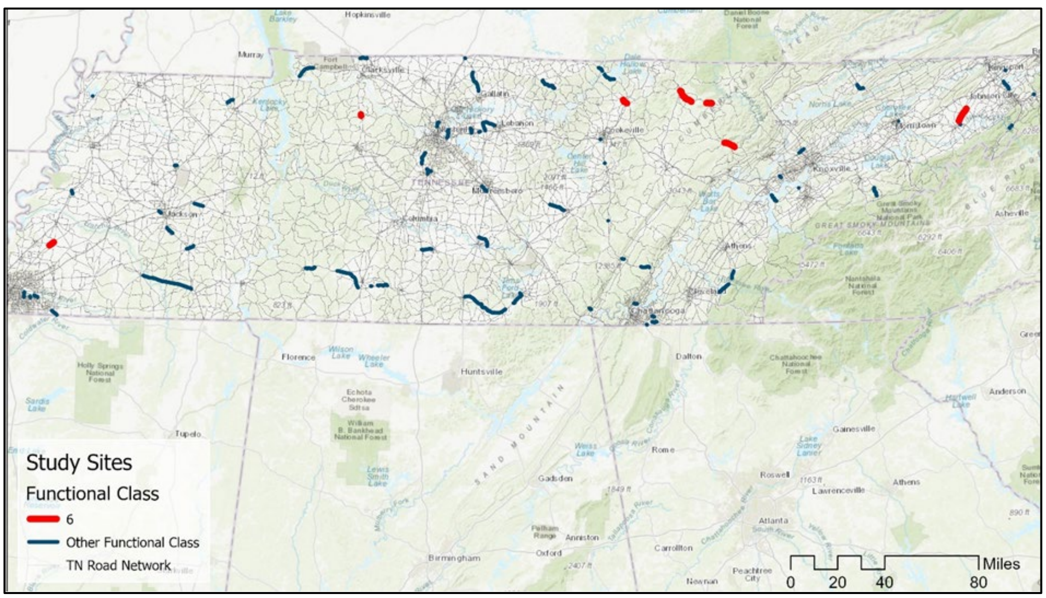

Figure 3-9 Study sites (functional class 6).

Initially, for the study sites within the functional class 6, all 120 observations for all speeds have been used for the analysis of changes in travel outcomes. There are 120 observations covering 10 years before project completion (N1=50) and 10 years after project completion (N=70) used in the statistical analysis. A t-test has been applied to 120 observations for comparison of means across the four measures on travel outcomes. TABLE B-0-3 (Appendix B) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 6 where all speeds are included (45mi/hr, 50 mi/hr, 55 mi/hr, and 70 mi/hr). No changes in travel outcomes have occurred when all speeds are used in the analysis. The speed limits for the study sites of this functional class include 45mi/hr, 50 mi/hr, 55 mi/hr, and 70 mi/hr. Below is the description of the analysis of travel outcome changes due to capacity enhancement broken down by the speed limit within this functional class.

3.3.3.1. Functional Class 6: Speed Limit 45mi/hr.

For the study sites (functional Class 6 with the limit of speed 45 mi/hr), there are 50 observations covering 10 years before project completion (N1=20) and 10 years after project completion (N2=30) used in the statistical analysis. A t-test has been applied to 50 observations for comparison of means across the four measures on travel outcomes.

TABLE C-0-6 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 6 with a speed limit of 45 mi/hr.

For the study sites of functional Class 6 with the speed limit of 45mi/hr, there were statistically significant decreases in AADT (AADTAft vs AADTBfr), daily VMT (VMTAft vs VMTAft), and in peak-hour VMT (VMTPkAft vs VMTPkBfr). On average, AADT (AADTAft vs AADTBfr) decreased by 22.51% (((4625.5-5969.3)/ 5969.3)*100), daily VMT (VMTAft vs VMTAft) decreased by 27.5% (((23268.1-32097.8)/32097.8)*100), and peak-hour VMT (VMTPkAft vs VMTPkBfr) decreased by 21.08% (((1400.4-1774.4)/ 1774.4)*100) after the implementation of road capacity improvement. Peak-hour traffic flows (FlowAft vs FlowBfr) had no statistically significant increases in value. The results are supported by both the 1-tail test (a directional test) and the 2-tail test (a non-directional test).

3.3.3.2. Functional Class 6: Speed Limit 50mi/hr.

For the study sites (functional Class 6, speed limit of 50mi/hr), there are 20 observations including 10 observations covering 10 years before project completion (N1=10) and 10 observations for the 10 years after project completion (N2=10) which have been used in the statistical analysis. A t-test has been applied to 20 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-7 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 6 with a speed limit of 50 mi/hr.

For the study sites of functional Class 6 with the speed limit of 50 mi/hr, there were statistically significant decreases in AADT (AADTAft vs AADTBfr) as AADT decreased by 5.36% (((1721.5-1819)/ 1819)*100), and daily VMT (VMTAft vs VMTAft) which also decreased by 5.35% (((10156.9-10732.1)/ 10732.1)*100).

On the other hand, for the study sites (functional Class 6, speed limit of 50mi/hr), there were statistically significant increases in peak-hour traffic flows (FlowAft vs FlowBfr), and in peak-hour VMT (VMTPkAft vs VMTPkBfr). On average, peak-hour traffic flows (FlowAft vs FlowBfr) grew by 8.67%, (((102.8-94.6)/ 94.6)*100), and peak-hour VMT (VMTPkAft vs VMTPkBfr) increased by 8.73% (((606.79-558.07)/ 558.07)*100) after the implementation of road capacity improvement.

3.3.3.3. Functional Class 6: Speed Limit 55mi/hr.

For the study sites (functional class 6, speed limit 55mi/hr), there are 40 observations covering 10 years before (N1=20) and 10 years after project completion (N2=20) used in the statistical analysis. A t-test has been applied to 40 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-8 (Appendix C) reports the results of a Two-

Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 6 with the speed limit of 55 mi/hr. No changes in travel outcomes have been observed for the study sites (functional Class 6, speed 55mi/hr) after road capacity enhancement.

3.3.4. Functional Class 7: All Speed Limits.

These are Rural Major Collectors. Collectors mostly provide travel of intracounty importance, travel distances on these routes are shorter than on arterial routes.

Figure 3-10 provides a geographical context. It shows the location of the study sites (functional class 7) (in a red color in the map) and all study sites shown in a blue color used in this study. On average, more moderate speeds are typical for the routes of this functional class. In this study, the study sites of functional class 7 have speeds of 30mi/hr, and 50mi/hr.

For the study sites (functional class 7, all speeds including 30mi/hr, and 50mi/hr), there are 56 observations covering 10 years before (N1=30) and 10 years after project completion (N2=26) used in the statistical analysis. A t-test has been applied to 56 observations for comparison of means across the four measures on travel outcomes.

TABLE B-0-4 (Appendix B) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 7 with all speeds (30mi/hr, and 50mi/hr). There are 30 observations for the "before" period and 26 observations for the "after" period (total N=56 observations). No substantial changes in travel outcomes are observed when all observations are used with all speed limits.

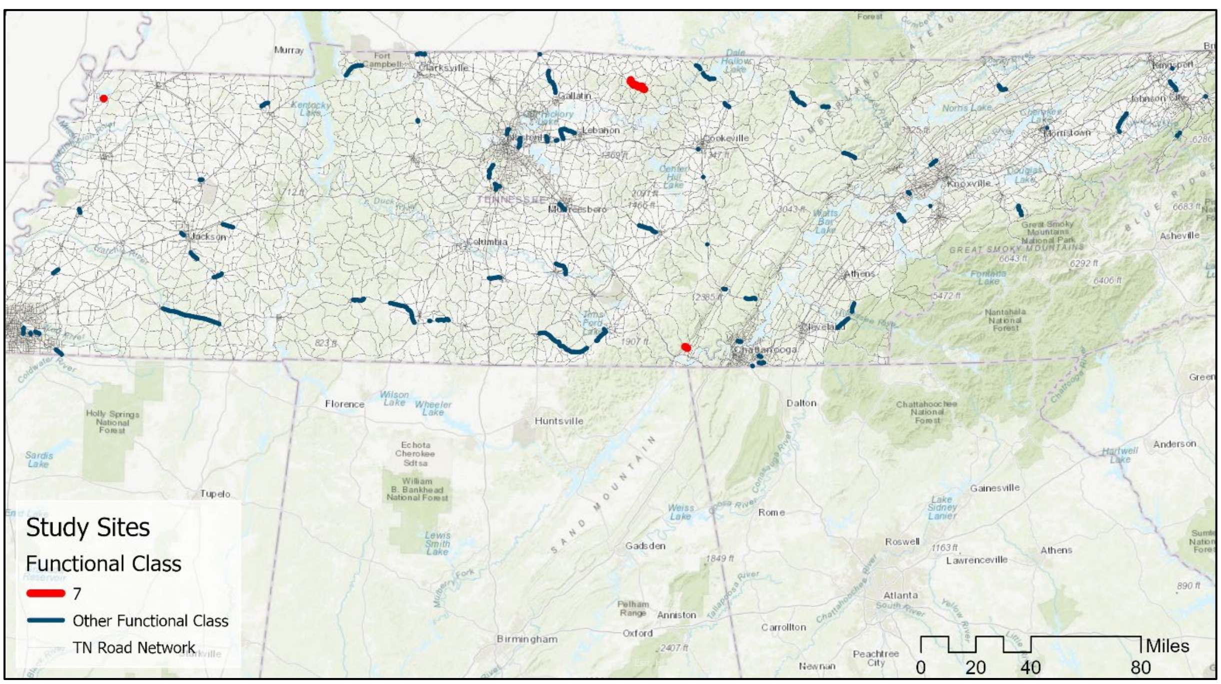

Figure 3-10 Study sites (functional class 7).

Speed limits for the study sites of this functional class include 30mi/hr, and 50mi/hr. Below is a description of the analysis of travel outcome changes due to capacity enhancement broken down by the speed limit within this functional class.

3.3.4.1. Functional Class 7: Speed Limit 30mi/hr.

For the study sites (functional class 7, speed limit 30mi/hr), there are 16 observations covering 10 years before (N1=10) ("before" period) and 10 years after project completion (N2=6) ("after" period) used in the statistical analysis. A t-test has been applied to 16 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-9 Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for study sites of functional Class 7 with a speed limit of 30mi/hr.

For functional Class 7 (all speeds include 30mi/hr, and 50mi/hr), the study sites with the speed limit of 30 mi/hr, had statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 30.11%, (((214.7-165)/165)*100), AADT (AADTAft vs AADTBfr) has experienced an increase by 11.16%, (((3326.33-2747.1)/ 2747.1)*100), while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew by 21.08%, (((4477.2-3697.6)/ 3697.6)*100) and 30.11%, (((288.93-222.06)/ 222.06)*100), respectively.

3.3.4.2. Functional Class 7: Speed Limit 50mi/hr.

For the study sites (functional class 7, speed limit 50mi/hr), there are 40 observations covering 10 years before (N1=20) ("before" period) and 10 years after project completion (N2=20) ("after" period) used in the statistical analysis. A t-test has been applied to 40 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-10 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 7 with the speed limit of 50mi/hr. For the study sites (functional class 7, speed limit 50mi/hr), there were no changes in travel outcomes.

3.3.5. Functional Class 8: All Speed Limits.

These are Rural Minor Collectors. Figure 3-11provides a geographical context. It shows the location of the study sites (functional class 8) (shown in a red color in the map) as well as all study sites shown in a blue color used in this study. For the study sites (functional class 8 with all speeds including 25mi/hr, 45mi/hr, 55mi/hr), there are 79 observations covering 10 years before (N1=30) ("before" period) and 10 years after project completion (N2=49) ("after" period) used in the statistical analysis. A t-test has been applied to 79 observations for comparison of means across the four measures on travel outcomes. TABLE B-0-5 (Appendix B) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 8 where all speeds are included (25mi/hr, 45mi/hr, 55mi/hr). For the study sites (functional class 8 with all speeds including 25mi/hr, 45mi/hr, 55mi/hr), no substantial changes in travel outcomes are observed when all observations are used with all speed limits.

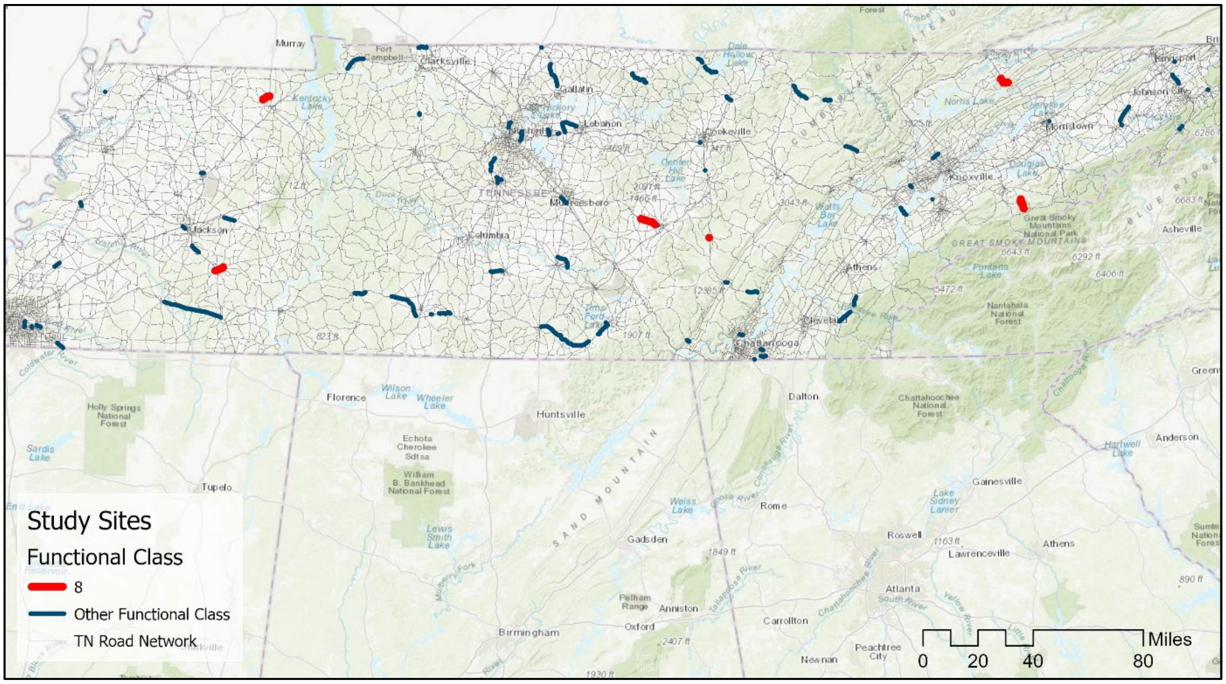

Figure 3-11 Study sites (functional class 8).

Speed limits for the study sites of this functional class 8 include 25mi/hr, 45mi/hr, and 55mi/hr. Below is the description of the analysis of travel outcome changes due to capacity enhancement broken down by the speed limit within this functional class.

3.3.5.1. Functional Class 7: Speed Limit 25mi/hr.

For the study sites (functional class 8, speed limit 25mi/hr), there are 20 observations covering 10 years before (N1=10) ("before" period) and 10 years after project completion (N2=10) ("after" period) used in the statistical analysis. A t-test has been applied to 20 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-11 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 8 with the speed limit of 25mi/hr.

For the study sites of functional Class 8 with the speed limit of 25 mi/hr, there were statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 38.71%, (((419.6-302.5)/ 302.5)*100), AADT (AADTAft vs AADTBfr) has experienced an increase by 27.81%, (((6695-5238.2)/ 5238.2)*100), while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew by 27.81%, (((21424-16762.2)/ 16762.2)*100) and 38.74%, (((1342.9-967.9)/ 967.9)*100), respectively.

3.3.5.2. Functional Class 7: Speed Limit 45mi/hr.

For the study sites (functional class 8, speed limit 45 mi/hr), there are 29 observations covering 10 years before (N1=10) ("before" period) and 10 years after project completion (N2=19) ("after" period) used in the statistical analysis. A t-test has been applied to 29 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-12 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 8 with the speed limit of 45mi/hr.

For the study sites of functional Class 8 with the speed limit of 45 mi/hr, there were highly statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has changed increasing from the average of 48 vehicles in the peak hour to 183 vehicles on the average in the peak hour, AADT (AADTAft vs AADTBfr) has changed from 799 vehicles daily on the average to 3459 vehicles daily on average, while daily VMT (VMTAft vs VMTAft) grew from 846 vehicle miles travelled to almost 18,000 vehicle miles travelled daily on average, and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew from the 51 vehicle miles travelled to almost 927 vehicle miles travelled to almost in the peak hour.

3.3.5.3. Functional Class 7: Speed Limit 55mi/hr.

For the study sites (functional class 8, speed limit 55 mi/hr), there are 30 observations covering 10 years before (N1=10) ("before" period) and 10 years after project completion (N2=20) ("after" period) used in the statistical analysis. A t-test has been applied to 30 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-13 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 8 with the speed limit of 55mi/hr.

Significant decreases in travel outcomes: For the study sites of functional Class 8 with the speed limit of 55 mi/hr, there was observed an opposite pattern to the one observed for other functional classes (where at higher speeds more traffic flow and higher VMT was found within the same functional class). Here, at a higher speed limit, less traffic flows and lower VMT was found within the same functional class. There were highly statistically significant decreases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has decreased on average by 26.52%, (((395.9-538.75)/ 538.75)*100), AADT (AADTAft vs AADTBfr) has experienced a decrease by 27.4%, (((7617.3-10487.7)/ 10487.7)*100), while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) dropped by 29.93%, (((27926.48-39853.26)/ 39853.26)*100) and 29.75 (((1438.17-2047.23)/ 2047.23)*100), respectively.

3.3.6. Functional Class 11: All Speed Limits.

These are Urban Principal Arterial – Interstates. Routes designated as Interstate Highways. Figure 3-12 provides a geographical context. It shows the location of the study site (functional class 11) (shown in a red color in the map) as well as all study sites shown in a blue color used in this study.

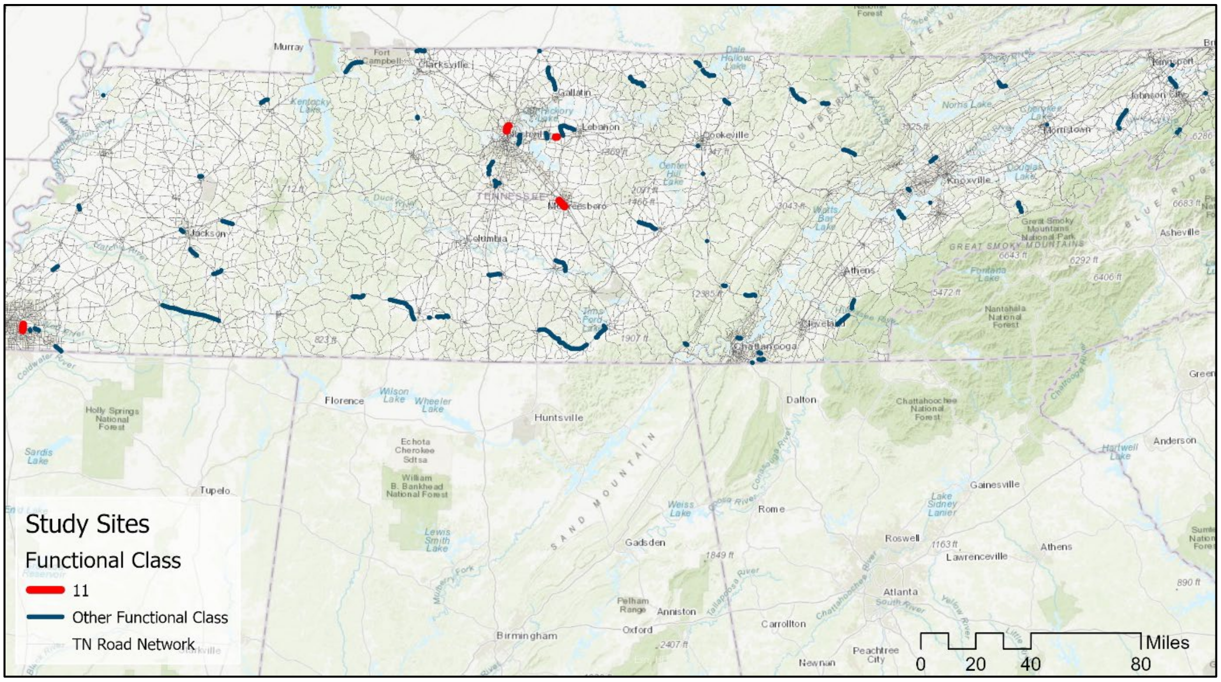

Figure 3-12 Study sites (functional class 11).

