GEORGIA DOT RESEARCH PROJECT 24-08

FINAL REPORT

LIFECYCLE ECONOMIC AND ENERGY EFFICIENCY BENEFITS OF MANAGED LANE CORRIDORS IN METRO ATLANTA

Office of Performance-based Management and Research
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16. Abstract:

This report describes the development of a spreadsheet-based modeling framework for calculating lifecycle economic and energy costs of new Express Lane facilities. The report discusses relevant background information, spreadsheet-based model structures, and development of spreadsheet calculation methodologies. The report also describes the development of a PTV VISSIM™ model for the project case study, in which the team applied the modeling framework to reversible Express Lanes constructed in Metro Atlanta Georgia on the Northwest Corridor (NWC), comparing the results to a synthetic corridor expansion project that would have constructed new general-purpose lanes on both sides of the corridor (two new inbound lanes + two new outbound lanes) instead of constructing only two reversible lanes. Total lifecycle costs and energy use include energy embedded in infrastructure, energy used in construction, on-road energy consumed by different vehicle classes (e.g., passenger cars and trucks) under different congestion conditions, and energy associated with Managed Lane operations and maintenance. The tools and results from this project will help planners better understand the benefits and tradeoff opportunities with the expansion of Georgia's Express Lanes systems, will help generate information for NEPA EA/EIS analyses, and support public engagement efforts.

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Final Report

LIFECYCLE ECONOMIC AND ENERGY EFFICIENCY BENEFITS OF MANAGED LANE CORRIDORS IN METRO ATLANTA

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATION

ABM	Activity-Based Model
AASHTO	American Association of State Highway and Trans. Officials
AERMOD	American Meteorological Society / EPA Regulatory Model
APA	Administrative Procedure Act
ARC	Atlanta Regional Commission
CE	Categorical Exclusion
CO	Carbon Monoxide
CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
COM	Component Object Model
DBF	Design-Build-Finance
DEIS	Draft Environmental Impact Statement
DNR	Department of Natural Resources
DOT	Department of Transportation
DTA	Dynamic Traffic Assignment
EA	Environmental Assessment
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FEIS	Final Environmental Impact Statement
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
GP	General-Purpose

HDT	Heavy-Duty Truck
HDV	Heavy-Duty Vehicle
HOV	High-Occupancy Vehicle
HOT	High-Occupancy Toll
HPC	High-Performance Computing
I/M	Inspection and Maintenance
ITS	Intelligent Transportation Systems
LDV	Light-Duty Vehicle
LCCA	Life-Cycle Cost Analysis
LS	Lump Sum
MDT	Medium-Duty Truck
MDV	Medium-Duty Vehicle
ML	Managed Lanes
MnPASS	Minnesota Pay-As-You-Go Express Lanes
MOVES	MOtor Vehicle Emissions Simulator (USEPA Model)
MOVES3	MOVES Version 3
MOVES5	MOVES Version 5
MOVES2014a	MOVES 2014a Version
NEPA	National Environmental Policy Act
NOX	Oxides of Nitrogen
NWC	Northwest Corridor
O-D	Origin-Destination
PACE	Partnership for an Advanced Computing Environment

PM10	Particulate Matter (10 Microns or less in aerodynamic diameter)
PM2.5	Particulate Matter (2.5 Microns or less in aerodynamic diameter)
PTV	Planung Transport Verkehr (German Software Company)
QPL	Qualified Product List
RBC	Ring Barrier Controller
ROW	Right-of-Way
SR	State Route
SRTA	State Road and Tollway Authority
STIP	State Transportation Improvement Program
TCM	Transportation Control Measure
TIFIA	Transportation Infrastructure Finance and Innovation Act
TNM	Traffic Noise Model
USDOT	United States Department of Transportation
USEPA	United States Environmental Protection Agency
VISSIM	PTV's Microscopic Traffic Simulation Software
VSL	Variable Speed Limit
VSP	Vehicle Specific Power
VOC	Volatile Organic Compounds

EXECUTIVE SUMMARY

Traditional freeway capacity expansion projects come with significant capital costs associated with construction and land acquisition. Construction of reversible lane corridors can provide the same capacity expansion effect, at significantly reduced capital costs. With reversible lanes, the same infrastructure can serve a peak travel demand inbound from suburbs into the central city in the morning and outbound from the central city to the suburbs in the afternoon. While the cost per lane-mile may be higher due to constructing cantilevered sections and flyovers that might not otherwise be necessary, the system requires less land acquisition and results in the construction of fewer lanes-miles. Reversible managed lanes that employ dynamic toll pricing also minimize congestion and allow vehicles to operate under their most efficient operating conditions, lowering vehicle energy use and saving travelers time and money. When tolls are collected, reversible Express Lane facilities can also generate revenue to help offset the cost of capacity expansion. Systems designed to quantify the costs and benefits of reversible lane systems will provide agencies with information that can be considered in the managed lane system decision-making process and selection of project alternatives.