For the study sites (functional class 11 with all speeds including 55mi/hr, 65mi/hr, 70mi/hr), there are 61 observations covering 10 years before (N1=26) ("before" period) and 10 years after project completion (N2=35) ("after" period) used in the statistical analysis. A t-test has been applied to 61 observations for comparison of means across the four measures on travel outcomes. TABLE B-0-6 (Appendix B) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 11 where all speeds are included (55mi/hr, 65mi/hr, 70mi/hr).

Decreases in peak-hour traffic flows when all speeds are used (functional class 11, speed limits 55mi/hr, 65mi/hr, 70mi/hr): For the study sites (functional class 11 with all speeds including 55mi/hr, 65mi/hr, 70mi/hr), substantial changes in a single travel outcome are observed, as significantly lower peak-hour traffic flows occurred after road capacity improvement (p-value=0.04). No substantial changes across other travel outcomes are observed when all observations are used with all speed limits.

Speed limits for the study sites of this functional class include 55mi/hr, 65mi/hr, and 70mi/hr. Below is the description of the analysis of travel outcome changes due to capacity enhancement broken down by the speed limit within this functional class.

3.3.6.1. Functional Class 11: Speed Limit 55mi/hr.

For the study sites (functional class 11, speed 55mi/hr), there are 18 observations covering 10 years before (N1=10) ("before" period) and 10 years after project completion (N2=8) ("after" period) used in the statistical analysis. A t-test has been applied to 18 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-14 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 11 with the speed limit of 55mi/hr. No substantial changes across all four travel outcomes are found for the observations with the speed limit 0f 55 mi/hr.

3.3.6.2. Functional Class 11: Speed Limit 65mi/hr.

For the study sites (functional class 11, speed 65mi/hr), there are 17 observations covering 10 years before (N1=10) ("before" period) and 10 years after project completion (N2=7) ("after" period) used in the statistical analysis. A t-test has been applied to 17 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-15 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 11 with the speed limit of 65mi/hr. Substantial changes occurred across all travel outcomes. Significant increases are observed for the observations with the speed limit of 65mi/hr, supported by both one-directional (1-tailed tests) and non-directional (2-tailed tests) t-tests.

For functional Class 11 (for the functional Class 11 all speeds include 55mi/hr, 65mi/hr, and 70mi/hr), the study sites with the speed limit of 65 mi/hr, there were statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 7.81%, (((7479.74-6937.87)/ 6937.87)*100), AADT (AADTAft vs AADTBfr) has also experienced an increase by 7.81%, (((104611.71-97033.1)/ 97033.1)*100), while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) similarly grew by 7.81% each, (((156917.57-145549.65)/ 145549.65)*100) and (((11219.61-10406.8)/ 10406.8)*100), respectively.

3.3.6.3. Functional Class 11: Speed Limit 70mi/hr.

For the study sites (functional class 11, speed 70 mi/hr), there are 26 observations covering 10 years before (N1=6) ("before" period) and 10 years after project completion (N2=20) ("after" period) used in the statistical analysis (*). A t-test has been applied to 26 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-16 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 11 with the speed limit of 70mi/hr. Similarly to the results found for the study sites of functional class 11 with the speed limt of 65mi/hr, substantial changes occurred across all travel outcomes.

For the study sites of functional Class 11 with the speed limit of 70 mi/hr, there were highly statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 16.81%, (((3973.85-3402.03)/ 3402.03)*100), AADT (AADTAft vs AADTBfr) has also experienced an increase by 20.97%, (((80692.55-66706.5)/ 66706.5)*100), while daily VMT (VMTAft vs VMTAft) grew from 36,555 vehicle miles travelled to 173,310 vehicle miles travelled daily on average, and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew from the 1,864 vehicle miles travelled to 8,311 vehicle miles travelled to in the peak hour.

3.3.7. Functional Class 12: All Speed Limits (55mi/hr only).

These are Urban Principal Arterial - Other Freeways and Expressways. The routes are Non - Interstate principal arterials. In this study, the study sites (Functional Class 12) have a single speed limit of 55mi/hr. Figure 3-13 provides a geographical context. It shows the location of the study sites (functional class 12) (shown in red color in the map) as well as all study sites shown in blue color used in this study.

For the study sites (functional class 12 with the speed limit 55mi/hr), there are 80 observations covering 10 years before (N1=40) ("before" period) and 10 years after project completion (N2=40) ("after" period) used in the statistical analysis. A t-test has been applied to 80 observations for comparison of means across the four measures on travel outcomes. TABLE B-0-7 (Appendix B) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 12 with the speed limit of 55mi/hr. Substantial changes occurred across all travel outcomes.

For the study sites of functional Class 12 with the speed limit of 55 mi/hr, there were statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 53.42%, (((3696.95-2409.71)/ 2409.71)*100), AADT (AADTAft vs AADTBfr) has also experienced an increase by 25.48%, (((57729.9-46006.6)/ 46006.6)*100), while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew by 26.35%, (((70619.11-55888.23)/ 55888.23)*100) and by 51.5% (((4455.09-2940.71)/ 2940.71)*100), respectively.

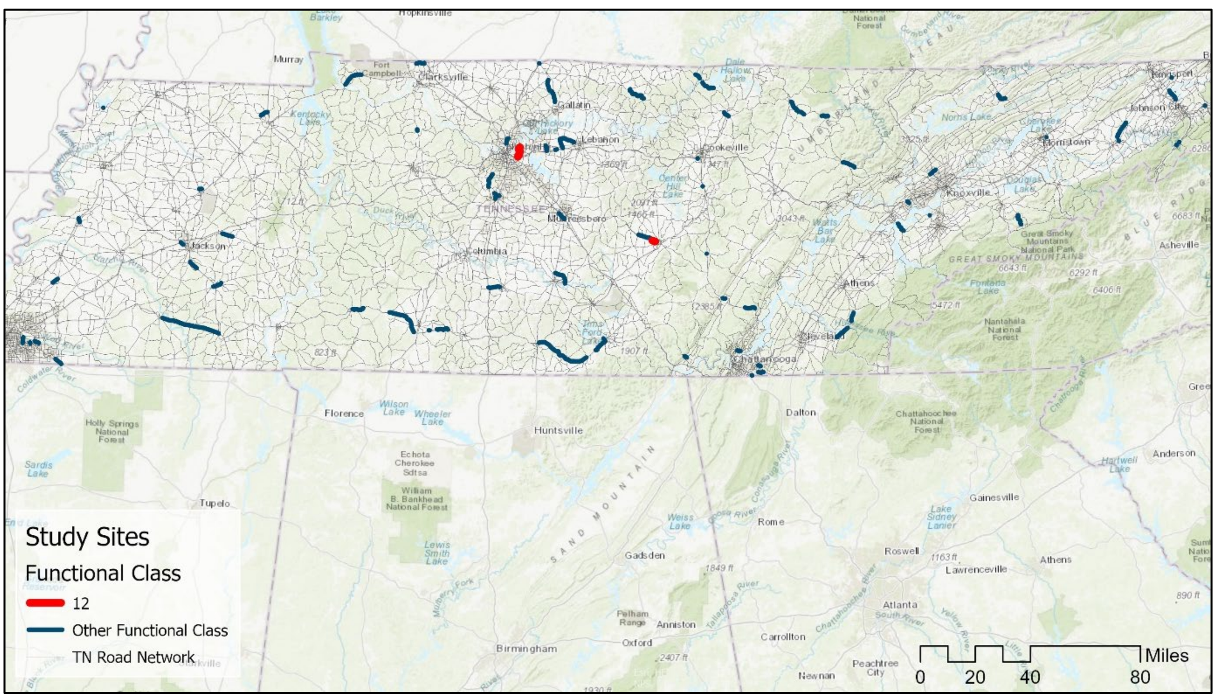

Figure 3-13 Study sites (functional class 12).

3.3.8. Functional Class 14: All Speed Limits.

These are Urban Principal Arterial - Other (no control of access). Figure 3-14 provides a geographical context. It shows the location of the study sites (functional class 14) (shown in red color in the map) as well as all study sites shown in blue color used in this study.

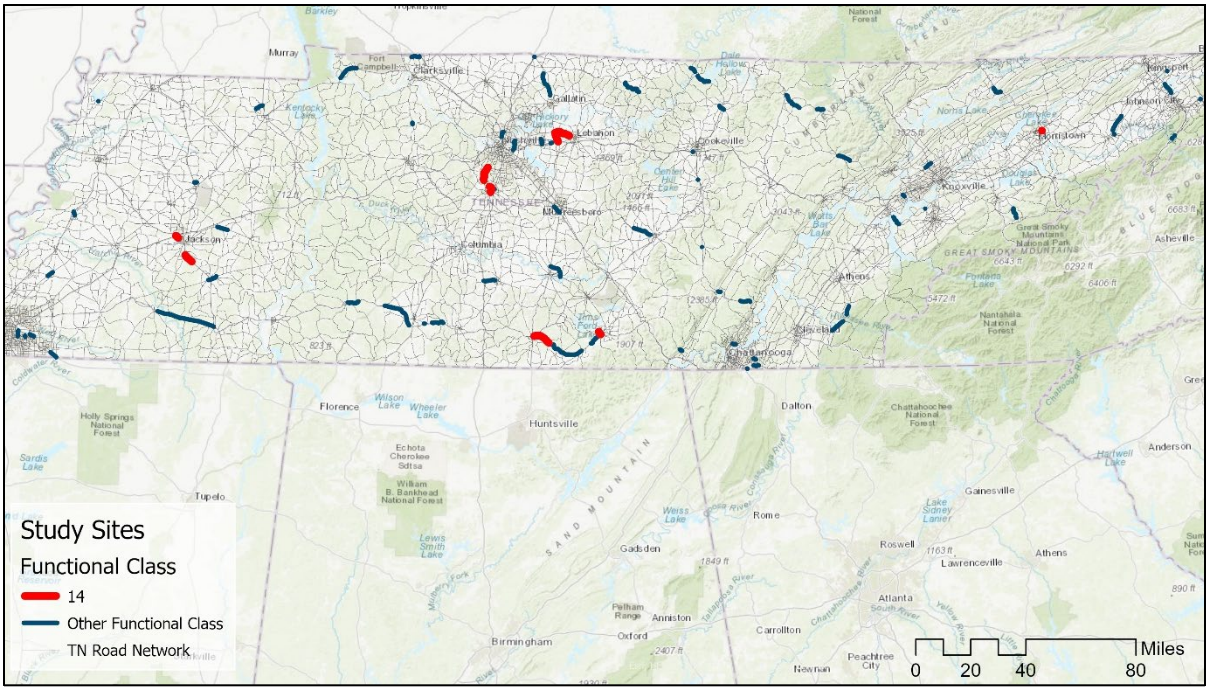

Figure 3-14 Study sites (functional class 14).

For the study sites (functional class 14 with all speeds including 40mi/hr, 45mi/hr, 50mi/hr, 55mi/hr), there are 204 observations covering 10 years before (N1=100) ("before" period) and 10 years after project completion (N2=104) ("after" period) used in the statistical analysis. A t-test has been applied to 204 observations for comparison of means across the four measures on travel outcomes. TABLE B-0-8 (Appendix B) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 14 where all speeds are included (40mi/hr, 45mi/hr, 50mi/hr, 55mi/hr). No changes in travel outcomes have been found across the four measures when the observations for all study sites with various speeds have been used in the analysis.

Speed limits for the study sites of this functional class include 40mi/hr, 45mi/hr, 50mi/hr, and 55mi/hr. Below is the description of the analysis of travel outcome changes due to capacity enhancement broken down by speed limit within this functional class.

3.3.8.1. Functional Class 14: Speed Limit 40mi/hr.

For the study sites (functional class 14, speed limit 40mi/hr), there are 26 observations covering 10 years before (N1=10) ("before" period) and 10 years after project completion (N2=16) ("after" period) used in the statistical analysis for the study sites of functional class 14 with the speed of 40mi/hr. A t-test has been applied to 26 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-17 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 14 with the speed limit of 40mi/hr. For the study sites of functional Class 14, (where all speeds are 40mi/hr, 45mi/hr, 50mi/hr, and 55mi/hr), no changes in travel outcomes have been found across the four measures for the observations for the study sites with lower speeds (40mi/hr) within this functional class.

3.3.8.2. Functional Class 14: Speed Limit 45mi/hr.

For the study sites (functional class 14, speed limit 45mi/hr), there are 60 observations covering 10 years before (N1=30) ("before" period) and 10 years after project completion (N2=30) ("after" period) used in the statistical analysis. A t-test has been applied to 79 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-18 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 14 with the speed limit of 45mi/hr. For the study sites (functional class 14, speed limit 45mi/hr), a significant increase in the average value of the AADT have been found after capacity improvement (p-value=0.04), specifically, AADT (AADTAft vs AADTBfr) has experienced a significant increase by 14.15%, (((19311.93-16917.13)/ 16917.13)*100), while no changes across other travel outcomes have been observed.

3.3.8.3. Functional Class 14: Speed Limit 50mi/hr.

For the study sites (functional class 14, speed limit 50 mi/hr), there are 78 observations covering 10 years before (N1=40) ("before" period) and 10 years after project completion (N2=38) ("after" period) used in the statistical analysis. A t-test has been applied to 78 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-19 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 14 with the speed limit of 50mi/hr. No changes across four travel outcomes have been observed for the study sites of functional Class 14 with speeds of 50mi/hr.

3.3.8.4. Functional Class 14: Speed Limit 55mi/hr.

For the study sites (functional class 14, speed limit 55mi/hr), there are 40 observations covering 10 years before (N1=20) ("before" period) and 10 years after project completion (N2=20) ("after" period) used in the statistical analysis. A t-test has been applied to 40 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-20 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 14 with the speed limit of 55mi/hr.

After road capacity enhancement, for the study sites (functional class 14, speed limit 55mi/hr), there were significantly higher AADT (greater AADTAft vs AADTBfr) (p-value=0.01) and daily VMT (greater VMTAft vs VMTBfr) (p-value=0.009), with AADT increasing by 21.02% on average (((20753.85-17147.75)/17147.75)*100) and daily VMT increasing by 20.89% (((61394.81-50784.42)/ 50784.42)*100). There were no significant changes found in peak-hour traffic flow (FlowAft vs FlowBfr) nor in peak-hour VMT (VMTPkAft vs VMTPkBfr) after road capacity enhancement for the study sites of functional Class 14 with the speed limit of 55mi/hr.

3.3.9. Functional Class 16: All Speed Limits.

These are Urban Minor Arterials. This system interconnects with and augments the urban principal arterial system and serve trips of moderate length at somewhat lower of travel mobility than principal arterials. Urban Minor Arterials are spaced at not more than 1 mile in fully developed areas. Figure 3-15 provides a geographical context. It shows the location of the study sites (functional class 16) (shown in red color) and all study sites in blue color used in this study.

For the study sites (functional class 16, all speed limits including 30mi/hr, 35mi/hr, 40mi/hr, 45mi/hr, 55mi/hr), there are 310 observations covering 10 years before (N1=160) ("before" period) and 10 years after project completion (N2=150) ("after" period) used in the statistical analysis. A t-test has been applied to 310 observations for comparison of means across the four measures on travel outcomes. TABLE B-0-9 (Appendix B) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 16 where all speeds are included (30mi/hr, 35mi/hr, 40mi/hr, 45mi/hr, 55mi/hr). No changes in travel outcomes occurred when all observations for the study sites with all speeds including (30mi/hr, 35mi/hr, 40mi/hr, 45mi/hr, 55mi/hr) have been used in the analysis.

Speed limits for the study sites of this functional class include 30mi/hr, 35mi/hr, 40mi/hr, 45mi/hr, and 55mi/hr. Below is the description of the analysis of travel outcome changes due to capacity enhancement broken down by the speed limit within this functional class.

3.3.9.1. Functional Class 16: Speed Limit 30mi/hr.

For the study sites (functional class 16, speed limits 30mi/hr), there are 35 observations covering 10 years before (N1=20) ("before" period) and 10 years after project completion (N2=15) ("after" period) used in the statistical analysis. A t-test has been applied to 35 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-21 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 16 with the speed limit of 30mi/hr. For the study sites (Functional Class 16, speed limit 30mi/hr), no changes in travel outcomes occurred.

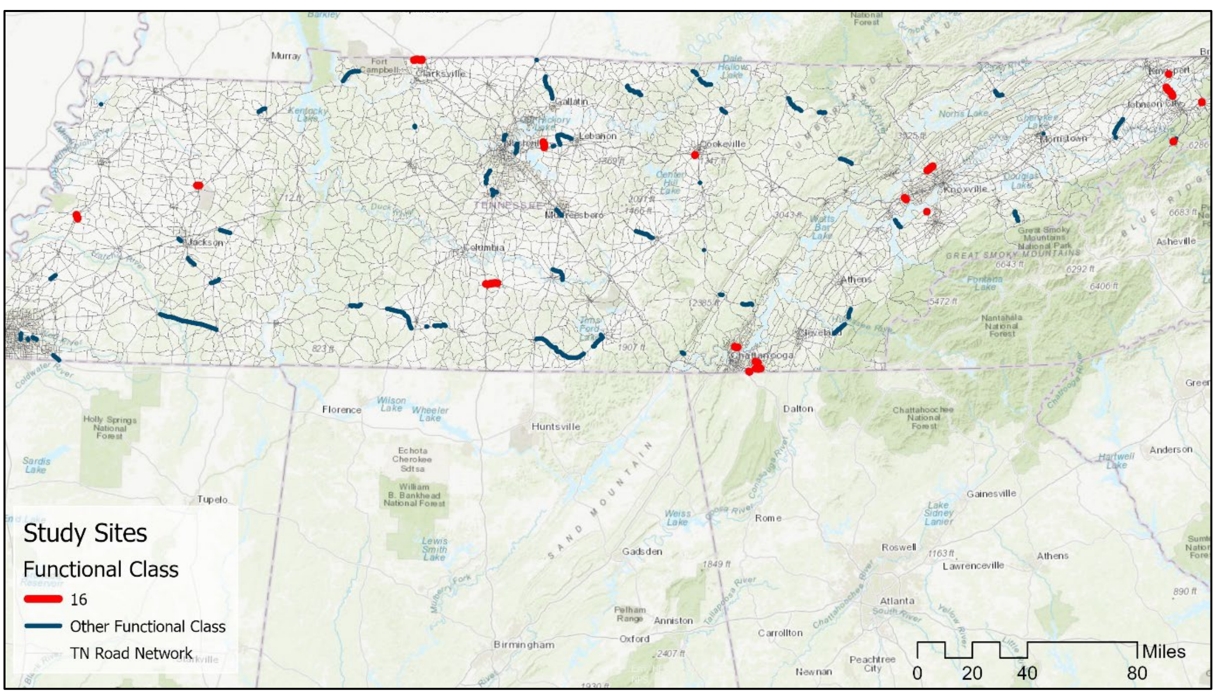

Figure 3-15 Study sites (functional class 16).

3.3.9.2. Functional Class 16: Speed Limit 35mi/hr.

For the study sites (functional class 16, speed limits 35 mi/hr), there are 44 observations covering 10 years before (N1=20) ("before" period) and 10 years after project completion (N2=24) ("after" period) used in the statistical analysis. A t-test has been applied to 44 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-22 (Appendix C) reports the results of a Two-Sample t-Test for travel outcomes for functional Class 16 with the speed limit of 35mi/hr. For these study sites, no changes in travel outcomes occurred.

3.3.9.3. Functional Class 16: Speed Limit 40mi/hr.

For the study sites (functional class 16, speed limits 40 mi/hr), there are 114 observations covering 10 years before (N1=60) ("before" period) and 10 years after project completion (N2=54) ("after" period) used in the statistical analysis. A t-test has been applied to 114 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-23 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 16 with a speed limit of 40mi/hr. For the study sites (Functional Class 16, speed limit 40 mi/hr), no changes in travel outcomes occurred.

3.3.9.4. Functional Class 16: Speed Limit 45mi/hr.

For the study sites (functional class 16, speed limits 45 mi/hr), there are 77 observations covering 10 years before (N1=40) ("before" period) and 10 years after project completion (N2=37) ("after" period) used in the statistical analysis. A t-test has been applied to 77 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-24 (Appendix C) reports the results of a Two-Sample t-Test for travel outcomes for functional Class 16 with the speed limit of 45mi/hr.

For the study sites of functional Class 16 with the speed limit of 45 mi/hr, there were statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 27.68%, (((996.4-780.4)/ 780.4)*100), AADT (AADTAft vs AADTBfr) has also experienced an increase by 33.68%, (((19076.2-14269.3)/ 14269.3)*100), while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew by 35.26%, (((45194.2-33410.7)/ 33410.7)*100) and by 25.24% (((2301.3-1837.5)/ 1837.5)*100), respectively.

3.3.9.5. Functional Class 16: Speed Limit 55mi/hr.

For the study sites (functional class 16, speed limits 55 mi/hr), there are 40 observations covering 10 years before (N1=20) ("before" period) and 10 years after project completion (N2=20) ("after" period) used in the statistical analysis. A t-test has been applied to 40 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-25 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 16 with the speed limit of 55mi/hr. For the study sites of functional Class 16 with the speed limit of 55 mi/hr, no significant increases in travel outcomes are observed.

3.3.10. Functional Class 17: All Speed Limits.

These are Urban Collectors. Figure 3-16 provides a geographical context. It shows the location of the study sites (functional class 2) (shown in red color) and all study sites shown in blue color.

For the study sites (functional class 17, all speed limits including 30mi/hr, 35mi/hr, 40mi/hr), there are 74 observations covering 10 years before (N1=24) ("before" period) and 10 years after project completion (N2=50) ("after" period) used in the statistical analysis. A t-test has been applied to 74 observations for comparison of means across the four measures on travel outcomes. TABLE B-0-10 (Appendix B) reports the results of a Two-Sample t-Test for travel outcomes for the study sites of functional Class 17 where all speeds are included (30mi/hr, 35mi/hr, 40mi/hr).

For the study sites (functional class 17, all speed limits including 30mi/hr, 35mi/hr, 40mi/hr), Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 53.35%, (((693.71-452.37)/ 452.37)*100), and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew by 70.26%, (((1138.39-668.62)/ 668.62)*100), respectively. No changes in AADT nor daily VMT have been observed.

Speed limits for the study sites of this functional class 17 include 30mi/hr, 35mi/hr, and 40mi/hr. Below is the description of the analysis of travel outcome changes due to capacity enhancement broken down by the speed limit within this functional class.

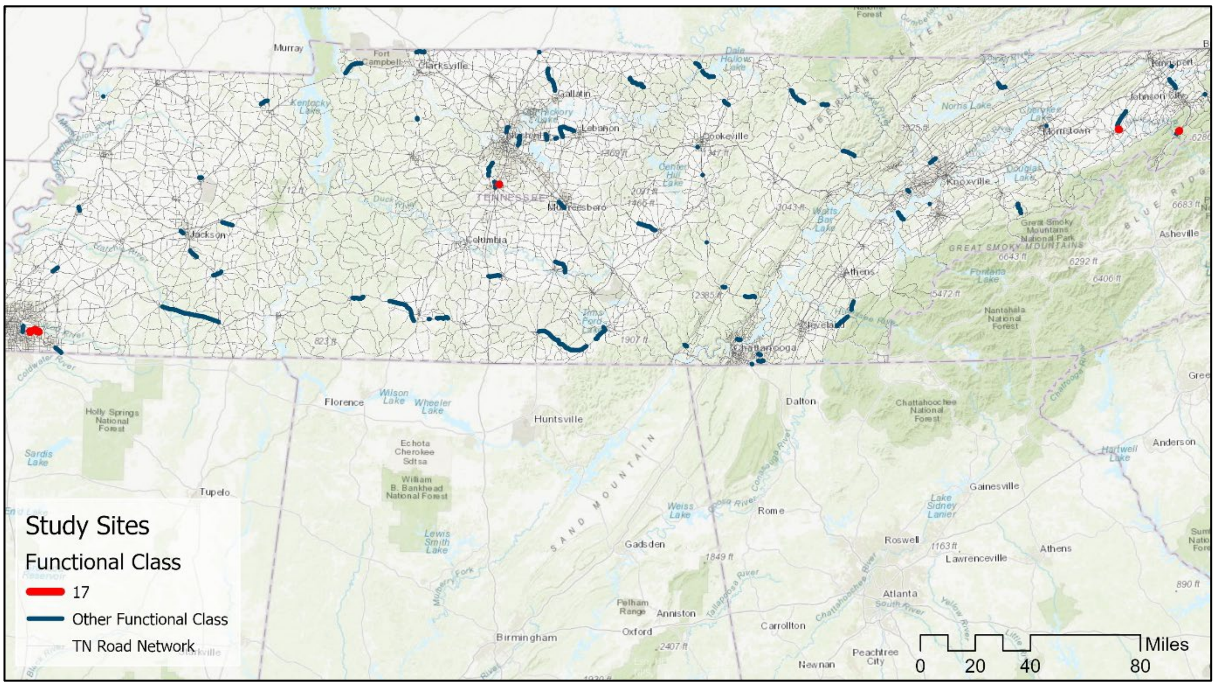

Figure 3-16 Study sites (functional class 17).

3.3.10.1. Functional Class 17: Speed Limit 30mi/hr.

For the study sites (functional class 17, speed limit 30mi/hr), there are 50 observations covering 10 years before (N1=20) ("before" period) and 10 years after project completion (N2=30) ("after" period) used in the statistical analysis. A t-test has been applied to 79 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-26 (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 17 with the speed limit of 30mi/hr. For functional Class 17 (where all speeds are 30mi/hr, 35mi/hr, and 40mi/hr), for the study sites with the lower speed limit of 30mi/hr), no changes in travel outcomes have been observed.

3.3.10.2. Functional Class 17: Speed Limit 40mi/hr.

For the study sites (functional class 17, speed limit 40 mi/hr), there are 14 observations covering 10 years before (N1=4) ("before" period) and 10 years after project completion (N2=10) ("after" period) used in the statistical analysis. A t-test has been applied to 14 observations for comparison of means across the four measures on travel outcomes. TABLE C-0-27I (Appendix C) reports the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes for the study sites of functional Class 17 with the speed limit of 40mi/hr.

For the study sites (functional class 17, speed limit 40 mi/hr), statistically significant decreases in AADT and daily VMT have been found. No significant changes in peak-hour traffic flows nor peak-hour VMT have been observed.

3.4 OLS Regression and 2SLS Modeling.

We use data from the Tennessee Traffic Information Management and Evaluation System (TN-TIMES) to retrieve data of interest and to construct the dependent and independent variables for our induced travel regressions. Specifically, we used data on VMT as our dependent variable and lane-miles as our primary explanatory variable of interest.

3.4.1. Data Collection Procedures.

Here we describe the data construction. The shapefiles of road segments that experienced improvement in Tennessee have been obtained from the TDOT. It should be noted that capacity projects are not random and are often chosen due to the availability of certain road characteristics and meeting the project criteria. However, capacity projects used in the study are spatially distributed across various settings across the state. For induced travel modelling, only those road segments that experienced capacity enhancement across Tennessee between 2000 and 2019 (referred to as the "study sites") have been used. After selecting the segments with the desired values of interest (segment length, lanes, VMT, locality, project improvement implementation, etc.), 84 study sites were identified in this research. Since the 84 study sites represented segments before the capacity enhancement, these are also referred to as the short data set, and the same data have been used to cover a period of 20 years (10 years prior to/and post enhancement), referred to as the full data set.

We have also identified 127 roads that did not undergo any capacity enhancement across Tennessee (referred to as the "comparison sites"). These sites are selected based on desired values of interest (same geographical locality corresponding to its study site segment, similar number of lanes, demographic conditions). Figure 3-17 displays the geographical location and distribution of the study sites and the comparison sites in Tennessee used in this study. Figure 3-18 provides urban and rural context of road improvement sites across Tennessee.

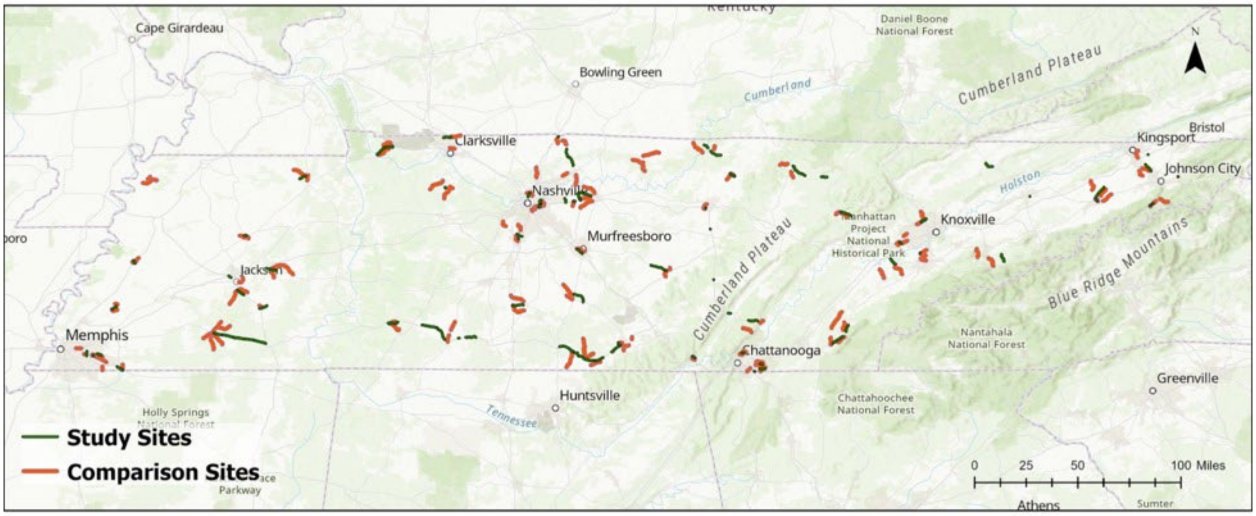

Figure 3-17 Location of the study and comparison sites in Tennessee.

We used employment density and developed land density as controls since a place with a larger employment tends to increase transportation infrastructure (Duranton & Turner, 2011). For the former, we used the United States Census Bureau's "OntheMap" web service to gather employment data, which classifies industries with 2-digit NACIS codes. Employment data from 2002-2022 were obtained as point features, with total jobs calculated by summing all NACIS categories. The data were then spatially joined with a buffer to calculate employment density by dividing total employment by buffer area.

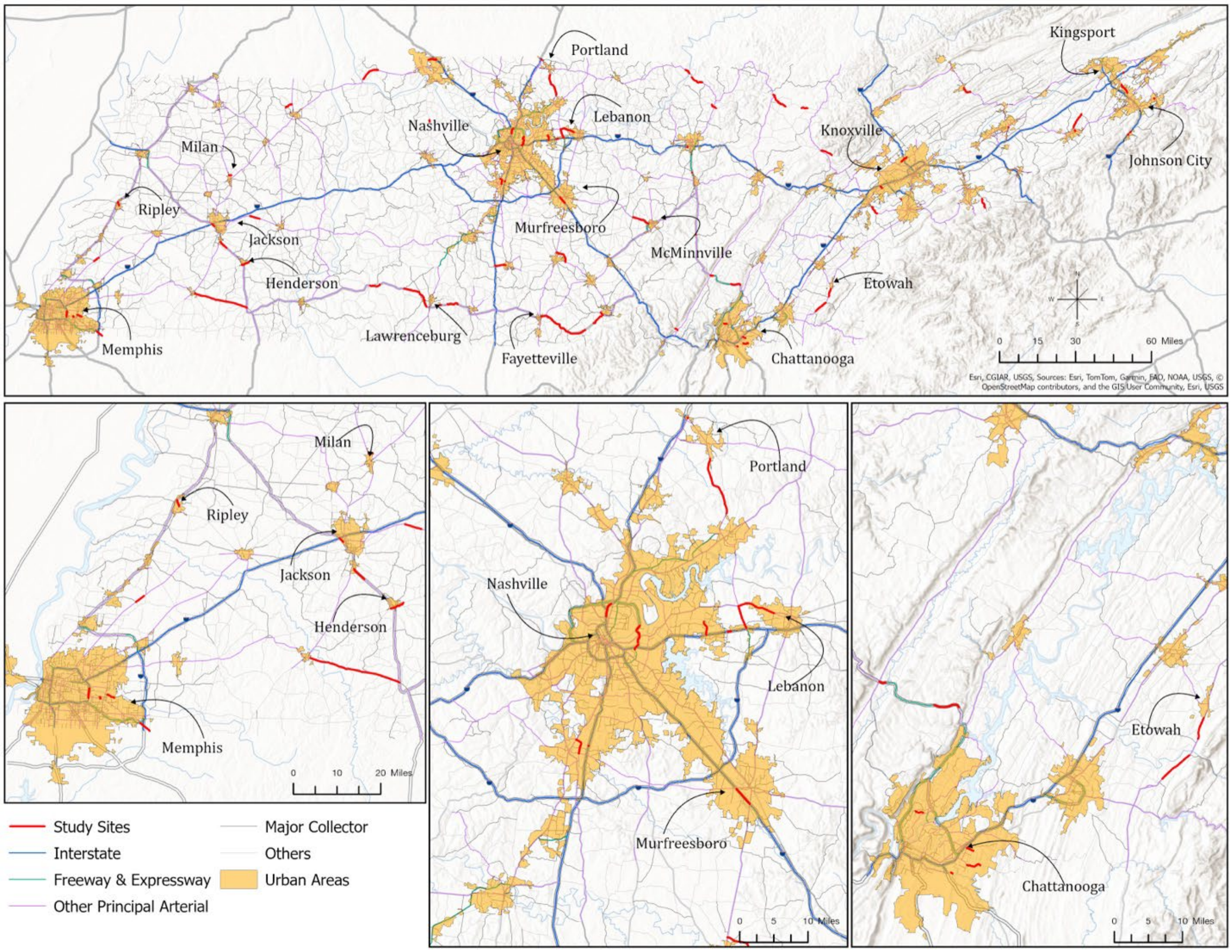

Figure 3-18 Urban and Rural Context of Road Improvement Sites across Tennessee.

We used land use land cover data to construct another independent variable (developed land density). By the same logic, built-up land versus non-developed land uses are more likely to add transportation infrastructure and increase travel. We used the USGS NLCD dataset (1985-2023) from the MRLC consortium to calculate development density in the study area. Land cover data were clipped to four-mile buffers around each site. Development density was determined by counting "Developed" pixels, each representing 900 m^2 at 30-meter resolution. The total developed pixels were multiplied by 900 m^2 and converted to square miles to estimate the developed area, which was then divided by the buffer area for density.

Various roads in Tennessee experienced capacity improvement (via widening the existing road or constructing a new road) between 2000 and 2020. To capture the longer-term effect of such capacity enhancement, we used a 20-year period (consisting of 10 years prior to the road improvement and 10 years after the road capacity enhancement). For example, a capacity enhancement project was implemented in 2000. We used the relevant data for this study site for 10 years prior to the improvement project implementation (covering 1990-1999) and 10 years post the improvement project implementation (covering 2001-2010), overall spanning 20 years for the same study site. Figure 3-19 offers some explanation of the time period used in the study. Shown in Figure 3-19, we retrieved 2006-2015 data for the project implemented in 2016 (TN_TIMES_ID =90000141) (the period is labelled as "before") and 2017-2023 labelled as "after") (Data are unavailable for the period of 2024-2026 yet.)

Segment_I	TN_TIMES_	Year	LANES	Length	Fun_class	Sites	Improvem	Post	Post_Treat	Area_cont	Rural_Urb	Time_indic	Flow	AADT	LNMile	VMT	VMTPf	PlanHwyLI	Pl
0	90000141	2006	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	226.98	3492	5.936581	10365.27	673.7425	8.15566	
0	90000141	2007	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	246.87	3798	5.936581	11273.57	732.7818	8.15566	
0	90000141	2008	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	240.63	3702	5.936581	10988.61	714.2597	8.15566	
0	90000141	2009	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	239.005	3677	5.936581	10914.4	709.4362	8.15566	
0	90000141	2010	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	272.7725	3815	5.936581	11324.03	809.6679	8.15566	
0	90000141	2011	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	234.65	3610	5.936581	10715.53	696.5093	8.15566	
0	90000141	2012	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	292.6495	4093	5.936581	12149.21	868.6686	8.15566	
0	90000141	2013	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	360.672	4624	5.936581	13725.37	1070.579	8.15566	
0	90000141	2014	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	308.165	4741	5.936581	14072.66	914.7232	8.15566	
0	90000141	2015	2	2.96829	Major Coll	Comparisc	0	0	0	Urban	1	Before	284.7	4380	5.936581	13001.11	845.0722	8.15566	
0	90000141	2017	2	2.96829	Major Coll	Comparisc	0	1	0	Urban	1	After	269.62	4148	5.936581	12312.47	800.3104	8.15566	
0	90000141	2018	2	2.96829	Major Coll	Comparisc	0	1	0	Urban	1	After	226.07	3478	5.936581	10323.71	671.0414	8.15566	
0	90000141	2019	2	2.96829	Major Coll	Comparisc	0	1	0	Urban	1	After	341.406	4377	5.936581	12992.21	1013.392	8.15566	
0	90000141	2020	2	2.96829	Major Coll	Comparisc	0	1	0	Urban	1	After	271.7314	3878	5.936581	11511.03	806.5778	8.15566	
0	90000141	2021	2	2.96829	Major Coll	Comparisc	0	1	0	Urban	1	After	246.5752	2773	5.936581	8231.069	731.9067	8.15566	
0	90000141	2022	2	2.96829	Major Coll	Comparisc	0	1	0	Urban	1	After	251.0976	3840	5.936581	11398.23	745.3305	8.15566	
0	90000141	2023	2	2.96829	Major Coll	Comparisc	0	1	0	Urban	1	After	287.3957	4187	5.936581	12428.23	853.0738	8.15566	
0	90000004	2006	2	4.1	Other Prin	Study	1	0	0	Urban	1	Before	578.0385	9881	8.2	40512.1	2369.958	8.08206	0.
0	90000004	2007	2	4.1	Other Prin	Study	1	0	0	Urban	1	Before	714.22	10988	8.2	45050.8	2928.302	8.08206	0.
0	90000004	2008	2	4.1	Other Prin	Study	1	0	0	Urban	1	Before	649.5255	11103	8.2	45522.3	2663.055	8.08206	0.
0	90000004	2009	2	4.1	Other Prin	Study	1	0	0	Urban	1	Before	718.445	11053	8.2	45317.3	2945.624	8.08206	0.

Figure 3-19 Explanation of the 20 years used in the study.

3.4.2. OLS Regression Modeling.

In an estimation of induced travel (measured with the VMT) equation (1), we predict VMT as a function of capacity and city characteristics. Below we describe the dependent and independent variables and their sources.

First, we run the ordinary least squares (OLS) regression to estimate VMT (using the log VMT) (assuming exogeneity). We predict VMT as a function of the road capacity (using the log of lane-miles) and socio-economic characteristics as controls (Equation 1). This gives us the "baseline" estimates. Using OLS, a simple regression was run between the travel distance (VMT) (a dependent variable) and lane miles (an independent variable) on the data represented by a single year prior to capacity enhancement (referred to as the "short data set"). It included just the initial study sites (N=84, shown in Figure 3-17). Then, we repeated the modelling on data covering 20 years (referred to as the "full data set"). Figure 3-19 illustrates the 20 years used in the study. For controls, we initially used employment/developed land density and then kept the better performing factor.

$$Y = a_1 + b_1 X + c_1 T + \varepsilon \qquad (6)$$

Where Y is the dependent variable (ln_VMT), X is the endogenous regressor (here, ln_Lane-Mile), T=socio-economic control, and e and u are error terms.