The research summarized in this report has resulted in the development of a spreadsheet-based modeling tool to support the quantification of lifecycle costs and benefits of managed lanes corridor configurations. The report then describes how the modeling tool can be applied to a variety of projects, including complex Express Lanes projects, traditional at-grade corridor conversion to limited access highways, corridor traffic signal coordination, and the development of categorical exclusion for HOV-to-HOT conversion projects. To demonstrate how the modeling system can be employed, the research team then performed a lifecycle economic and energy assessment for the I-75 Northwest Corridor (NWC) Express Lanes (two reversible lanes inbound toward Atlanta in the morning and outbound in the afternoon) to an alternative operational design that would have added two general-purpose lanes to both sides of the corridor (i.e., two new inbound lanes plus two new outbound lanes providing roughly equivalent capacity expansion). The case-study demonstration also shows how the spreadsheet-based modeling tool supports the use of regional travel demand model outputs coupled with corridor-level PTV VISSIM™ simulation for the reversible lane facility and for the hypothetical general-purpose-lane expansion. Total lifecycle costs and energy use include embodied energy in infrastructure, energy used in construction, on-road energy consumed by vehicles (freight, passenger cars, and transit) during operations, and energy use associated with Managed Lane operations, on a per vehicle mile traveled basis, across the various system elements and lifecycle stages.

This report describes the process of developing a spreadsheet-based model for calculating lifecycle economic and energy costs for Express Lane facilities, including relevant background information, calculation methodologies, and model structure. The report describes a variety of applicable scenarios to which the model can be applied, describes the development of the detailed case study scenarios for the current NWC reversible lanes and the synthetic corridor expansion project, and describes the results of the case study simulations. The tools and results from this project will help planners better understand the benefits and tradeoff opportunities with the expansion of Georgia's Express Lanes systems, help generate information for NEPA EA/EIS analyses, and support public engagement efforts.

CHAPTER 1. INTRODUCTION

“Managed Lanes” is a term that encompasses a variety of freeway corridor designs and operation strategies that typically manage which users (or vehicle types) may access the corridor, what times of day specific users may access the corridor, and often how much specific users will have to pay to access the corridor. Managed lanes include traditional high-occupancy vehicle (HOV) carpool lanes, traditional toll facilities, high-occupancy toll (HOT) lanes, dynamically priced express toll lanes, and reversible facilities (with or without tolls) that serve traffic at different times of day. Since the 1950s, managed lanes across the United States and abroad have proven to enhance mobility in highly congested freeways, increase vehicle throughput, and improve travel time reliability.

The development of managed lane systems, especially with dynamic pricing, can increase effective corridor capacity at a much lower cost of construction than capacity expansion via traditional lane addition. The effects of congestion are non-linear, in that once demand exceeds the effective capacity of a freeway, both speeds and traffic volumes drop to low levels and congestion queues form on the roadway until decreased demand is sufficient to clear the backlog of congested traffic. As congestion increases on general-purpose lanes, demand for unconstrained travel increases, and users choose to pay a toll on the managed lane facility to access faster travel speeds (where their willingness to pay is a function of their value of travel time and perception of cost savings relative to the toll). The shift of travel from congested general-purpose lanes onto a managed lane can lead to congestion on the managed lane and ultimately in demand exceeding capacity on the toll lane as well. In response, the managed lane system increases the toll price to manage demand and ensures that demand never exceeds the capacity of the managed lane system (typically striving to maintain a minimum of 45 mph on the managed lane facility, which ensures that managed lanes speeds and flows do not drop). Economic benefits are potentially even greater for reversible managed lane facilities, where each peak direction of travel is served by the same additional capacity, inbound to the center city in the morning and outbound to the suburbs in the evening.