3.4.3. Identification of instrumental variables.

Instrumental variables (IV) is an important econometric technique to address endogeneity (Angrist & Krueger, 2001; Hansen & Huang, 1997; Heckman, 1979). Endogeneity is mostly caused by simultaneity, omitted variables, and measurement error. When endogeneity occurs, an independent variable is correlated with the error term in a regression model. If unaddressed, the modelled relationship between variables and conclusions may turn out inaccurate.

Our empirical findings suggested an independent variable (lane-mile) may be potentially correlated with the error term (e) in a regression model, indicating endogeneity. Thus, initial modeling of the relationship between capacity enhancement and VMT found a discernible pattern between lane-miles and the error term and required us using instruments to address potential endogeneity likely caused by unobserved variables impacting both lane capacity (lane-mile) and VMT.

Historical infrastructure plans and networks are widely used instruments. For example, the 1947 US Interstate Highway System Plan has been used as an instrument for urban area mileage (Duranton & Turner, 2011; K. Hymel, 2019; Volker et al., 2020). Other historical data used as instruments include railroad routes (from 1898, 1870, and 1810), since many roads followed old railway lines while their historical placement is unlikely to correlate directly with current traffic demand, and 1835-1850 exploration routes as an instrument for lane-mile development (Duranton & Turner, 2011).

Almost all IV-based induced travel studies operate at the area-wide or metropolitan scale. This aggregated approach, while statistically powerful, masks the effect of capacity enhancement on individual road segments, where decisions such as lane widening or new lane construction are actually made and evaluated. A small number of studies have attempted more disaggregated analyses. Anderson et al. (2021) estimated induced travel elasticities for specific congested freeway corridor expansion in California, working still within a regional framework. No prior study to our knowledge has systematically identified and validated instrumental variables specifically for facility-level induced travel modeling. This study searches for and identifies instrumental variables at a disaggregate level to further examine the impact of changes in the transportation system on induced travel (measured by VMT).

3.4.4. Challenge in Identifying Valid Instruments.

A significant challenge across all of these studies is identifying variables that simultaneously meet the relevance condition (strong correlation with the endogenous variable, i.e., lane-miles) and the exogeneity condition (no direct correlation with the outcome, i.e., VMT, other than through lane-miles). Many proposed instruments have come under scrutiny for potentially violating the exclusion restriction, or the requirement that the instrument affects the outcome only through the endogenous regressor.

Weak instruments represent a particular concern: if the correlation between the instrument and the endogenous variable is insufficiently strong, IV estimators can themselves be biased and inconsistent, potentially performing worse than OLS (Angrist & Pischke, 2009). The conventional threshold for instrument strength is a first-stage F-statistic exceeding 10 (the Stock & Yogo (2005) rule of thumb), though recent work recommends higher thresholds in many settings. This concern is especially acute at the disaggregated facility level, where sample sizes are smaller and correlation structures are more variable than at the MSA level, making the careful, step-by-step instrument evaluation process described in the paper all the more necessary.

In this study, we search for instrumental variables that influence lane-miles and that are independent of unmeasured factors that could also affect VMT. Drawing on the literature reviewed above, we test a set of historical road network variables, including the 1947 US Interstate Highway System Plan (coded as *PlannedHwy47*), the 1956 Shell Interstate Highway

Network (*ShellRdLN_4M, ShellHwy56*), and railroad proximity (*Railroad10*) as well as contemporary variables including distance to future and ongoing road improvement projects (*CurrentFutureRd, CurrentFutureRdLn*) and distance to major roads (*MajorRd_FE_I, MajorRd_all*).

3.4.5. 2SLS Modeling.

After running OLS, we are using a two-stage least squares (2SLS) method, also known as the instrumental variable (IV) method (Equations (7) and (8) below). Using the IVs serves the purpose of purging the regressors of their correlation with the residuals to avoid violation of a key assumption of the ordinary regression analysis (the independent variables must be statistically independent of the unobserved error term of the model).

Further, since there is no added efficiency by estimating the system of two pairs of equations jointly (e.g., with 2SLS) (Duranton & Turner, 2011c), we estimate equations (1) and (2) separately, using proc reg in SAS. First, we estimate equation (3) and obtain the predicted values for lane-mile using various instruments and a socio-economic characteristic as a control in the first stage of the model, and then we estimate equation (2) as we model VMT using the predicted values for lane-mile (obtained in the first stage) while using the same exogenous variable in the second stage.

$$Y = a_1 + b_1 X + c_1 T + \varepsilon \quad (7)$$

Where Y is the dependent variable (ln_VMT), X is the endogenous regressor (here, ln_Lane-MileHat), T=socio-economic control, and e is error terms.

$$Y = a_2 + b_2 Z + c_2 T + u \quad (8)$$

Where Y is the dependent variable (ln_Lane-Mile), Z=instrumental variable, T=socio-economic control, and e and u are error terms.

Accordingly, to address the issue of this endogeneity, we started a search for appropriate instruments. In a 2SLS model, assuming exogeneity, we used instrumental variables. We describe below what data we used to construct potential instrumental variables, followed by a selection of appropriate instruments based on certain criteria, and their application in a 2SLS model.

3.4.5.1. Instrument criteria.

To find a valid instrument, we identify a set of potential variables using previous research on the matter as guidance. The variables should influence highway capacity decisions, but do not directly impact VMT through any other mechanism other than their impact on lane-miles.

Selecting instruments for an induced travel study is a very difficult task as well as an important one. Weak instruments can introduce biases in the results. To select the instruments for our study, we followed the following criteria based on prior studies:

1. Instruments must be highly correlated with the endogenous independent variable, that is, be relevant (Anderson et al., 2021; Chen & Klaiber, 2020; Noland, 2001). In our study, the instrument relevance should be indicated by a statistically significant correlation between the instrument and lane-miles.
2. Instruments must not directly impact the dependent variable and must be exogenous. In other words, the IV should not be correlated with the VMT and should not be correlated with the error term (proxied by residuals) (unobserved factors affecting

VMT) (Chen & Klaiber, 2020; Duranton & Turner, 2011; Fulton et al., 2000; K. Hymel, 2019). This is often the most challenging condition to satisfy.

3.4.5.2. Identification of the potential instruments.

Next, we had to identify variables as the potential instruments. It's impossible to immediately determine whether or not a potential variable can be used as an instrument. First, we need to do the measurements and then check if it is valid or not (for example, with the correlation analysis or by generating plots). We describe in detail the variables used and the issues found to inform others.

In our search for valid instrumental variables, we used a few historical road networks (which is a common practice in studies on the impact of highway capacity on travel). Specifically, we were using the historical road network for the total road length measured within buffers of various sizes around the study sites and the proximity of each study site to the historical roads. Thus, based on prior research, we identified the following potential instrumental variables to use to predict lane-miles in the study.

To construct our instruments based on the 1947 planned highways instrument, we used a digital image of the 1947 highway plan and calculated three distance-based measurements.

(1) Based on Duranton & Turner (2011c), we used the 1947 plan of the interstate highway system to derive our first potential instrument, the distance from the 1947 US Interstate Highway System Plan (measured from each study site in miles) (coded as *PlannedHwy47*).
(2) Using the same historical 1947 plan of the interstate highway system, we derived our second potential instrument, the total length of 1947 US Interstate Highway System (within a half-mile buffer area of a study site coded as *PlanHwyLN*).
(3) Using still the same historical 1947 plan, another potential instrument was identified, total length of 1947 US Interstate Highway System (within a 4-mile buffer area of a study site, coded as *PlanHwyLN_4M*), respectively.

We used another historical data, the 1956 Interstate Highway Network created by Shell Oil in 1956 to construct three other potential instruments. We were guided by the same rationale that the earlier road network may influence later lane-mile development (i.e., it determines road capacity) by providing a pre-determined structure. Thus, three potential instruments were as follows:

(4) The fourth constructed instrument was the total length of 1956 Shell Interstate Highway Network (within a 4-mile buffer area of a study site, coded as *ShellRdLN_4M*).
(5) The fifth constructed instrument was the total length of 1956 Shell Interstate Highway Network (within a half-mile buffer area of a study site coded as *ShellRdLN_half*).
(6) The sixth constructed instrument was the distance to 1956 Shell Interstate Highway Network (measured in mile between each study site and the 1956 interstates coded as *ShellHwy56*), respectively.

Next, the data on the future and ongoing road improvement projects were used to construct the instrument of the future and ongoing road improvement projects in Tennessee. This instrument was selected as the U.S. states are allocated federal highway funds based on their planned projects. Thus, we chose the following:

(7) The seventh constructed instrument was the number (i.e., a count of such projects within a 20-mile buffer area of a study site (coded as *N_OngoingFutureRd*).

(8) The eighth constructed instrument was the proximity (measured as the distance in mile from the study sites (coded as *CurrentFutureRd*) to the future and ongoing road improvement projects.

(9) The ninth constructed instrument was the total length of ongoing and future road improvement project (within a 20-mile buffer area of a study site (coded as *CurrentFutureRdLn*) for our other three instruments.

We used the 2010 railroad network to construct another potential instrument, as follows:

(10) The tenth constructed potential instrument was the distance to the 2010 railroad network (measured in miles from each study site and the railroad (coded as *Railroad10*). We used the data on major roads in Tennessee (including freeway, interstate, and other principal arterial) found in the ArcGIS Online and created two other measurements as potential instruments.

We used the current major road network (freeways, interstates, and other principal arterials) to construct our last two potential instruments, as follows:

(11) For one instrument, we measured the distance to these road types (measured in miles from each study site and the major road coded as *MajorRd_all*).

(12) For another instrument, using this data (but excluding other principal arterials), we measured the distance from each study site to just freeways and interstates (coded as *MajorRd_FE_I*).

Our main variables, the identified potential instruments. and summary statistics are described in TABLE 3-2.

TABLE 3-2 SUMMARY STATISTICS FOR MAIN VARIABLES AND IDENTIFIED POTENTIAL INSTRUMENTS.

Name	***Label***	***Mean***	***StDev***
ln_LNMile	ln(Lane-Mile)	1.57	0.99
ln_VMT	ln(VMT)	9.87	1.25
PlanHwyLN_4M	Total length of 1947 US Interstate Highway System (4 miles)	8.13	2.92
PlanHwyLN	Total length of 1947 US Interstate Highway System (half mile)	1.20	0.67
ShellRdLN_4M	Total length of 1956 Shell Interstate Highway Network (4 miles)	13.28	5.62
ShellRdLN_half	Total length of 1956 Shell Interstate Highway Network (half mile)	2.21	1.33
CurrentFutureRdLn	Total length of ongoing and future road improvement project (20 miles)	5.20	6.45
PlannedHwy47	Distance to 1947 US Interstate Highway System	13.28	11.35
Railroad10	Distance to 2010 Railroad Network	3.09	4.86

ShellHwy56	Distance to 1956 Shell Interstate Highway Network	1.82	3.21
CurrentFutureRd	Distance to ongoing and future road improvement project	10.07	8.79
MajorRd_all	Distance to Major Road (Freeway, Interstate, & Other Principal Arterial)	0.88	1.82
MajorRd_FE_I	Distance to Major Road (Freeway and Interstate)	10.16	10.35
MajorRd_all	Distance to Major Road (Freeway, Interstate, & Other Principal Arterial)	0.88	1.82
MajorRd_FE_I	Distance to Major Road (Freeway and Interstate)	10.16	10.35
MajorRd_FE_I	Distance to Major Road (Freeway and Interstate)	10.16	10.35

Note: Averages are across 84 project sites.

3.4.5.3. Evaluating the potential instruments for relevance.

In order to select the instruments from the initially identified variables, they must first meet the relevance condition indicated by a statistically significant correlation between the instrument and lane-miles, and second, they have to not correlate with the residuals. For the first requirement, we measured the Pearson Correlation Coefficients between the above measurements and the endogenous variable (log of lane-miles) to identify relevant instruments for the study. We excluded those measurements from the considerations that had weak and statistically insignificant values as not relevant. The remaining variables were deemed relevant. including the following five variables (significance is provided in the brackets):

1. Distance to 1947 US Interstate Highway System PlannedHwy47: the ability of the 1947 US Interstate Highway System to predict the lane-miles is demonstrated by the 0.37 (**) correlation between the log of lane-miles and itself.
2. Distance to Major Road (Freeway and Interstate) MajorRd_FE_I (correlation with log of lane-miles =0.28 (*)
3. Distance to ongoing and future road improvement project CurrentFutureRd (correlation with log of lane-miles =0.3 (*)
4. Total length of 1956 Shell Interstate Highway Network (4 miles) ShellRdLN_4M (correlation with log of lane-miles =0.26 (*)
5. Total length of ongoing and future road improvement project (20 miles) CurrentFutureRdLn (correlation with log of lane-miles =-0.29 (*).

We checked current normative guidance regarding the interpretation of Pearson correlation coefficients. Gignac & Szodorai (2016) and Hemphill (2003) suggested the following guidelines regarding interpreting Pearson correlation coefficients as small when r< 0.20; medium when r ranges 0.20 to 0.30, and large for r values > 0.30. We adopt these normative guidelines, and we interpret our obtained correlations of the measurements with the endogenous variable (ln_LNMile) as moderate to large, all of them statistically significant. Further, the unit of analysis (individual observations versus group and aggregated values) and the level of measurement (individual correlations versus group mean correlation) matter for the strength of correlation. Past induced travel studies often applied an instrumental variable approach for the data at the aggregated level. For example, Duranton & Turner (2011) carried out the study at the scale of MSAs. In contrast, our study is carried out at the individual facility level. Typically, area-wide correlations represented by group means tend to be higher than individual correlations measured directly on individual observations. Thus, we feel confident that the above measurements (*PlannedHwy47, MajorRd_FE_I, CurrentFutureRd, ShellRdLN_4M, CurrentFutureRdLn*) meet the relevance requirement. In order to be selected as instrumental variables, they need to meet yet another requirement of not correlating with the residuals.

3.4.5.4. Using instruments to predict lane-miles.

Next, we separately used all five potential instruments (*PlannedHwy47, MajorRd_FE_I, CurrentFutureRd, ShellRdLN_4M, CurrentFutureRdLn*) in the 2SLS model, where one instrument at a time is used to predict the endogenous variable (ln_LNMile) in the first stage and get (ln_LNMilehat). We estimate ln_LNMile using equations (9), (10), (11), (12) and (13), as follows:

$$\ln(LNMile) = intercept + \ b_2 \times PlannedHwy47 + c_2 \times DevDensity + u \qquad (9)$$

$$\ln(LNMile) = intercept + \ b_2 \times MajorRd\_FE\_I + c_2 \times DevDensity + u \qquad (10)$$

$$\ln(LNMile) = intercept + \ b_2 \times CurrentFutureRd + c_2 \times DevDensity + u \qquad (11)$$

$$\ln(LNMile) = intercept + \ b_2 \times ShellRdLN\_4M + c_2 \times DevDensity + u \qquad (12)$$

$$\ln(LNMile) = intercept + \ b_2 \times CurrentFutureRdLn + c_2 \times DevDensity + u \qquad (13)$$

At stage 2 of the 2SLS, those predicted values (ln_LNMilehat) are plugged in (14) as follows:

$$\ln(LNMile) = intercept + \ b_2 \times CurrentFutureRdLn + c_2 \times DevDensity + u \qquad (14)$$

3.4.5.5. Evaluating the potential instruments for exogeneity.

To ensure that the initially selected five variables can be used as instrumental variables, they need to satisfy the exogeneity condition (i.e., they should not correlate with the residuals). We examined plots of residuals against the regressor of interest and observed if there was a discernible pattern, such as a curve or trend. The presence of a pattern suggests a relationship between the regressor and the error term.

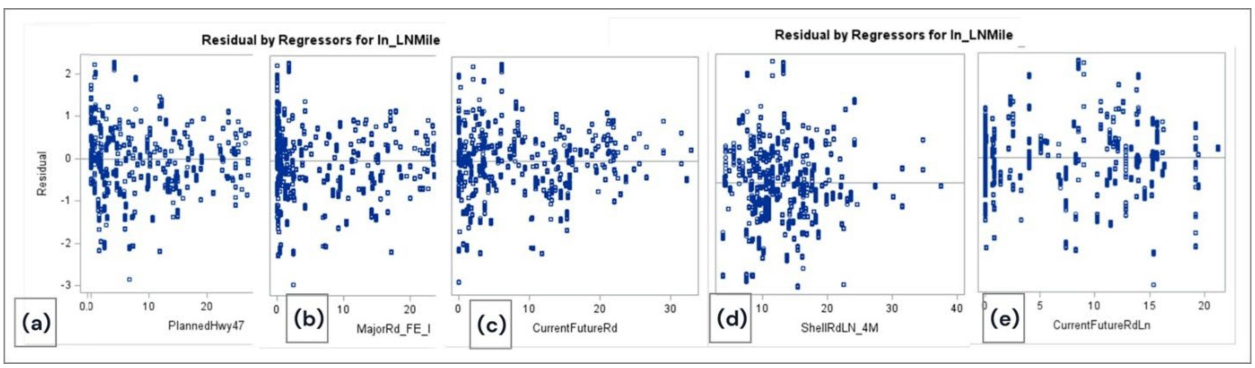

Figure 3-20 Residual plots of all instrumental variables.

Figure 3-20 shows all five potential instruments (*PlannedHwy47, MajorRd_FE_I, CurrentFutureRd, ShellRdLN_4M, CurrentFutureRdLn*) plotted against residuals in the 1st stage of the 2SLS model using the full set of data (20-year-long). The first three (*PlannedHwy47, MajorRd_FE_I, CurrentFutureRd*) appear to correlate with the residuals indicated by a distinct pattern (shown in Figure 3-20 a, b, c). Further, these variables are not significant in the 1st stage of the 2SLS model, and thus, are not reported in the results table. However, the last two potential instrumental variables (*ShellRdLN_4M, CurrentFutureRdLn*) seem to have a weak/no correlation with the residuals, evidenced by almost a circular pattern (shown in Figure 3-20 d, e), which satisfies the exogeneity requirement. Additionally, both variables are also statistically significant (reported in Table 4-3 of the main IV results). Thus, based on the residuals plot of the potential instruments plotted against residuals and no significance, *PlannedHwy47, MajorRd_FE_I, CurrentFutureRd* do not meet the requirement of no correlation with the model residuals. We keep *ShellRdLN_4M and CurrentFutureRdLn* as our instrumental variables and apply these in 2SLS modelling.

We chose the *ShellRdLN_4M* as our instrument 1 based on:

(1) its moderate but statistically significant correlation with the endogenous variable, ln_LNMile (correlation =0.26 at the level of significance =.05).
(2) It also seems not to correlate with the residuals in the model.
(3) This instrument is statistically significant in the 2SLS model (at stage 1, it is statistically significant for estimating ln_LNMile, and at stage 2, the predicted values of the log of lane-miles are statistically significant in estimating the VMT).

We chose CurrentFutureRd as our instrument 2, using the same rationale. It has a moderate but statistically significant correlation with the endogenous variable, ln_LNMile (correlation = 0.3 at a level of significance of 0.05), and the residuals plot shows no apparent correlation with the residuals in the model.

3.5. Factors Influencing Induced Demand

In addition to measuring changes in travel outcomes, this study examines the factors associated with induced demand following roadway capacity expansion. Observed variation in traffic outcomes across study sites indicates that demand response is not uniform and depends on roadway characteristics and surrounding context. Past induced travel research has predominantly relied on the elasticity of VMT with respect to lane-miles, which is informative at an aggregated scale but does not, on its own, identify the segment- or context-level factors that planners can act on at the design stage. To address this gap, we developed a complementary modeling framework in which the presence of induced travel is operationalized as an ordered outcome with three levels, defined formally in Section 3.5.2, and is regressed on a set of socio-demographic, employment, safety, road, and project characteristics.

The objective of this framework is to identify how these variables influence the likelihood of a facility experiencing higher levels of induced demand. By structuring the outcome as an ordered classification, the analysis allows for interpretation of how changes in roadway and contextual characteristics shift the probability of demand response.

3.5.1. Data Assembly and Descriptive Statistics

The factors analysis built on the capacity enhancement projects described in Section 3.2 and augmented the TN-TIMES traffic data with four additional data sources. These included road attribute and crash records from the Enhanced Tennessee Roadway Information Management System (ETRIMS), socio-demographic data from the Land Use and Land Change Model at the

Traffic Analysis Zone (TAZ) level, employment data from the U.S. Census Bureau's Longitudinal Employer–Household Dynamics (LEHD) program, and project-level attributes provided by TDOT.

The ETRIMS database provided roadway characteristics such as number of lanes, lane width, presence of a two-way left-turn lane, divided or undivided status, posted speed limit, and functional classification. For widening projects, pre-expansion roadway conditions were reconstructed using historical Google Street View imagery, satellite imagery, and available TDOT project documentation. These pre- and post-expansion configurations were used with procedures from the Highway Capacity Manual (Transportation Research Board, 2010) to estimate segment capacity for each period, which formed the basis for the level-of-service classification described in Section 3.5.2.

Population, household, and employment variables were originally available at different temporal resolutions. Crash and employment data were available annually, while household data were reported at five-year intervals. To enable year-by-year analysis, household data were linearly interpolated to annual values at the TAZ level, and block-level employment data were aggregated to the same spatial units. Employment was grouped into seven categories based on the North American Industry Classification System to capture differences in the type of nearby economic activity rather than only overall employment density. The NAICS groupings are detailed in the footnote to Table 3-3.

The analysis period spanned 2002 to 2019, defined by the availability of LEHD and crash data and excluding the disruptions associated with COVID-19. Widening projects contributed observations for the full study period, while newly constructed segments contributed observations from the year of completion onward. After merging all data sources and removing observations with missing values that could not be reliably addressed, the final dataset consisted of 1,239 segment-year observations across 85 projects.

The descriptive statistics for the explanatory variables are presented in Table 3-3 for continuous variables and Table 3-4 for categorical variables. These statistics summarizes the range and distribution of roadway, demographic, and employment characteristics used in the subsequent analysis and provided context for interpreting the modeling results presented in later sections.

Table 3-3 Descriptive Statistics For Factors Study (Continuous Variable)

Continuous Variables	***Mean***	***SD***	***Min.***	***Max***
Household Characteristics				
Household Density (1000/square mile)	0.22	0.29	0	1.23
Average Household Size	2.45	0.22	1.7	3.67
Average Household Income (in $100,000)	0.57	0.19	0.33	1.15
Average Household Workers	1.07	0.14	0.75	1.45
Average Household Vehicles	1.91	0.18	1.42	2.35
Average Household Students	0.43	0.07	0.27	0.62
Average Senior Household	0.41	0.09	0.06	0.68
Employment Characteristics				
Employment Density	0.41	0.79	0	4.28

Basic Employment Ratio[1]	0.11	0.15	0	1
Governmental Employment Ratio[2]	0.03	0.07	0	0.64
Industrial Employment Ratio[3]	0.26	0.24	0	1
Retail Employment Ratio[4]	0.15	0.13	0	0.78
Food Service Employment Ratio[5]	0.09	0.09	0	0.48
Professional Service Employment Ratio[6]	0.3	0.23	0	0.92
Other Employment Ratio[7]	0.03	0.05	0	0.78
Population Characteristics				
Population Density (1000/square mile)	0.53	0.68	0.01	2.82
Project Characteristics				
Project Length (in miles)	3.04	1.87	0.19	8.4
Road Characteristics				
Speed Limit (miles/hour)	51.22	10.28	25	70

[1]Basic EMP= NAICS[+](11 + 21 + 23)
[2]Governmental EMP = NAICS[+](92)
[3]Industrial EMP = NAICS[+](22 + 3133 + 54 + 55 + 56 + 61 + 62 + 92)
[4]Retail EMP = NAICS[+](4445)
[5]Food Industry EMP = NAICS[+](72)
[6]Professional Service EMP = NAICS[+](51 + 52 + 53 +54 + 55 + 56 + 61 + 62 + 92)
[7]Other EMP = NAICS[+](71 + 81)
[+]NAICS = North American Industry Classification System

Table 3-4 Descriptive Statistics For Factors Study (Categorical Variable)

Categorical Variables	***Count***	***Proportion***
Functional Classification of Road		
Urban Principal Arterial	270	0.22
Urban Minor Arterial	304	0.25
Rural Principal Arterial	465	0.38
Collector	200	0.16
Induced Travel (IT)		
Presence of IT	33	0.03
Approaching IT	38	0.03

3.5.2. Determining the Presence of Induced Travel

Capacity enhancement projects were designed to achieve a target level of service (LOS) at the design year, with the design year already incorporating expected natural growth in traffic. A drop in LOS observed shortly after project completion, occurring earlier than the design year and beyond what natural growth alone would explain, was therefore interpreted as evidence that travel beyond the planned trajectory had been induced by the improvement. This concept was operationalized as a three-level ordinal indicator.

For each segment-year observation, the volume-to-capacity (v/c) ratio was computed using peak-hour flow, derived from AADT, K-factor, and D-factor as described in Section 3.1, along with the HCM-based segment capacity for the corresponding year, either pre- or post-expansion. Each v/c ratio was then mapped to a LOS letter grade from A through F using HCM thresholds. Segments whose post-enhancement LOS deteriorated by one grade relative to the immediate post-project baseline were classified as approaching induced travel. Segments whose LOS deteriorated by two or more grades were classified as experiencing induced travel. The remaining segments, where LOS held steady or improved relative to the post-project baseline, were classified as showing no induced travel. These three categories were coded as 0, 1, and 2 and formed the dependent variable used in the subsequent model.

The three-level construction was adopted for three reasons. First, using LOS rather than the raw v/c ratio aligned with how TDOT and other agencies evaluate post-project performance and allowed the classification rule to be expressed in operational terms familiar to practitioners. Second, distinguishing between a one-grade drop and a two-or-more-grade drop captured a meaningful difference in system response. A one-grade drop reflected early signs of induced travel, where performance margins began to erode, while a two-grade drop indicated that the post-project condition had effectively returned to, or fallen below, levels comparable to the pre-project baseline. Third, treating the outcome as ordinal preserved information contained in the intermediate “approaching” category, which represents the stage at which intervention remains feasible through demand management strategies.

Figure 3-21 illustrates the classification rule for a representative study site. Capacity enhancement was completed in 2006 and improved the segment LOS from D to B. In subsequent years, LOS declined from B to C, which was classified as approaching induced travel, and later from C to D, which was classified as induced travel present. The observed deterioration from the improved condition toward the pre-project baseline was interpreted as evidence of demand beyond the design assumptions. Across the 85 projects in the panel, 12 projects exhibited at least one segment-year classified as approaching or present induced travel, corresponding to 71 out of 1,239 observations, as reported in Table 3-4.

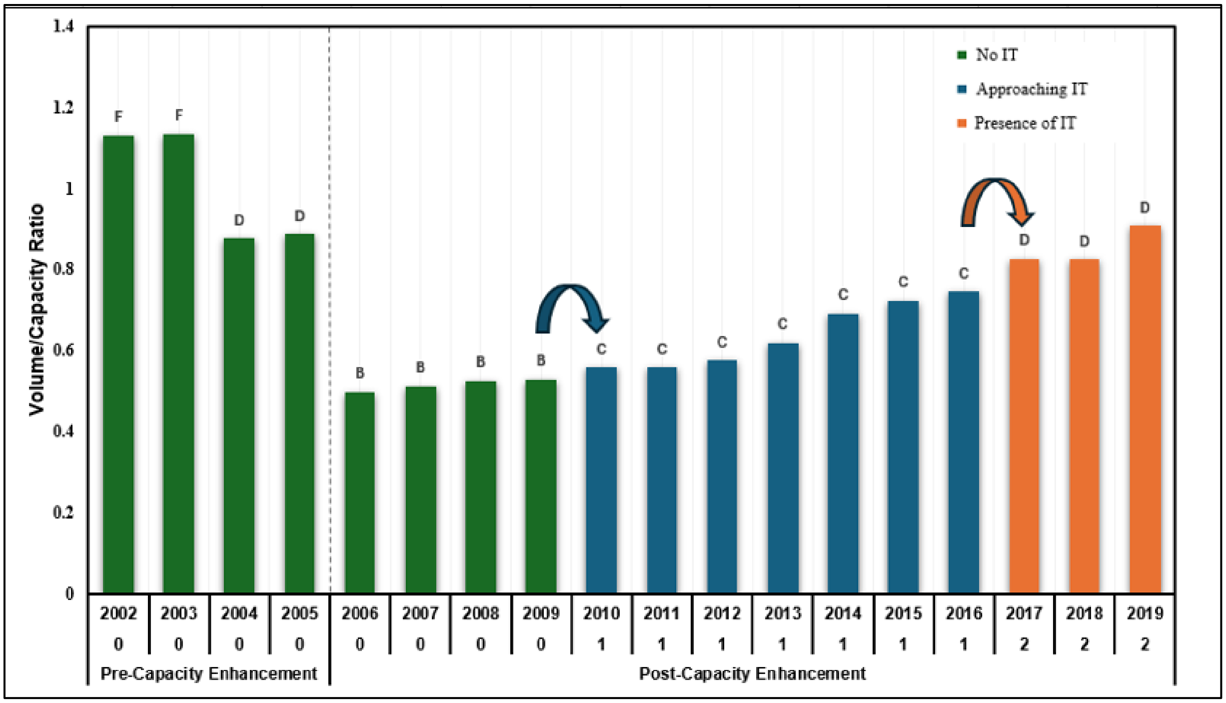

Figure 3-21 Induced Travel Determination.

3.5.3. Modeling Approach

An ordinal logistic regression model was used to examine the relationship between explanatory variables and the likelihood of induced demand. This approach is appropriate because the dependent variable represents ordered categories rather than independent alternatives. The model is based on an underlying latent variable formulation in which the propensity for induced demand is expressed as a function of explanatory variables and a random error term.

$$y_i^* = X_i\beta + \varepsilon_i \qquad (15)$$

where y_i^* represents an unobserved continuous propensity for induced demand, X_i is a vector of explanatory variables, β is a vector of parameters to be estimated, and ε_i is a random error term assumed to follow a logistic distribution.

The observed outcome is determined by comparing the latent variable to a set of threshold values that divide the latent scale into ordered categories. As the value of $X_i\beta$ increases, the probability of a project falling into a higher induced demand category also increases. Within this framework, the estimated coefficients indicate the direction and relative influence of each variable. A positive coefficient implies a higher likelihood of induced demand, while a negative coefficient implies a lower likelihood. The model assumes proportional odds, where the effect of explanatory variables remains constant across outcome thresholds. This assumption was tested using the Wald test proposed by Brant (1990). In cases where the assumption was not satisfied, a partial proportional odds specification was considered to allow selected variables to vary across outcome levels. Model performance was evaluated using the Akaike Information Criterion, and goodness of fit was assessed using McFadden's R^2. Multicollinearity among explanatory variables was examined using the Variance Inflation Factor.

Chapter 4 Results and Discussion

This chapter presents the empirical findings of the study. The analysis focuses on a single question. It examines whether road capacity expansion in Tennessee generates additional travel, how large the effect is, and under what conditions it is most likely to occur. The question involves both measurement and explanation, which require different analytical approaches, so the study applies four complementary methods presented in the sections that follow.

Section 4.1 examines changes in traffic outcomes before and after capacity expansion and shows how the response varies across functional class and posted speed. Sections 4.2 and 4.3 estimate the relationship between added lane-miles and total vehicle travel at the network level. The ordinary least squares results provide a baseline estimate, while the two stage least squares results account for the joint relationship between capacity and travel. Section 4.4 examines how corridor characteristics influence the likelihood of induced travel, focusing on household, employment, roadway, and project attributes.

Each analysis addresses a different part of the problem. The before and after comparison identifies where changes occur. The regression results quantify the magnitude of the effect across the network. The factors analysis explains why some corridors respond differently than others. Section 4.5 brings these results together and interprets what they imply for how capacity expansion is evaluated and understood in practice.

4.1. Travel outcome results before- and after capacity enhancement.

Travel outcomes have been compared at study sites before- and after capacity enhancement broken down by functional class and speed. Within the same functional road class there was a different response to changes in capacity.

4.1.1. Decreased Travel outcomes in roads with lower speeds.

After capacity enhancement implementation, there were either no changes or decreases in travel outcomes (Peak-hour traffic flow, Annual average daily traffic (AADT), Peak-hour VMT, Daily VMT) at study sites with lower speed limits, that is, within the same functional class, lower speeds often seem associated either with no changes or significant decreases in some or all measures of travel outcomes after road capacity enhancement.

4.1.1.1 Functional class 2: speeds 30 mi/hr, and 45 mi/hr.

Specifically, for the functional class 2 (which has speeds including 30 mi/hr, 45 mi/hr, 55 mi/hr, 60 mi/hr, 65 mi/hr, and 70 mi/hr), the study sites with the lower speed limit (30 mi/hr) within the same functional class experienced statistically significant decreases across all measures of travel outcomes following capacity improvement. On average, peak-period flows and peak-period VMT decreased by 9.5%, and AADT and daily VMT dropped by 7.4%, after road capacity enhancement at these study sites. Similarly, there are significant decreases in peak-hour traffic flow and in AADT for the study sites of the same functional class 2 with the speed limit of 45 mi/hr, and no significant changes have been found for the peak-hour VMT and daily VMT for the study sites of functional class 2 with the speed limit of 45 mi/hr (supported by both 1-tail test, and the 2-tail tests).

4.1.1.2 Functional class 6: speeds 45mi/hr and 50mi/hr.

Next, within functional Class 6 (which have various speed limits including 45mi/hr, 50 mi/hr, 55 mi/hr, and 70 mi/hr), at the study sites with lower speeds again there were decreases in some or all measures of travel outcomes after capacity enhancement. E.g., for the study sites of functional class 6 with the speed limit of 45mi/hr, there were statistically significant decreases in AADT, daily VMT and in peak-hour VMT. Similarly, at the study sites of functional Class 6 with the speed limits (e.g., 50 mi/hr), there were statistically significant decreases in AADT by 5.36%, and daily VMT which also decreased by 5.35%.

4.1.1.3 Functional class 14: speeds 45 mi/hr and 40mi/hr.

For the study sites of functional Class 14, (where all speeds are 40mi/hr, 45mi/hr, 50mi/hr, and 55mi/hr), no changes in travel outcomes have been found across the four measures for the observations for the study sites with lower speeds (40mi/hr) within this functional class.

4.1.1.4 Functional class 16: speeds 30 mi/hr, 35 mi/hr and 40mi/hr.

For functional Class 16 (where all speeds are (30mi/hr, 35mi/hr, 40mi/hr, 45mi/hr, 55mi/hr), study sites with the lower speed limits 30mi/hr, 35 mi/hr, and 40 mi/hr, had no changes in travel outcomes.

4.1.2. Increased Travel outcomes in roads with higher speeds.

After capacity enhancement implementation, at the study sites with higher speed limits there often were statistically significant increases in some or all of the measures of travel outcomes, that is, within the same functional class, higher speeds often seem associated either with significant increases in some or all measures of travel outcomes after road capacity enhancement.

4.1.2.1 Functional class 1: speeds 70mi/hr.

For the study sites of functional class 1, with the speed limit of 70mi/hr, peak-period traffic flow increased by 28% on average, daily traffic flow increased by 27.62% on average, peak-period VMT increased by 28.05% on average, and daily VMT increased by 27.62% on average after road capacity enhancement.

4.1.2.2 Functional class 2: speeds 55 mi/hr, 60 mi/hr, and 65 mi/hr.

For functional Class 2 (which has speeds including 30 mi/hr, 45 mi/hr, 55 mi/hr, 60 mi/hr, 65 mi/hr, and 70 mi/hr), study sites with the higher speed limit of 55 mi/hr, had statistically significant increases in daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr). Daily VMT increased by 11.82% and peak-hour VMT increased by 12.77%, on average. Travelers seem to prefer to take advantage of greater road capacity using facilities with higher speed limits. Similarly, for the study sites of the same functional Class 2 with the speed limit of 60 mi/hr, there were statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests indicating strong evidence of a real effect of capacity enhancement, and not random variation. Small p-values indicate strong evidence against the null hypothesis, leading to rejecting the null hypothesis of no effect of road capacity enhancement while supporting the alternative hypothesis of the real effect of road capacity enhancement on travel outcomes. Peak-hour traffic flows (FlowAft vs FlowBfr) have increased on average by 20.38%, AADT (AADTAft vs AADTBfr) has experienced an increase by 26.42%, while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew by

20.38% and 26.43%, respectively. Further, for the study sites of the same functional Class 2 with the speed 65mi/hr, there were statistically significant increases in daily VMT (VMTAft vs VMTAft), where daily VMT increased by 17.1% after the implementation of road capacity improvement.

4.1.2.3 Functional class 6: speeds 50 mi/hr.

For the study sites of the functional Class 6 with the speed limit of 50mi/hr, there were statistically significant increases in peak-hour traffic flows, and in peak-hour VMT, as travelers seem to prefer take advantage of the larger capacity during the peak-hour period for this facility. On average, peak-hour traffic flows grew by 8.67%, and peak-hour VMT increased by 8.73% after the implementation of road capacity improvement.

4.1.2.4 Functional class 11: speeds 65 mi/hr, 70 mi/hr.

Next, in functional Class 11 (all speeds include 55mi/hr, 65mi/hr, and 70mi/hr), the study sites with the greater speed limit of 65 mi/hr, had statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 7.81%, AADT (AADTAft vs AADTBfr) has also experienced an increase by 7.81%, while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) similarly grew by 7.81% each. Further, for the study sites of the same functional Class 11 with the greater speed limit of 70 mi/hr, there were statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 16.81%, AADT (AADTAft vs AADTBfr) has also experienced an increase by 20.97%, while daily VMT (VMTAft vs VMTAft) grew from 36,555 vehicle miles travelled to 173,310 vehicle miles travelled daily on average, and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew from the 1,864 vehicle miles travelled to 8,311 vehicle miles travelled to in the peak hour.

4.1.2.5 Functional class 12: speeds 55 mi/hr.

For the study sites of functional Class 12 with the speed limit of 55 mi/hr, there were statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flow (FlowAft vs FlowBfr) has increased on average by 53.42%, AADT (AADTAft vs AADTBfr) has also experienced an increase by 25.48%, while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew by 26.35%, and by 51.5%, respectively.

4.1.2.6 Functional class 14: speeds 45 mi/hr, and 55 mi/hr.

For study sites of the functional class 14, with the speed limit 45mi/hr, a significant increase in the average value of the AADT has been found after capacity improvement (p-value=0.04), specifically, AADT (AADTAft vs AADTBfr) has experienced a significant increase by 14.15%, while no changes across other travel outcomes have been observed.

After road capacity enhancement, for the study sites of the functional class 14, with the speed limit of 55 mi/hr, there were significantly higher AADT (greater AADTAft vs AADTBfr) (p-value=0.01) and daily VMT (greater VMTAft vs VMTBfr) (p-value=0.009), with AADT increasing by 21.02% on average and daily VMT increasing by 20.89%. There were no significant changes found in peak-hour traffic flow (FlowAft vs FlowBfr) nor in peak-hour VMT (VMTPkAft vs

VMTPkBfr) after road capacity enhancement for the study sites of functional Class 14 with the speed limit of 55mi/hr.

4.1.2.7 Functional class 16: speeds 45 mi/hr.

For functional Class 16 with the higher speed limit of 45 mi/hr, there were statistically significant increases in all measures of travel outcomes after the implementation of road capacity enhancement, supported by both one-tail (a directional test) and two-tail (non-directional) tests. Peak-hour traffic flows (FlowAft vs FlowBfr) have increased on average by 27.68%, AADT (AADTAft vs AADTBfr) has also experienced an increase by 33.68%, while daily VMT (VMTAft vs VMTAft) and peak-hour VMT (VMTPkAft vs VMTPkBfr) grew by 35.26%, and by 25.24% respectively.

Table 4-1summarizes the results for all subgroups, reporting the direction and magnitude of statistically significant changes. Subgroups with fewer than 30 observations are identified in the table.