Freeway capacity expansion projects typically come with significant costs associated with overpass reconstruction and land acquisition (unless new lanes are being added within infrastructure that had already been designed to accommodate the expansion when the facility was originally designed and constructed). However, properly designed reversible lane corridors can provide the same expansion of inbound-outbound capacity with fewer lanes and less land acquisition. Even though the non-traditional construction design aspects that are often associated with reversible lane facilities cost more per-mile to construct (elevated flyover facilities, cantilevered lanes, special entry/exit designs, and access/safety technology infrastructure), the net construction costs for a reversible facility tends to be much lower, given only about half the lane miles need to be constructed to provide the same inbound/outbound roadway capacity expansion. With reversible lanes, transportation system operators must also absorb (or charge a fee to cover) the higher operating costs associated with reversing operational direction each day. Nevertheless, reversible lane facilities can come with significantly lower land acquisition and construction costs, and slightly higher operational costs for a reversible facility, and deliver the same congestion reduction benefits. Furthermore, reversible managed lanes with dynamic pricing designed to minimize congestion formation allow vehicles to operate under their most efficient operating conditions, lowering vehicle energy use and saving travelers time and money.

Relatively little research has been conducted to investigate and quantify the lifecycle costs and benefits of operational managed lane strategies. Quantifying these costs and benefits should provide agencies with better information that can be considered in the managed lane system decision-making process and selection of project alternatives. This research develops a spreadsheet-based modeling tool designed to support the quantification of lifecycle costs and benefits of managed lanes corridor configurations. The team then discusses four use-case examples (Express Lane corridors, traditional at-grade corridor conversion to a limited access facility, corridor traffic signal coordination, and the development of a HOV-to-HOT categorical exclusion under NEPA. The report then applies the tool to assess the specific costs and benefits of the reversible Northwest Corridor Express Lanes.

In this project, the research team performed a lifecycle economic and energy assessment of the I-75 Northwest Corridor Express Lanes (reversible lanes facility with tolling) against a reasonably equivalent corridor expansion project that would have added two non-reversible general-purpose lanes to both sides of the corridor. To support operations analysis, this research team implemented a PTV VISSIM™ simulation model for the NWC to compare on-road operations for the reversible lane facility constructed on the NWC (two reversible lanes inbound in the AM and outbound in the PM) and an alternative operational design that added two lanes on both sides of the corridor (two new inbound lanes + two new outbound lanes). Total lifecycle costs and energy use include energy embedded in infrastructure, energy used in construction, on-road energy consumed by vehicles (freight, passenger cars, and transit) during operations, and energy associated with Managed Lane operations, and maintenance, on a per vehicle mile traveled basis across the various system elements and lifecycle stages.

This report describes the process of developing a spreadsheet-based model for calculating lifecycle economic and energy costs for Express Lanes facilities, including relevant background information, calculation methodologies, and model structure. The report also describes the development of a synthetic corridor expansion project that provides similar expansion of capacity in each direction for the Northwest Corridor and simulates system performance given current monitored corridor travel data using PTV VISSIM™. Total on-road vehicle activity, energy use, travel time costs are modeled for the current Express Lanes using activity data outputs from the Atlanta Regional Commission's activity-based travel demand model, previously collected vehicle classification data for the corridor, and MOVES energy use and emission rates. These results are compared to the simulation results for the synthetic general-purpose lanes expansion. Finally, the spreadsheet-based model is used to compare lifecycle costs and benefits associated with the Northwest Corridor and synthetic corridor projects.

A variety of specialized modeling software tools have been integrated within, or linked to, the spreadsheet modeling tool, to enhance the accuracy of calculations made within the spreadsheet. For example, On-road energy use and pollutant emissions rates from USEPA's MOtor Vehicle Emissions Simulator (MOVES), as discussed in Chapter 4, have been adapted and integrated for the calculation of materials transport costs and other construction and maintenance activities, as well as for the calculation of on-road energy use and emissions across design alternatives. Chapters 5 and 6 provide an overview of how the various modeling tools work together and have been integrated as algorithms in the spreadsheet structure. Chapter 7 describes four use-case analyses that can be performed using the modeling tool. Finally, as an example of how vehicle activity data can be employed in the analytical framework, outputs from PTV VISSIM™ scenario analysis for the current reversible roadway design and an alternative construction scenario which would have added new inbound and outbound lanes to all directions (and the resulting traffic volumes, operating speeds, etc.) have been integrated to show how the tool can be used to assess energy use impacts of the on-road conditions that flow into the network structure of the spreadsheet (Chapters 8 and 9).

The tools and results from this project will help planners better understand the benefits and tradeoff opportunities with the expansion of Georgia's Express Lanes systems, will help generate information for NEPA EA/EIS analyses, and support public engagement efforts.

CHAPTER 2. BACKGROUND ON MANAGED LANES

Managed Lanes are freeway or highway lanes operated with temporary or permanent restrictions associated with the cost of using the lane, the types of vehicles permitted to use the lane, and/or the availability of the lane itself. Common examples are described in Table 1 (derived from Fuhs, 2023a and 2023b).

Table 1: Common Managed Lane Examples

Type of Managed Lane	Description of Managed Lane
Toll Lane	Vehicles are charged a fixed toll to use the lane.
Dynamic Tolling Lane	Vehicles are charged a toll to use the lane. The toll price varies based on traffic congestion to maintain a desired traffic flow rate.
High Occupancy Vehicle (HOV) Lane	Access is restricted to vehicles with a certain minimum number of occupants (typically 2+ or 3+). HOV restrictions can be permanent, or only in effect for specific times / days (e.g., 6 AM to 9 AM Monday to Friday).
High Occupancy Toll (HOT) Lane	Tolls are assessed for vehicles that carry fewer than the minimum number of occupants (typically 2+ or 3+). Tolls can be fixed or dynamic.
Vehicle Class Restricted Lanes	Access is restricted to a specific class of vehicle (e.g., bus only, truck only). Alternatively, access can be granted to every vehicle class except for a specific class of vehicle (e.g., trucks prohibited).
Dynamic Shoulder Lanes	Shoulder lanes that may be used as travel lanes during peak congestion hours.
Reversable Lanes	Lanes that reverse directionality to accommodate increased traffic in one direction of travel, as may be common with morning and evening rush hour commuting patterns.

Managed lanes date back to the 1960s with the implementation of exclusive busways, such as the Shirley Highway busway in Virginia (Federal Highway Administration, 2020). Further experimentation in the late 1960s and 1970s led to the first contraflow bus lane on Route 495 in 1970 and later busways (Fuhs 2023a). High-occupancy vehicle

(HOV) lanes came after the bus lanes in 1969 to improve traffic flow and encourage carpooling (Federal Highway Administration, 2021). HOV lanes became more popular in the 1970s to encourage carpooling as a mitigation strategy for volatile oil prices. Managed lanes continued to evolve throughout the late 20th century and early 21st century through the introduction of new managed lane types and through the optimization of managed lane utility through dynamic management.

Managed lanes can be an effective strategy for making highways and roadways more efficient, both for users of the managed lanes and for users of adjacent general-purpose lanes. A Georgia State Road and tollway Authority (SRTA) study conducted by the Georgia Institute of Technology found that managed lanes construction in the Northwest Corridor (NWC) increased person throughput and overall reduced congestion on general-purpose lanes (Guensler et al., 2022a, Guensler et al., 2022b), providing benefits for users and non-users of the managed lanes.

While many people utilize and prioritize the use of managed lanes, there are several deterrents to consider. There is a public perception that managed lanes are inconsistent and not equally fair for all users (HNTB Corporation, 2010). Inconsistent pricing structures and a lack of convenience for shorter trips may dissuade people from using these corridors. Toll pricing may deter low-income drivers from using managed lanes, especially during peak hours. However, previous studies have found many drivers from lower income households do use tolled managed lanes, particularly in circumstances in which the driver’s time is more valuable than the cost of the toll, such as running late to work. When managed lanes reduce congestion on adjacent general-purpose lanes, all user groups benefit from the service expansion. However, these usage patterns can be difficult to predict, which may make it difficult to manage dynamic systems efficiently.

Managed lanes provide consumer options, and traffic congestion without managed lanes would be even worse than what we see today. Furthermore, most managed lanes are scalable and can be expanded to adjacent general-purpose lanes as needed in the future. Hence, managed lanes corridors can handle the new increased demand of users and can support the prevention of sprawling land use development. However, studies also show that when HOV lanes are constructed, there is also an increase in housing consumption further away from city centers which may also contribute to sprawl (Zhao, 2020). The studies performed by Georgia Tech for SRTA also noted significant expansion of the commutershed area and a slight reduction in vehicle occupancy (persons per vehicle) when new managed lane facilities open (Guensler, et al, 2022a, 2022b). Hence, there is a balance to consider between land use, congestion relief, and pricing.

GEORGIA'S NORTHWEST CORRIDOR EXPRESS LANES

The I-75 / I-575 Northwest Corridor (NWC) is a region of Interstate 75 and Interstate 575 in the northwest quadrant of metro Atlanta. This study area consists of 29.7 miles of highway and contains two reversable express toll lanes on I-75, as well as one reversable express toll lane on I-575. The NWC was developed under a Design-Build-Finance (DBF) agreement between Archer Western Contractors, The Hubbard Group, Parsons Corporation, and the Georgia State Road and Tollway Authority. An overview of the NWC project location can be seen in Figure 1.