Table 4-1 Statistically Significant Changes In Travel Outcomes After Capacity Enhancement By Functional Class And Posted Speed Limit

Functional Class	Speed (mi/hr)	Observation-years (Bfr / Aft)	Peak-hour Flow	AADT	Peak-hour VMT	Daily VMT	Appendix
1. Rural Principal Arterial – Interstate	70	10 / 8 †	+28.0%	+27.6%	+28.0%	+27.6%	B-0-1
2. Rural Principal Arterial – Other	30	10 / 10 †	−9.5%	−7.4%	−9.5%	−7.4%	C-0-1
	45	20 / 30	−sig.	−sig.	—	—	C-0-2
	55	90 / 134	—	—	+12.8%	+11.8%	C-0-3
	60	8 / 10 †	+20.4%	+26.4%	+26.4%	+20.4%	C-0-4
	65	58 / 70	—	—	—	+17.1%	C-0-5
6. Rural Minor Arterial	45	20 / 30	—	−22.5%	−21.1%	−27.5%	C-0-6
	50	10 / 10 †	+8.7%	−5.4%	+8.7%	−5.4%	C-0-7
	55	20 / 20 †	—	—	—	—	C-0-8
7. Rural Major Collector	30	10 / 6 †	+30.1%	+11.2%	+30.1%	+21.1%	C-0-9
	50	20 / 20 †	—	—	—	—	C-0-10
8. Rural Minor Collector	25	10 / 10 †	+38.7%	+27.8%	+38.7%	+27.8%	C-0-11
	45	10 / 19 †	+281.2%	+332.9%	+1717.6%	+2027.7%	C-0-12
	55	10 / 20 †	−26.5%	−27.4%	−29.8%	−29.9%	C-0-13
11. Urban Principal Arterial – Interstate	55	10 / 8 †	—	—	—	—	C-0-14
	65	10 / 7 †	+7.8%	+7.8%	+7.8%	+7.8%	C-0-15
	70	6 / 20 †	+16.8%	+21.0%	+345.9%	+374.1%	C-0-16

Functional Class	Speed (mi/hr)	Observation-years (Bfr / Aft)	Peak-hour Flow	AADT	Peak-hour VMT	Daily VMT	Appendix
12. Urban Principal Arterial – Other Freeway	55	40 / 40	+53.4%	+25.5%	+51.5%	+26.4%	B-0-7
14. Urban Principal Arterial – Other	40	10 / 16 †	—	—	—	—	C-0-17
	45	30 / 30	—	+14.2%	—	—	C-0-18
	50	40 / 38	—	—	—	—	C-0-19
	55	20 / 20 †	—	+21.0%	—	+20.9%	C-0-20
16. Urban Minor Arterial	30	20 / 15 †	—	—	—	—	C-0-21
	35	20 / 24 †	—	—	—	—	C-0-22
	40	60 / 54	—	—	—	—	C-0-23
	45	40 / 37	+27.7%	+33.7%	+25.2%	+35.3%	C-0-24
	55	20 / 20 †	—	—	—	—	C-0-25
17. Urban Collector	30	20 / 30	—	—	—	—	C-0-26
	40	4 / 10 †	—	−sig.	—	−sig.	C-0-27

NOTE: (i) Values represent average percent change between the before and after periods for each subgroup.
(ii) Cells marked "—" indicate no statistically significant change at $p < 0.05$.
(iii) Cells marked with † indicate subgroups with fewer than 30 observations. Percent changes for very small subgroups may reflect low pre-project baseline values.
(iv) Corresponding mean values are reported in Appendix C.

4.2. Ordinary Least Squares (OLS) results.

TABLE 4-2 and 4-3 present OLS regressions, predicting the log VMT as a function of the road capacity and socio-economic characteristics as controls. The results are reported for a short dataset (one year before capacity enhancement has been carried out) and for a full dataset (in Italicized underlined font) spanning 20 years (10 years before capacity improvement and 10 years after project implementation). As shown in TABLE 4-2 and 4-3, we include only two regressors, the log of lane-miles and employment/developed land density. TABLE 4-1 and 4-2 include only employment /developed land density and lane-miles as controls. As expected, travel grows with more road capacity. Despite differences across model specifications (using employment and developed land densities), the OLS elasticity of VMT relative to road capacity is quite high (the point estimate for this coefficient is 1.25 and 1.20227, respectively). It implied a 10% increase in lane-miles is associated with a 12.51%-12.02% increase in VMT, holding covariates fixed. If we restrict attention to regressions predicting VMT as a function of lane-miles and developed land density as a control, the estimate is higher at 1.20227.

The coefficients for employment density and developed land densities are positive and statistically different from zero in both OLS model specifications (0.04 (*) for the former and 1.87 (***) for the latter, respectively. Interestingly, the point estimate for this coefficient is lower than lane-miles. Past studies showed that socio-economic and demographic factors appear to be the major determinants of travel demand (Heanue, 1998). Because of the higher model performance with the developed land density (versus employment density, with the R-squared adjusted value of .71 versus .59), we kept the former as a control in other models.

Table 4-2 PARAMETER ESTIMATES LN_VMT IS A DEPENDENT VARIABLE, DEVDENSITY AS A CONTROL

OLS Variable	*Parameter Estimate*	*Standard Error*	*t Value (Pr > |t|)*
Intercept (Full)	*5.99738*	*0.06027*	*99.51****
Intercept(short)	7.23768	0.25987	27.85***
ln_LNMile (Full)	*1.25117*	*0.02208*	*56.66****
ln_LNMile (short)	1.20227	0.09799	12.27***
DevDensity (Full)	*2.71824*	*0.06294*	*43.19****
DevDensity (short)	1.87337	0.32299	5.80***
R^2 adj (Full)	*0.48*	R^2 adj (short)	0.71
F-value(Full)	*1745.54*	F-value(short)	75.36
N (Full)	*3780*	N (short)	62

Note: ITALICIZED UNDERLINED INDICATES A FULL DATA SET (20-YEAR DATA)
Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

Table 4-3 PARAMETER ESTIMATES LN_VMT IS A DEPENDENT VARIABLE, EMPDENSITY AS A CONTROL

OLS Variable	*Parameter Estimate*	*Standard Error*	*t Value (Pr > |t|)*
Intercept (Full)	*7.16351*	*0.06737*	*106.33****
Intercept(short)	7.994310	0.27010	29.41***
ln_LNMile (Full)	*1.05499*	*0.02802*	*37.65****
ln_LNMile (short)	1.10933	0.12160	9.12***
EmpDensity (Full)	*0.05394*	*0.00329*	*16.4****
EmpDensity (short)	0.04189	0.01654	2.53***
R^2 adj (Full)	*0.30*	R^2 adj (short)	0.59
F-value(Full)	*728.84*	F-value(short)	44.72
N (Full)	*3438*	N (short)	62

Note: ITALICIZED UNDERLINED INDICATES A FULL DATA SET (20-YEAR DATA)
Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

OLS models relying solely on cross-sectional data may capture long-run effects but can suffer from simultaneity bias. The theory suggests that VMT and road capacity (lane-miles) are jointly determined (that is, endogeneity exists).

We checked for endogeneity using our empirical data. After running the OLS, we examined the regressor of interest (lane-mile) plotted against the error term e (proxied by residuals). We are using residuals as the estimate of the error term in the equation (in this example here, the residuals are represented by the difference between the predicted and actual VMT values). Otherwise, if correlation with residuals occurs, the parameter estimates are biased as the model produces inconsistent results. A correlation has been indicated by a discernible pattern. A clear trend observed in a plot of residuals means that a relationship is likely to exist between lane-mile and the error term. Thus, lane miles appear to be an endogenous variable.

4.3. 2-Stage Least Squares (2SLS) Results.

TABLE 4-4 reports the main IV results. Specifically, we present the results of first-stage of the 2 Stage Least Squares (2SLS) model to estimate the lane-miles (using logs of lane-miles) (Eq.8) using *ShellRdLN_4M* as an instrument and developed density as a control (based on the short dataset). Shown in the italicized underlined font, Table 4-4 also reports the results of the first-stage regression of the 2SLS model using the full dataset (with similar results). TABLE 4-4 then reports the results of the second-stage models and provides the estimates of equation (Eq.7) using predicted values of logs of lane-miles (based on *ShellRdLN_4M* as an instrument) and shows that this instrument predicts the initial level of VMT before project implementation, conditional on the control we used in estimates of the lane-miles as well as for the full data set. Per 2SLS, elasticity of VMT relative to road capacity is 1.103 and 1.959, respectively). It implied a 10% increase in lane-miles is associated with a 11%-19.6% increase in VMT, holding covariates fixed.

We repeated these steps for the other instrument (*CurrentFutureRdLn*). The results are presented in TABLE 4-5.

Table 4-4 PARAMETER ESTIMATES, 1ST AND 2ND STAGE DEPENDENT VARIABLE: LN_ LNMILE; INSTRUMENT: SHELLRDLN_4M

1st Stage 2SLS Variable	*Parameter Estimate*	*Standard Error*	*t Value (Pr > |t|)*
Intercept Short	1.64922	0.29200	5.64 ***
Intercept Full	*2.01816*	*0.03358*	*60.1****
DevDensity Short	-1.73183	0.34705	-4.99***
DevDensity Full	*-1.66118*	*0.03979*	*-41.75****
ShellRdLN_4M Short	0.05643	0.01824	3.09**
ShellRdLN_4M Full	*0.04074*	*0.00223*	*18.26****
R^2 adj (Short)	0.34	R^2 adj (full)	*0.35*
F-value (short)	15.40	F-value (full)	*920.28*
N (short)	56	N (full)	*3375*
2ND Stage 2SLS Variable	Parameter Estimate	Standard Error	t Value (Pr > |t|)
Intercept Short	7.40653	1.27405	5.81***
Intercept Full	*4.22711*	*0.26532*	*15.93****
ln_LNMilehat Short	1.10313	0.52866	2.09*
ln_LNMilehat Full	*1.95991*	*0.10516*	*18.64****
DevDensity Short	1.70240	1.01782	1.67
DevDensity Full	*3.76502*	*0.17564*	*21.44****
R^2 adj (Short)	0.04	R^2 adj (full)	*0.12*
F-value (short)	2.19	F-value (full)	*231.36*
N (short)	53	N (full)	*3336*

Note: ITALICIZED UNDERLINED INDICATES A FULL DATA SET (20-YEAR DATA)
Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

Table 4-5 2SLS PARAMETER ESTIMATES, 1ST AND 2ND STAGE DEPENDENT VARIABLE: LN_ LNMILE; INSTRUMENT: CURRENTFUTURERDLN

1st Stage 2SLS Variable	*Parameter Estimate*	*Standard Error*	*t Value (Pr > |t|)*
Intercept Short	2.19206	0.20197	10.85***

Intercept Full	*2.40381*	*0.02062*	*116.56****
DevDensity Short	-1.33724	0.47927	-2.79**
DevDensity Full	*-1.61725*	*0.04662*	*-34.69****
CurrentFutureRdLn Short	-0.00739	0.02090	-0.35
CurrentFutureRdLn Full	*0.01547*	*0.00223*	*6.95****
R^2 adj (Short)	0.16	R^2 adj (full)	*0.26*
F-value (short)	7.03	F-value (full)	*689.69*
N (short)	65	N (full)	*3824*
2ND Stage 2SLS Variable	Parameter Estimate	Standard Error	t Value (Pr > |t|)
Intercept Short	*2.21022*	*0.64003*	*3.45***
Intercept Full	-4.33032	3.91249	-1.11
ln_LNMilehat Short	*2.81359*	*0.26409*	*10.65****
ln_LNMilehat Full	-6.08993	5.64224	-1.08
DevDensity Short	*4.98124*	*0.38906*	*12.8****
DevDensity Full	19.30848	8.58159	2.25*
R^2 adj (Short)	-0.01	R^2 adj (full)	*0.07*
F-value (short)	0.64	F-value (full)	*134.99*
N (short)	62	N (full)	*3780*

Note: ITALICIZED UNDERLINED INDICATES A FULL DATA SET (20-YEAR DATA)
Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

4.4. Factors Influencing Induced Travel

This section reports the results of the factors analysis described in Section 3.5. The analysis examines how characteristics of roadway segments, surrounding land use, and project attributes influence the likelihood of induced travel following capacity enhancement. Twelve factors were identified as statistically associated with induced travel, spanning household, employment, population, roadway, and project characteristics. The full model results are reported in Appendix D (Table D-0-1).

The results of the factors analysis are shown in Figure 4-1, which reports the odds ratios for each explanatory variable along with 95% confidence intervals. Among the eleven factors retained in the model, employment density has the largest effect. A one-standard-deviation increase in employment density raises the odds of induced travel by a factor of 3.84, indicating that projects in employment-intensive areas are more likely to experience demand growth after capacity enhancement. The remaining significant factors are smaller in magnitude but still contribute to the observed patterns.

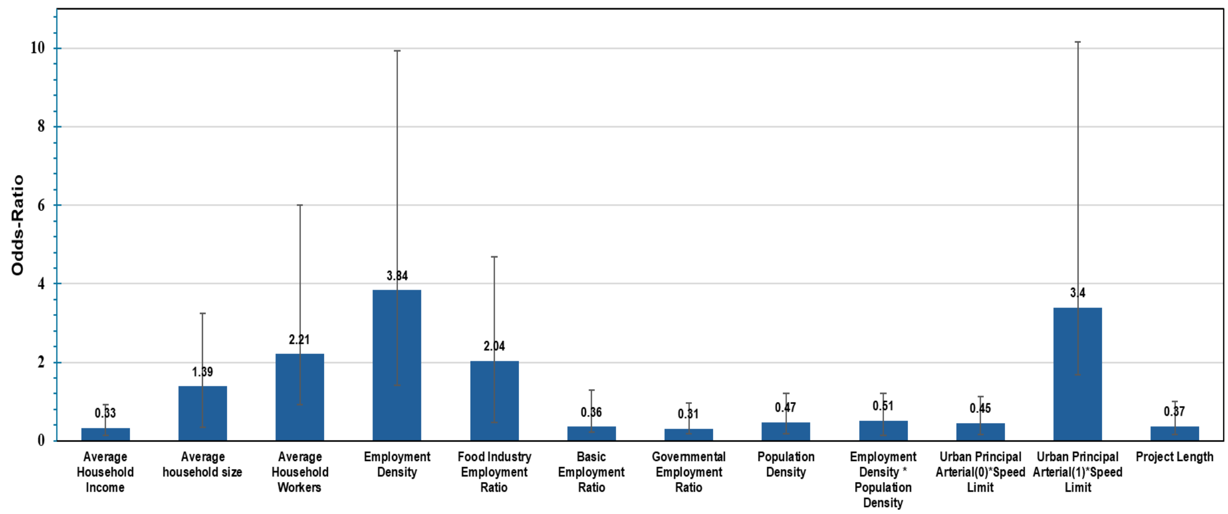

Figure 4-1 Distribution of Odds-Ratio from Factor Analysis

At the household level, household size and the number of workers per household both increase the likelihood of induced travel, and the two variables reinforce each other. A one-standard-deviation increase in average household size raises the odds of induced travel by approximately 39%, while a similar increase in the number of workers raises the odds by a factor of 2.21. Larger households represent a higher base level of travel demand, and additional workers increase the likelihood that improved travel conditions translate into additional trips. Reduced travel time expands the range of feasible destinations for each household member, particularly for work and discretionary travel. This pattern is consistent with Barr (2000).

In contrast, higher household income is associated with lower induced travel. A one-standard-deviation increase in income reduces the odds by approximately 67%. Lower-income areas appear to have unmet travel demand that becomes realized when travel time and cost are reduced, while in higher-income areas trip-making is closer to saturation before project completion. Improvements in these areas primarily affect travel conditions rather than trip frequency. This suggests that capacity enhancement in lower-income corridors is more likely to generate additional demand.

Turning to employment characteristics, the results show where induced trips are most likely to occur and also produce the largest effect in the model. A one-standard-deviation increase in employment density raises the odds of induced travel by a factor of 3.84, while a higher food-sector employment share increases the odds by a factor of 2.03. These effects point to the role of consumer-oriented destinations. Corridors serving restaurants, retail, and service activities generate more discretionary trips when travel becomes faster. By comparison, areas dominated by governmental or basic-sector employment show lower induced-travel propensity, with odds ratios of 0.31 and 0.36. These activities generate trips that are fixed in purpose and timing and are less sensitive to travel-time changes. This indicates that employment composition, not just density, influences induced travel outcomes.

Population characteristics modify this pattern. A one-standard-deviation increase in population density reduces the odds of induced travel by approximately 53%, and the interaction between population and employment density further reduces the effect. In dense areas, additional capacity does not translate into proportional increases in vehicle travel due to constraints such as congestion on connecting links, limited parking, and the presence of alternative travel modes. This indicates that dense corridors respond differently to capacity improvements and tend to show a more limited demand response.

At the network level, the role of road classification is not a simple distinction between urban arterials and other roads. The effect operates through an interaction with posted speed limit. On urban principal arterials, higher speed limits increase the likelihood of induced travel. On other functional classes, higher speed limits reduce it. Urban principal arterials connect major activity centers and carry higher traffic volumes, so higher design speeds make these corridors more attractive for both longer-distance trips and route substitution. The opposite effect on other functional classes suggests that higher speeds in those settings primarily serve through-traffic, with limited potential for additional discretionary trips. The marginal effects also show that the induced travel response on urban principal arterials develop over time, with a modest initial effect that strengthens as corridor accessibility improves.

At the project level, project length shows a consistent negative effect. A one-standard-deviation increase in project length reduces the odds of induced travel by approximately 72%. Shorter projects affect local travel patterns and make it easier to add or repeat trips, while longer projects primarily influence longer-distance trips that are less flexible. This indicates that smaller, localized capacity projects may carry higher induced-travel potential than longer corridor-scale projects.

4.5. Implications for TDOT

The three analyses in this study provide a consistent view of how induced travel operates and how it can be incorporated into planning and project evaluation. The before-and-after comparison shows that traffic outcomes do change after capacity expansion, but not uniformly across roadway types. The regression analysis quantifies the magnitude of that response at the network level, and the factor-based model identifies the conditions under which it is most likely to occur. Read together, these results indicate that induced travel is not a uniform outcome of capacity projects, but a context-dependent response that can be anticipated using observable corridor characteristics.

At a broader planning level, the estimated relationship between lane-miles and VMT indicates that additional capacity is associated with a proportional increase in travel that is at least as large as the increase in supply. This has direct implications for how long-run congestion relief is interpreted. Forecasts that assume a one-to-one improvement in operating conditions are likely to overstate the persistence of congestion reduction, particularly on corridors where demand is responsive to travel-time changes. Incorporating an adjustment based on observed elasticity values would bring forecasts closer to observed outcomes. The before-and-after analysis further shows that aggregate averages can mask substantial variation, since higher-speed corridors tend to show increases in traffic outcomes while lower-speed corridors show little change or decreases. This suggests that disaggregation by roadway type and operating conditions is necessary to identify where demand response is likely to be strongest.

At the project level, the factors analysis shows that induced travel is concentrated on a specific subset of corridors rather than being distributed across all projects. Employment density, employment composition, household characteristics, roadway classification, posted speed, and project scale together define a set of conditions under which additional travel is more likely to occur. Corridors with high employment density and strong consumer-oriented activity show the highest sensitivity, particularly when combined with lower household income and urban arterial characteristics. The interaction between speed and functional class indicates that higher speeds increase the likelihood of induced travel on urban principal arterials while reducing it on other roadway types. Shorter projects also show a stronger response than longer ones. These patterns indicate that capacity expansion draws out additional trips most strongly where accessibility gains interact with existing latent demand and trip-generating land uses.

These same characteristics provide a basis for screening projects before construction and for interpreting outcomes after they are completed. Projects located in corridors with multiple high-response characteristics warrant closer examination, as they are more likely to convert capacity gains into additional travel rather than sustained congestion relief. In such cases, capacity expansion alone may not achieve the intended long-run performance improvements. Combining capacity expansion with demand-side measures, or considering alternative investments, may produce more stable outcomes depending on corridor conditions. The results do not suggest that capacity expansion is ineffective, but they indicate that its performance depends on where and how it is applied.

After project completion, the temporal pattern observed in the before-and-after analysis indicates that the response to capacity expansion develops over time rather than occurring immediately. In higher-response corridors, traffic conditions may initially improve and then gradually return toward pre-project levels as travel patterns adjust. This creates a period in the early years after project opening during which changes in travel behavior are still forming. Monitoring traffic conditions during this period provides an opportunity to identify emerging demand patterns before they become fully established.

Taken as a whole, the findings show that induced travel can be incorporated into planning and evaluation without introducing new decision frameworks. The three analytical perspectives used in this study align with existing stages of project development, from system-level forecasting to corridor-level screening and post-project evaluation. Integrating these signals into current practice would allow demand response to be considered as a routine part of project assessment rather than as a separate or exceptional consideration.

4.6. Key Recommendations for TDOT

This section gives actionable suggestions for the future.

The key recommendations of this study are as follows:

- At the project level, agencies should include induced demand screening into project evaluation. Roadway characteristics should be used to identify projects where capacity expansion is likely to generate additional demand rather than relieve congestion. At the minimum, it should include a functional class, and a speed regime.

- Explore alternate strategies to capacity expansion on high-speed urban arterials since these facilities show the strongest increases in traffic demand and are more likely to experience demand rebound after expansion.
- Planners and policymakers should adopt site specific planning approaches, as the response to capacity expansion varies across roadway types, with rural collectors showing accessibility-driven growth and urban facilities exhibiting capacity-driven demand increases.
- Before advancing a capacity project, agencies should have a closer review of surrounding activity levels and screen corridors in areas with high employment density, strong consumer activity, lower household income, and urban arterial characteristics.
- For high-risk corridors, agencies should use a combined approach of capacity expansion with demand management strategies such as employer-based trip reduction, incentive programs, or pricing approaches.
- Demand management and operational strategies in high-risk corridors should be prioritized, since induced demand is driven by identifiable structural factors and can be mitigated through targeted interventions rather than additional capacity.
- At the program level, additional travel generated by new capacity should be incorporated into forecasting and planning models since in some corridors induced travel is more likely than in others. Current modelling approaches do not account for demand feedback and are likely to overestimate the long-term congestion relief benefits of expansion projects.

Chapter 5 Conclusion

Roadway congestion remains one of the most persistent challenges for transportation agencies in Tennessee, and capacity expansion through widening or new construction has long been used to address it. Evidence from other regions shows that some portion of added capacity is absorbed by additional travel rather than lasting congestion relief. This study examined whether that effect is present in Tennessee, how large it is, and under what conditions it is most likely to occur using facility-level data from across the state. The analysis draws on a 20-year dataset covering 84 capacity expansion projects and combines three complementary approaches. Traffic outcomes were compared before and after project completion, statewide regression was used to estimate how additional lane-miles translate into vehicle travel, and a factor-based model was developed to identify the characteristics that make induced travel more likely. Each approach addresses a different part of the same question and together they provide a consistent view of how demand responds to added capacity.

Traffic outcomes do change after capacity expansion, but the response is not uniform. When all projects are considered together, the average change is small. Once the results are separated by functional class and speed, a clear pattern appears. Lower-speed corridors generally show little change or modest decreases in traffic outcomes, while higher-speed corridors, especially higher-speed urban arterials and rural principal arterials, show consistent increases in peak-hour flow, AADT, and VMT.

At the facility level, significant long-run (during 10 years after capacity enhancement) increases in peak-hour and daily traffic flow and VMT occurred along freeways and principal arterials in urban areas. E.g., for the samples of at least 30 observations, urban freeways with speeds of 55mph, had long-run increases in peak-hour flow and AADT by 53% and 26% and in peak-hour VMT and daily VMT by 51.5% and 26%, on average, respectively. Urban minor arterials with speeds of 45mph had average increases in peak-hour flow and AADT by 28% and 34%, and peak-hour VMT and daily VMT by 25% and 35%, respectively. Rural principal arterials with speeds of 55mph and 65mph had long-run increases in peak-hour VMT and daily VMT is about 13% and 12%-17%, on average, respectively. This variation explains why aggregate comparisons often fail to detect induced travel. The effect is not absent, it is uneven and masked when different roadway types are pooled together. At the statewide level, added capacity is associated with a proportional increase in travel that is at least as large as the increase in capacity itself. A 10% increase in lane-miles is associated with roughly an 11% to 20% increase in VMT depending on the model specification.

Specifically, results of modelling using OLS regression (the "baseline" estimates) imply a 10% increase in lane-miles is associated with a 12.5% increase in VMT in the long run (10 years post enhancement). Using 2SLS modelling to address a simultaneity bias reveals even greater increases in VMT occurring at the facility level: using instruments to predict VMT implied a 10% increase in lane-miles is associated with 19.6% increase in VMT in the long term (10 years post enhancement). This indicates that, on average, the additional travel generated by capacity expansion matches or exceeds the added supply and is consistent with both national findings and the patterns observed in the facility-level analysis.

The factor-level results show that induced travel is concentrated on a specific set of corridors rather than being spread uniformly across the network. Employment density is the strongest predictor of induced travel in the model. In practical terms, this effect is most associated with corridors serving concentrated commercial and activity centers rather than lower-intensity suburban or rural areas. Corridors serving consumer-oriented activities such as food services, retail, and professional services show higher sensitivity than those serving administrative or basic-sector employment. Household characteristics reinforce this pattern, as larger households, more workers per household, and lower income levels are associated with a higher likelihood of induced travel, indicating that capacity expansion draws out additional trips where latent demand already exists. Road characteristics do not operate through a simple classification effect. On urban principal arterials, higher posted speeds increase the likelihood of induced travel, while on other functional classes higher speeds reduce it. Project scale also matters, with shorter projects showing a higher likelihood of induced travel than longer projects, suggesting that localized capacity gains are more easily converted into additional trips.

These findings indicate that induced travel in Tennessee is not a uniform outcome of all capacity projects but a condition that can be anticipated using observable characteristics. At the program level, the elasticity estimates suggest that forecasts of long-run congestion relief should account for additional travel generated by new capacity, since assuming a one-to-one improvement in operating conditions is likely to overstate benefits in corridors where induced travel is likely. At the project level, the factor model provides a basis for screening corridors that may require closer review before advancing a capacity project, particularly those with high employment density, strong consumer activity, lower household income, and urban arterial characteristics. The strongest and most consistent post-expansion traffic increases in this study occurred on higher-speed urban freeways, urban arterials, and rural principal arterials. Corridors combining high employment density, strong retail or food-service activity, lower household income, and higher operating speeds on urban principal arterials showed the greatest propensity for induced travel and therefore represent the strongest candidates for additional review during project scoping. These corridors are candidates for combining capacity expansion with demand management strategies such as employer-based trip reduction, incentive programs, or pricing approaches. After project completion, the before-and-after framework allows to monitor evolving traffic conditions and to identify early signs of induced travel while travel patterns are still adjusting.

Limited observations in some subgroup comparisons represent a limitation in the before-and-after analysis, particularly within lower-volume functional classes with the results interpreted as directional evidence rather than precise effect estimates. However, the broader patterns observed across higher-mobility facilities were consistent across multiple analyses and were also supported by the statewide regression and factor-level modeling results. The analysis reflects conditions observed in Tennessee between 2002 and 2019, and effect magnitudes may differ under other conditions. Some variables such as rideshare and transit use were not available at the level needed for inclusion. These points define how the results should be applied but do not change the main findings. The study provides a consistent way to understand and manage induced travel by showing where the effect is likely to occur, how large it can be, and how it can be incorporated into planning, project selection, and post-project evaluation.

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Appendix A

Figures: Explanation of selection of study sites by the functional class.

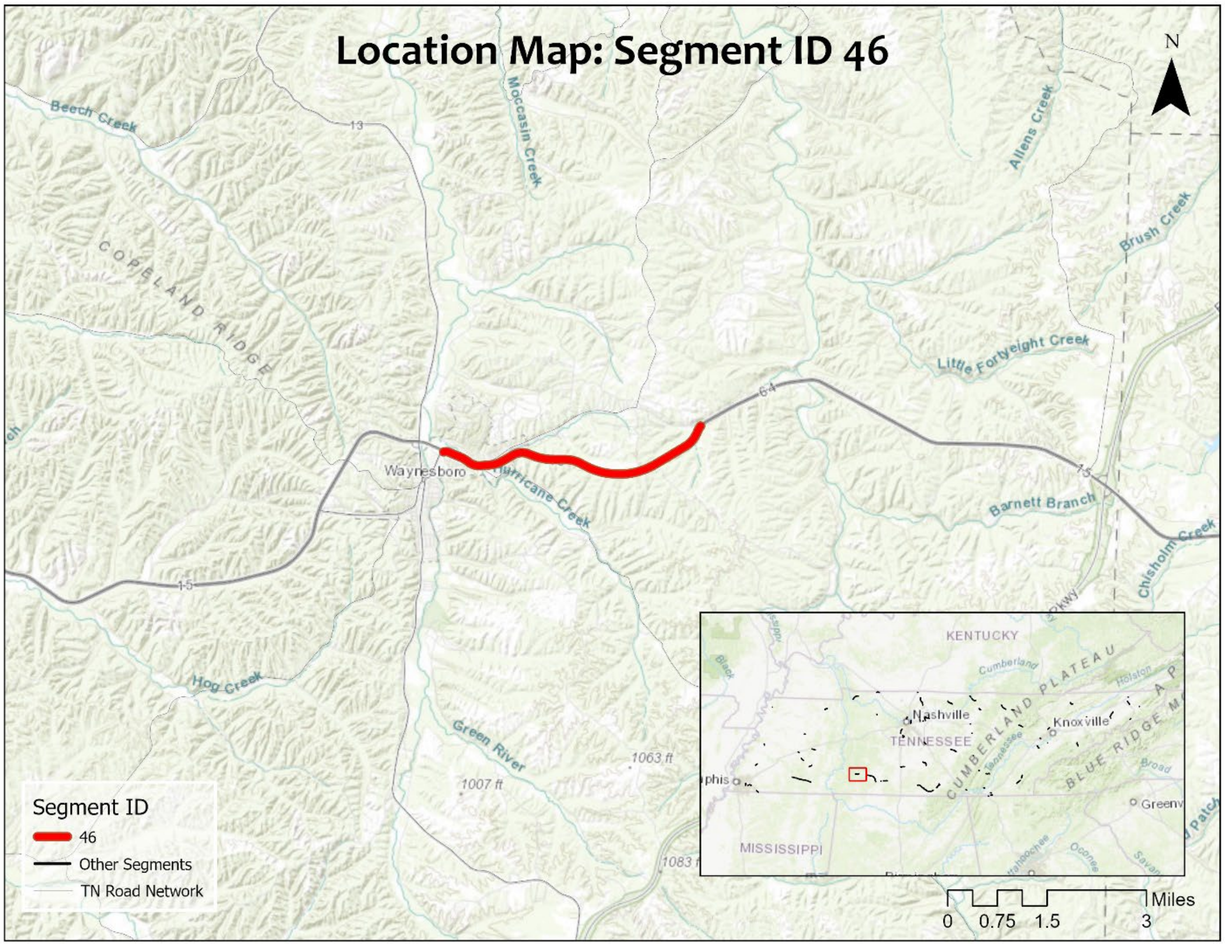

Figure A-0-1 Study site ID=46.

Appendix B

Tables: the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes by the Functional Class only

TABLE B-0-1 FUNCTIONAL CLASS 1, SPEED 70: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	484.43	620.08	9439.3	12046.63	3775.72	4818.65	193.7	248.03
Variance	1937.5	16778.94	681124.9	3163878	108980	506220.5	309.9	2684.6
Observations	10	8	10	8	10	8	10	8
df	8		9		9		8	
t Stat	-2.83		-3.83		-3.83		-2.83	
P(T<=t) one-tail	**0.01** (**)		**0.002** (**)		**0.002** (**)		**0.01** (**)	
t Critical one-tail	1.86		1.83		1.83		1.86	
P(T<=t) two-tail	**0.02** (*)		**0.004** (**)		**0.004** (**)		**0.02** (*)	
t Critical two-tail	2.31		2.26		2.26		2.31	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE B-0-2 FUNCTIONAL CLASS 2, ALL SPEEDS ARE INCLUDED (30 MI/HR, 45 MI/HR, 55 MI/HR, 60 MI/HR, 65 MI/HR, AND 70 MI/HR): RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	484.43	620.08	9439.3	12046.63	3775.72	4818.65	193.7	248.03
Variance	1937.5	16778.94	681124.9	3163878	108980	506220.5	309.9	2684.6
Observations	10	8	10	8	10	8	10	8
df	8		9		9		8	
t Stat	-2.83		-3.83		-3.83		-2.83	
P(T<=t) one-tail	**0.01** (**)		**0.002** (**)		**0.002** (**)		**0.01** (**)	
t Critical one-tail	1.86		1.83		1.83		1.86	
P(T<=t) two-tail	**0.02** (*)		**0.004** (**)		**0.004** (**)		**0.02** (*)	
t Critical two-tail	2.31		2.26		2.26		2.31	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE B-0-3 FUNCTIONAL CLASS 6, ALL SPEEDS ARE INCLUDED (45MI/HR, 50 MI/HR, 55 MI/HR, AND 70 MI/HR): RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	260.8	285.3	4515.2	4623.1	19688	17651	1133.2	1089.17
Variance	11885.2	24527.11	3128579	5288067	1.47E+08	1.6E+08	499293.7	666947.5
Observations	50	70	50	70	50	70	50	70
df	118		117		108		114	
t Stat	-1.009		-0.29		0.89		0.315	
P(T<=t) one-tail	0.157		0.38		0.18		0.37	
t Critical one-tail	1.65		1.65		1.65		1.65	
P(T<=t) two-tail	0.31		0.772		0.37		0.75	
t Critical two-tail	1.98		1.98		1.98		1.98	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE B-0-4 FUNCTIONAL CLASS 7, ALL SPEEDS (30MI/HR, AND 50MI/HR): RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	92.66	94.38	1523.73	1438.12	3164.95	3242.23	187.81	207.93
Variance	2786.95	4908.89	781124.82	1164781.07	4699552.83	5815370.31	16009.16	23751.52
Observations	30	26	30	26	30	26	30	26
df	46		48		51		48	
t Stat	-0.10		0.32		-0.13		-0.53	
P(T<=t) one-tail	0.46		0.37		0.45		0.30	
t Critical one-tail	1.68		1.68		1.68		1.68	
P(T<=t) two-tail	0.92		0.75		0.90		0.60	
t Critical two-tail	2.01		2.01		2.01		2.01	

Note: IEEE Style Tables Notes.
Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE B-0-5 FUNCTIONAL CLASS 8, ALL SPEEDS ARE INCLUDED (25MI/HR, 45MI/HR, 55MI/HR): RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	296.32	318.33	5508.30	5816.71	19153.88	22749.51	1021.90	1220.45
Variance	42176.32	25326.83	16336865.32	10271290.67	266722391.56	208064242.82	696294.65	486568.90
Observations	30	49	30	49	30	49	30	49
df	50		51		56		53	
t Stat	-0.50		-0.36		-0.99		-1.09	
P(T<=t) one-tail	0.31		0.36		0.16		0.14	
t Critical one-tail	1.68		1.68		1.67		1.67	
P(T<=t) two-tail	0.62		0.72		0.33		0.28	
t Critical two-tail	2.01		2.01		2.00		2.01	

Note: IEEE Style Tables Notes.
Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE B-0-6 FUNCTIONAL CLASS 11, ALL SPEEDS ARE INCLUDED (55MI/HR, 65MI/HR, 70MI/HR): RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	6678.83	5589.75	111356.65	103077.86	244448.68	241077.48	14334.61	12589.76
Variance	3978331.05	3844975.92	1305268734.40	1147726627.42	34882786099.66	29204555983.69	97367884.25	67739724.34
Observations	26	35	26	35	26	35	26	35
df	54		52		51		48	
t Stat	2.12		0.91		0.07		0.73	
P(T<=t) one-tail	**0.02 (*)**		0.18		0.47		0.23	
t Critical one-tail	1.67		1.67		1.68		1.68	
P(T<=t) two-tail	**0.04 (*)**		0.37		0.94		0.47	
t Critical two-tail	2.00		2.01		2.01		2.01	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE B-0-7 FUNCTIONAL CLASS 12, SPEED LIMIT 55MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	2409.71	3696.95	46006.6	57729.9	55888.23	70619.11	2940.71	4455.09
Variance	1506363.33	4106011.43	485139480.50	835740679.12	885478801.88	1603645427.88	2618114.33	6642912.32
Observations	40	40	40	40	40	40	40	40
df	64		73		72		66	
t Stat	-3.44		-2.04		-1.87		-3.15	
P(T<=t) one-tail	**0.0005 (***)**		**0.02 (*)**		**0.03 (*)**		**0.001 (***)**	
t Critical one-tail	1.67		1.67		1.67		1.67	
P(T<=t) two-tail	**0.00 (***)**		**0.04 (*)**		0.07		**0.00 (***)**	
t Critical two-tail	2.00		1.99		1.99		2.00	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE B-0-8 FUNCTIONAL CLASS 14, ALL SPEEDS ARE INCLUDED (40MI/HR, 45MI/HR, 50MI/HR, 55MI/HR): RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	921.52	958.02	16660.64	17958.10	45234.18	47571.90	2607.02	2565.92
Variance	40552.91	143679.16	19640573.36	48997950.42	571202104.82	727598834.23	2282878.12	2538448.03
Observations	100	104	100	104	100	104	100	104
df	158		175		201		202	
t Stat	-0.86		-1.59		-0.66		0.19	
P(T<=t) one-tail	0.19		0.06		0.26		0.43	
t Critical one-tail	1.65		1.65		1.65		1.65	
P(T<=t) two-tail	0.39		0.11		0.51		0.85	
t Critical two-tail	1.98		1.97		1.97		1.97	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE B-0-9 FUNCTIONAL CLASS 16, ALL SPEEDS ARE INCLUDED (30MI/HR, 35MI/HR, 40MI/HR, 45MI/HR, 55MI/HR): RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	690.29	732.62	12369.45	13610.26	24931.46	28135.12	1369.45	1463.50
Variance	127251.61	166298.97	43859674.64	64398932.19	516627379.82	748796379.43	1393851.75	1844634.62
Observations	160	150	160	150	160	150	160	150
df	296		289		290		296	
t Stat	-0.97		-1.48		-1.12		-0.65	
P(T<=t) one-tail	0.17		0.07		0.13		0.26	
t Critical one-tail	1.65		1.65		1.65		1.65	
P(T<=t) two-tail	0.33		0.14		0.26		0.52	
t Critical two-tail	1.97		1.97		1.97		1.97	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE B-0-10 FUNCTIONAL CLASS 17, ALL SPEEDS ARE INCLUDED (30MI/HR, 35MI/HR, 40MI/HR): RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	452.4	693.71	9267.25	12245.7	13631.4	19967.4	668.62	1138.4
Variance	183764.37	253455.30	63897198.37	75379191.97	331176674.32	319354385.51	1026001.32	1146747.65
Observations	24	50	24	50	24	50	24	50
df	53		49		45		48	
t Stat	-2.14		-1.46		-1.41		-1.83	
P(T<=t) one-tail	**0.019 (*)**		0.076		0.08		**0.037 (*)**	
t Critical one-tail	1.67		1.68		1.68		1.68	
P(T<=t) two-tail	**0.04 (*)**		0.15		0.17		0.07	
t Critical two-tail	2.01		2.01		2.01		2.01	

Note: IEEE Style Tables Notes.
Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

Appendix C

Tables: the results of a Two-Sample t-Test Assuming Unequal Variances for travel outcomes by the Functional Class and Speed

TABLE C-0-1 FUNCTIONAL CLASS 2, SPEED 30 MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	492.3	445.7	8701.6	8058.9	33066	30624	1870.6	1693.8
Variance	1907.8	3199.3	300909.2	463001.7	4345128	6685744	27549.9	46197.9
Observations	10	10	10	10	10	10	10	10
df	17		17		17		17	
t Stat	2.06		2.33		2.33		2.06	
P(T<=t) one-tail	**0.02 (*)**		**0.01 (**)**		**0.016 (*)**		**0.027 (*)**	
t Critical one-tail	1.74		1.74		1.74		1.74	
P(T<=t) two-tail	**0.055**		**0.032 (*)**		**0.032 (*)**		**0.055**	
t Critical two-tail	2.11		2.11		2.11		2.11	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-2 FUNCTIONAL CLASS 2, SPEED 45 MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	293.1	255.6	5262.7	4600.6	15431	16937	866.5	924.17
Variance	1274.131	5270.019	144853.1	1542237	44294559	46188530	156189.8	115610.7
Observations	20	30	20	30	20	30	20	30
df	45		37		41		37	
t Stat	2.43		2.73		-0.78		-0.53	
P(T<=t) one-tail	**0.009 (**)**		**0.004 (**)**		0.22		0.29	
t Critical one-tail	1.679427		1.687		1.68		1.68	
P(T<=t) two-tail	**0.019 (*)**		**0.009 (**)**		0.441		0.59	
t Critical two-tail	2.01		2.03		2.02		2.03	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-3 FUNCTIONAL CLASS 2, SPEED 55 MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	396.6	404.6	7615.6	7722.6	29095.5	32534.1	1528.1	1723.3
Variance	27846.3	45005.9	9428420	16239233	67945703	2.5E+08	265885	795462.3
Observations	90	134	90	134	90	134	90	134
df	216		218		211		218	
t Stat	-0.32		-0.23		-2.12		-2.07	
P(T<=t) one-tail	0.37		0.41		**0.012 (*)**		**0.019 (*)**	
t Critical one-tail	1.65		1.653		1.65		1.65	
P(T<=t) two-tail	0.75		0.82		**0.034 (*)**		**0.04 (*)**	
t Critical two-tail	1.971		1.97		1.97		1.97	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-4 FUNCTIONAL CLASS 2, SPEED 60 MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	339	408.1	6519.6	8242.4	576.3	693.8	11083	14012
Variance	4885.075	1868.501	1806611	231497.6	14117.87	5399.966	5221105	669028.1
Observations	8	10	8	10	8	10	8	10
df	11		8		11		8	
t Stat	-2.45		-3.45		-2.45		-3.45	
P(T<=t) one-tail	**0.016 (*)**		**0.004 (**)**		**0.016 (*)**		**0.0043 (**)**	
t Critical one-tail	1.8		1.86		1.79		1.86	
P(T<=t) two-tail	**0.032 (*)**		**0.008 (**)**		**0.032 (*)**		**0.008 (**)**	
t Critical two-tail	2.2		2.3		2.2		2.31	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-5 FUNCTIONAL CLASS 2, SPEED 65 MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	272.65	303.37	4871.5	5597.2	20813.9	24374	1163.9	1310.4
Variance	21996.43	40813.71	5784352	9031468	85064734	1.4E+08	334848.8	619217.7
Observations	58	70	58	70	58	70	58	70
df	124		126		126		124	
t Stat	-0.99		-1.51		-1.91		-1.21	
P(T<=t) one-tail	0.16		0.07		**0.029 (*)**		0.11	
t Critical one-tail	1.65		1.65		1.657		1.657	
P(T<=t) two-tail	0.324		0.131		**0.058**		0.227	
t Critical two-tail	1.98		1.97		1.97		1.97	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-6 FUNCTIONAL CLASS 6, SPEED 45 MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	327.2	279.4	5969.3	4625.5	32097.8	23268.1	1774.4	1400.4
Variance	1476.21	31056.12	954412.24	6729060.67	1839323.78	219660217.11	18170.40	920570.62
Observations	20	30	20	30	20	30	20	30
df	33		40		30		31	
t Stat	1.44		2.58		3.24		2.10	
P(T<=t) one-tail	0.08		**0.01 (**)**		**0.00 (***)**		**0.02 (*)**	
t Critical one-tail	1.69		1.68		1.70		1.70	
P(T<=t) two-tail	0.16		**0.01 (**)**		**0.00 (***)**		**0.04 (*)**	
t Critical two-tail	2.03		2.02		2.04		2.04	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-7 FUNCTIONAL CLASS 6, SPEED 50 MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	94.6	102.8	1819	1721.5	10732.1	10156.9	558.07	606.79
Variance	38.69	95.02	14309	10876	498085	378580	1346.8	3307.7
Observations	10	10	10	10	10	10	10	10
df	15		18		18		15	
t Stat	-2.26		1.94		1.94		-2.26	
P(T<=t) one-tail	**0.02 (*)**		**0.03 (*)**		**0.03 (*)**		**0.02 (*)**	
t Critical one-tail	1.75		1.73		1.73		1.75	
P(T<=t) two-tail	**0.04 (*)**		0.07		0.07		**0.04 (*)**	
t Critical two-tail	2.13		2.10		2.10		2.13	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-8 FUNCTIONAL CLASS 6, SPEED 55 MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	277.48	322.59	4409.1	5003.3	11757.27	13585.5	779.58	909.03
Variance	9679.314	11992.29	1043506	1775966	1.07E+08	1.46E+08	530316.6	687735.7
Observations	20	20	20	20	20	20	20	20
df	38		36		37		37	
t Stat	-1.37		-1.58		-0.51		-0.52	
P(T<=t) one-tail	0.08		0.06		0.31		0.3	
t Critical one-tail	1.68		1.68		1.68		1.68	
P(T<=t) two-tail	0.178		0.12		0.61		0.6	
t Critical two-tail	2.02		2.028		2.02		2.02	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-9 FUNCTIONAL CLASS 7, SPEED 30MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	164.9	214.7	2747.1	3326.33	3697.6	4477.24	222.06	288.93
Variance	118.09	1584.67	8056.54	200070.67	14596.17	362471.23	213.95	2870.96
Observations	10	6	10	6	10	6	10	6
df	5		5		5		5	
t Stat	-2.99		-3.13		-3.13		-2.99	
P(T<=t) one-tail	**0.02 (*)**		**0.01 (**)**		**0.01 (**)**		**0.02 (*)**	
t Critical one-tail	2.02		2.02		2.02		2.02	
P(T<=t) two-tail	**0.03 (*)**		**0.03 (*)**		**0.03 (*)**		**0.03 (*)**	
t Critical two-tail	2.57		2.57		2.57		2.57	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-10 FUNCTIONAL CLASS 7, SPEED 50MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	56.50	58.30	912.05	871.65	2898.62	2871.72	170.69	183.63
Variance	68.84	103.38	6880.05	16279.50	6942102.56	6930252.11	23407.92	27803.19
Observations	20	20	20	20	20	20	20	20
df	37		33		38		38	
t Stat	-0.61		1.19		0.03		-0.26	
P(T<=t) one-tail	0.27		0.12		0.49		0.40	
t Critical one-tail	1.69		1.69		1.69		1.69	
P(T<=t) two-tail	0.54		0.24		0.97		0.80	
t Critical two-tail	2.03		2.03		2.02		2.02	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-11 FUNCTIONAL CLASS 8, SPEED 25MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	302.5	419.6	5238.2	6695	16762.2	21424	967.9	1342.9
Variance	782.73	11402.65	162679.29	2100504.89	1665835.92	21509170.06	8015.12	116763.09
Observations	10	10	10	10	10	10	10	10
df	10		10		10		10	
t Stat	-3.36		-3.06		-3.06		-3.36	
P(T<=t) one-tail	**0.003 (**)**		**0.01 (**)**		**0.01 (**)**		**0.003 (**)**	
t Critical one-tail	1.81		1.81		1.81		1.81	
P(T<=t) two-tail	**0.01 (**)**		**0.01 (**)**		**0.01 (**)**		**0.01 (**)**	
t Critical two-tail	2.23		2.23		2.23		2.23	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-12 FUNCTIONAL CLASS 8, SPEED 45MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	47.76	183.29	799	3459.11	846.14	17997.71	50.57	926.84
Variance	26.13	22139.20	3516.67	8945000.32	3943.87	358625400.43	29.30	933426.72
Observations	10	19	10	19	10	19	10	19
df	18		18		18		18	
t Stat	-3.97		-3.88		-3.95		-3.95	
P(T<=t) one-tail	**0.0005 (***)**		**0.0006 (***)**		**0.0005 (***)**		**0.0005 (***)**	
t Critical one-tail	1.73		1.73		1.73		1.73	
P(T<=t) two-tail	**0.0009 (***)**		**0.0011 (**)**		**0.0009 (***)**		**0.0009 (***)**	
t Critical two-tail	2.10		2.10		2.10		2.10	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-13 FUNCTIONAL CLASS 8, SPEED 55MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	538.75	395.9	10487.7	7617.3	39853.26	27926.48	2047.23	1438.17
Variance	1101.70	7623.80	202720.23	7102277.91	2927280.17	123981103.61	15908.59	145629.36
Observations	10	20	10	20	10	20	10	20
df	27		21		21		26	
t Stat	6.44		4.68		4.68		6.47	
P(T<=t) one-tail	**0.0000003 (***)**		**0.00006 (***)**		**0.00006(***)**		**0.0000004 (***)**	
t Critical one-tail	1.70		1.72		1.72		1.71	
P(T<=t) two-tail	**0.0000007(***)**		**0.0001 (***)**		**0.00012(***)**		**0.0000007(***)**	
t Critical two-tail	2.05		2.08		2.08		2.06	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-14 FUNCTIONAL CLASS 11, SPEED 55MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	8385.87	7975.75	152470.30	157699.00	468083.82	484135.93	25744.61	24485.56
Variance	523820.09	256951.64	173163654.46	428082603.43	1632050126.88	4034635729.05	4936951.99	2421743.52
Observations	10	8	10	8	10	8	10	8
df	16		11		11		16	
t Stat	1.41		-0.62		-0.62		1.41	
P(T<=t) one-tail	0.09		0.27		0.27		0.09	
t Critical one-tail	1.75		1.80		1.80		1.75	
P(T<=t) two-tail	0.18		0.55		0.55		0.18	
t Critical two-tail	2.12		2.20		2.20		2.12	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-15 FUNCTIONAL CLASS 11, SPEED 65MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	6937.87	7479.74	97033.1	104611.71	145549.65	156917.57	10406.8	11219.61
Variance	23010.30	252597.50	4501012.10	49410244.57	10127277.23	111173050.29	51773.17	568344.38
Observations	10	7	10	7	10	7	10	7.
df	7		7		7		7	
t Stat	-2.77		-2.77		-2.77		-2.77	
P(T<=t) one-tail	**0.01 (**)**		**0.01 (**)**		**0.01 (**)**		**0.01 (**)**	
t Critical one-tail	1.89		1.89		1.89		1.89	
P(T<=t) two-tail	**0.03 (*)**		**0.03 (*)**		**0.03 (*)**		**0.03 (*)**	
t Critical two-tail	2.36		2.36		2.36		2.36	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-16 FUNCTIONAL CLASS 11, SPEED 70MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	3402.03	3973.85	66706.5	80692.55	36555.16	173310.06	1864.31	8310.99
Variance	60321.34	244418.39	23191596.30	95968585.42	6964529.14	18420917972.74	18114.74	40600520.33
Observations	6	20	6	20	6	20	6	20
df	18		18		19		19	
t Stat	-3.83		-4.75		-4.50		-4.52	
P(T<=t) one-tail	**0.00061 (***)**		**0.00008 (***)**		**0.00012 (***)**		**0.00012 (***)**	
t Critical one-tail	1.73		1.73		1.73		1.73	
P(T<=t) two-tail	**0.00122 (**)**		**0.00016 (***)**		**0.00024 (***)**		**0.00023 (***)**	
t Critical two-tail	2.10		2.10		2.09		2.09	

Note: IEEE Style Tables Notes.

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-17 FUNCTIONAL CLASS 14, SPEED 40MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	778.10	715.88	13426.30	11303.81	19696.38	16573.27	1141.47	1049.59
Variance	6667.28	177816.32	1196315.34	40930952.96	2574577.09	88312938.08	14348.57	383582.95
Observations	10	16	10	16	10	16	10	16
df	17		16		16		17	
t Stat	0.57		1.30		1.30		0.58	
P(T<=t) one-tail	0.29		0.11		0.11		0.29	
t Critical one-tail	1.74		1.75		1.75		1.74	
P(T<=t) two-tail	0.57		0.21		0.21		0.57	
t Critical two-tail	2.11		2.12		2.12		2.11	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-18 FUNCTIONAL CLASS 14, SPEED 45MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	961.54	1016.32	16917.13	19311.93	49219.39	50420.81	2825.74	2542.29
Variance	38254.00	151179.26	12187141.91	37943308.13	1021008249.05	1006060316.42	3403881.61	2445854.88
Observations	30	30	30	30	30	30	30	30
df	43		46		58		56	
t Stat	-0.69		-1.85		-0.15		0.64	
P(T<=t) one-tail	0.25		**0.04 (*)**		0.44		0.26	
t Critical one-tail	1.68		1.68		1.67		1.67	
P(T<=t) two-tail	0.49		0.07		0.88		0.52	
t Critical two-tail	2.02		2.01		2.00		2.00	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-19 FUNCTIONAL CLASS 14, SPEED 50MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	892.84	937.44	17033.30	18219.63	45854.60	51099.61	2645.52	2856.06
Variance	51326.69	93066.30	33881280.06	46898780.13	464479514.56	510815574.77	2516403.60	3005323.36
Observations	40	38	40	38	40	38	40	38
df	68		73		75		75	
t Stat	-0.73		-0.82		-1.05		-0.56	
P(T<=t) one-tail	0.23		0.21		0.15		0.29	
t Critical one-tail	1.67		1.67		1.67		1.67	
P(T<=t) two-tail	0.47		0.41		0.30		0.58	
t Critical two-tail	2.00		1.99		1.99		1.99	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-20 FUNCTIONAL CLASS 14, SPEED 55MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	990.58	1103.37	17147.75	20753.85	50784.42	61394.81	2934.71	3263.18
Variance	24294.16	148704.19	7472059.36	35517456.24	61692046.69	296293689.21	205421.11	1255392.55
Observations	20	20	20	20	20	20	20	20
df	25		27		27		25	
t Stat	-1.21		-2.46		-2.51		-1.22	
P(T<=t) one-tail	0.12		**0.01**		**0.009**		0.12	
t Critical one-tail	1.71		1.70		1.70		1.71	
P(T<=t) two-tail	0.24		0.02		0.02		0.24	
t Critical two-tail	2.06		2.05		2.05		2.06	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-21 FUNCTIONAL CLASS 16, SPEED 30MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	402.87	443.17	6556.30	6920.87	7124.88	6605.76	443.56	426.08
Variance	6543.13	13663.53	951338.33	2937784.55	22411426.95	7949746.41	95030.60	37682.10
Observations	20	15	20	15	20	15	20	15
df	24		21		32		32	
t Stat	-1.15		-0.74		0.40		0.21	
P(T<=t) one-tail	0.13		0.23		0.34		0.42	
t Critical one-tail	1.71		1.72		1.69		1.69	
P(T<=t) two-tail	0.26		0.47		0.69		0.84	
t Critical two-tail	2.06		2.08		2.04		2.04	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-22 FUNCTIONAL CLASS 16, SPEED 35MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	583.72	500.13	11305.55	9897.83	3694.16	3211.28	189.28	157.24
Variance	30139.97	41981.98	12594578.05	23531323.54	5104618.37	5798677.93	12821.88	11119.58
Observations	20	24	20	24	20	24	20	24
df	42		41		41		39	
t Stat	1.46		1.11		0.69		0.96	
P(T<=t) one-tail	0.08		0.14		0.25		0.17	
t Critical one-tail	1.68		1.68		1.68		1.68	
P(T<=t) two-tail	0.15		0.27		0.50		0.34	
t Critical two-tail	2.02		2.02		2.02		2.02	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-23 FUNCTIONAL CLASS 16, SPEED 40MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	865.73	849.80	15126.83	15395.46	23845.64	23401.89	1349.70	1255.33
Variance	155310.81	194338.87	47629725.19	61951426.74	235161763.85	263288619.82	709070.23	653115.10
Observations	60	54	60	54	60	54	60	54
df	107		106		109		112	
t Stat	0.20		-0.19		0.15		0.61	
P(T<=t) one-tail	0.42		0.42		0.44		0.27	
t Critical one-tail	1.66		1.66		1.66		1.66	
P(T<=t) two-tail	0.84		0.85		0.88		0.54	
t Critical two-tail	1.98		1.98		1.98		1.98	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-24 FUNCTIONAL CLASS 16, SPEED 45MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	780.4	996.4	14269.3	19076.2	33410.7	45194.2	1837.5	2301.3
Variance	104530.08	147555.71	49214408.57	75979259.40	396002372.37	763452404.27	1132308.33	1977615.44
Observations	40	37	40	37	40	37	40	37
df	71		69		65		67	
t Stat	-2.66		-2.65		-2.13		-1.62	
P(T<=t) one-tail	**0.0048 (**)**		**0.005 (**)**		**0.02 (*)**		**0.05 (*)**	
t Critical one-tail	1.67		1.67		1.67		1.67	
P(T<=t) two-tail	**0.01 (**)**		**0.01 (**)**		**0.04 (*)**		0.11	
t Critical two-tail	1.99		1.99		2.00		2.00	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-25 FUNCTIONAL CLASS 16, SPEED 55MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	377.8	424.3	7174.7	8150.2	50274.3	55411.1	2598.7	2821.3
Variance	15425.68	12503.34	7790647.40	6243880.03	1113081692.62	1114163459.42	2608992.92	2420192.77
Observations	20	20	20	20	20	20	20	20
df	38		38		38		38	
t Stat	-1.24		-1.16		-0.49		-0.44	
P(T<=t) one-tail	0.11		0.13		0.31		0.33	
t Critical one-tail	1.69		1.69		1.69		1.69	
P(T<=t) two-tail	0.22		0.25		0.63		0.66	
t Critical two-tail	2.02		2.02		2.02		2.02	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-26 FUNCTIONAL CLASS 17, SPEED 30MI/HR: RESULTS OF A TWO-SAMPLE t-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	272.6	358	6186.6	6927.6	6025.5	6966.7	236.5	344.4
Variance	12620.40	102752.08	16334318.37	49370192.53	30829662.55	73436224.42	37337.17	162598.71
Observations	20	30	20	30	20	30	20	30
df	39		47		48		44	
t Stat	-1.34		-0.47		-0.47		-1.26	
P(T<=t) one-tail	0.09		0.32		0.32		0.11	
t Critical one-tail	1.68		1.68		1.68		1.68	
P(T<=t) two-tail	0.19		0.64		0.64		0.21	
t Critical two-tail	2.02		2.01		2.01		2.02	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

TABLE C-0-27 FUNCTIONAL CLASS 17, SPEED 40MI/HR: RESULTS OF A TWO-SAMPLE T-TEST ASSUMING UNEQUAL VARIANCES FOR TRAVEL OUTCOMES.

	FlowBfr	FlowAft	AADTBfr	AADTAft	VMTBfr	VMTAft	VMTPkBfr	VMTPkAft
Mean	1351	1185	246701	20864	51661	43688	2829	2482.2
Variance	36358.89	52245.30	6799338.25	5557154.50	29813983.13	24367211.11	159427.77	229087.09
Observations	4	10	4	10	4	10	4	10
df	7		5		5		7	
t Stat	1.39		2.54		2.54		1.39	
P(T<=t) one-tail	0.104		**0.026 (*)**		**0.026 (*)**		0.104	
t Critical one-tail	1.89		2.02		2.02		1.89	
P(T<=t) two-tail	0.208		**0.052**		**0.052**		0.208	
t Critical two-tail	2.36		2.57		2.57		2.36	

Reason for asterisk (-significant at 0.05, **- significant at 0.01, ***- significant at 0.001.)

Appendix D

Table D-0-1 Factor Analysis Model Estimation Results

Variables	*Estimate*	*SE*	*t-statistic*	*P-Value*
Household Characteristics				
Average Household Size	0.33	0.15	2.22	0.00
Average Household Workers	0.79	0.28	2.88	0.00
Average Household Income	-1.11	0.28	-3.86	0.00
Employment Characteristics				
Employment Density	1.35	0.24	5.70	0.00
Food Service Employment Ratio	0.71	0.13	5.33	0.00
Basic Employment Ratio	-1.01	0.48	-2.10	0.04
Governmental Employment Ratio	-1.18	0.39	-3.03	0.00
Population Characteristics				
Population Density	-0.76	0.23	-3.32	0.01
*Population Density*Employment Density*	-0.67	0.16	-4.22	0.00
Project Characteristics				
Project Length	-0.99	0.27	-3.65	0.00
Road Characteristics				
*Urban Principal Arterial(0)*Speed Limit*	-0.81	0.21	-3.86	0.00
*Urban Principal Arterial(1)*Speed Limit*	1.22	0.35	3.50	0.00
Threshold Coefficients				
No IT|Approaching IT(Intercept)	4.64	0.41	11.25	0.00
Approaching IT|Presence of IT(Intercept)	5.73	0.45	12.68	0.00

N = 1,239
Level of significance (P-value): < 0.05
Initial log-likelihood: -320.98
Final log-likelihood: -212.10
AIC Value: 452.20
McFadden R2: 0.34