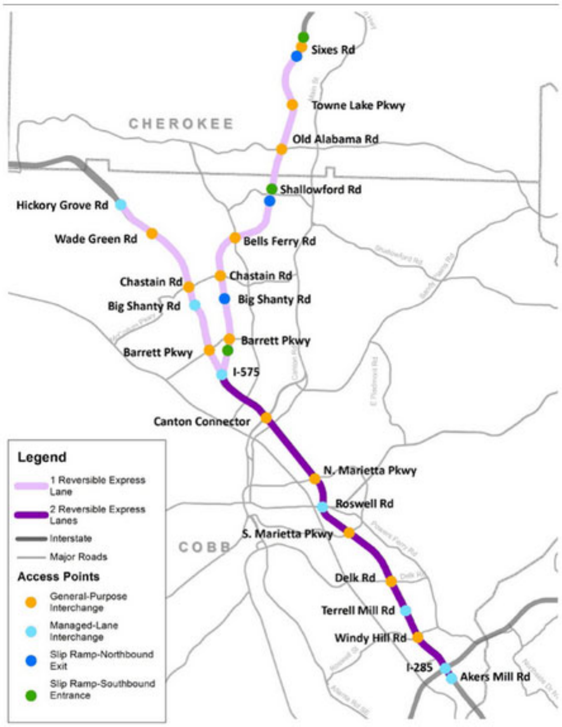

Figure 1: Map. I-75/575 Managed Lanes Corridor

The planning phase of the NWC project was initiated in 2004 with the completion of the Notice of Intent to prepare an Environmental Impact Statement. The final Environmental Impact Statement was submitted in 2011, with the Record of Decision issued in 2013. Construction began in November 2013 and was completed in June 2019.

SRTA was given the authority to provide financing for the project, as well as responsibility for designing, implementing, and operating tolling facilities on the NWC. Georgia Department of Transportation was responsible for overseeing the design and construction of all non-tolling components of the project.

Northwest Corridor Financing

The original Northwest Corridor Financial Plan (Georgia Department of Transportation, 2014) detailed the anticipated project expenses, anticipated sources of funding, and anticipated tolling revenues from the project. In total, the 2014 financial plan anticipated approximately $835,000,000 in total project expenses, including approximately $600,000,000 in design-build finance costs, approximately $110,000,000 in agency and administrative costs, approximately $60,000,000 in PE/ROW costs, and approximately $37,000,000 in prior costs. An additional $23,000,000 in contingency cost was included in the overall anticipated project cost (about 3% of the total cost).

Various state and federal funding sources were proposed for financing the NWC project with a $275,000,000 loan secured from the United States Department of Transportation through the Transportation Infrastructure Finance and Innovation Act (TIFIA), and $236,000,000 allocated to the project through Georgia's State Transportation Improvement Program (STIP). Remaining expenses were to be paid for using revenue from Georgia's state motor fuel taxes. However, the decision was made to instead finance the project via an at-risk public private partnership arrangement with Northwest Express Roadbuilders, a joint venture between Archer Western Contractors, LLC, and Hubbard Construction Company (Georgia Department of Transportation, 2013).

Northwest Corridor Design Evolution

The initial purpose and need for the NWC managed lane project was rooted in a desire to increase travel capacity. Between 1990 and 2000, the regions served by the NWC experienced a 39% increase in population and a 60% increase in employment opportunities, resulting in existing transportation infrastructure becoming overburdened.

Original concepts proposed a combination of new highway lanes as well as additional heavy and light rail capacity to facilitate the movement of people and goods throughout the region.

As the project progressed, funding constraints became a more prominent factor, and the project goals were refined. Instead of purely focusing on maximizing capacity, emphasis was placed on increasing reliability and the predictability of travel times, as well as improving congestion, air quality, and connectivity between regional centers that had been disconnected due to congestion, such as Cumberland and Marietta. The DEIS (2007) and FEIS (2011) recognized that it would have been financially infeasible to add additional capacity through a traditional widening project and identified a managed lane public private partnership scenario as an alternative that best balanced the project objectives with existing financial constraints.

Northwest Corridor Economic Assessments

Cost estimation varied a great deal throughout the planning phase of the project, largely due to fluctuating right of way acquisition costs and shifting design goals. Initial estimates in 2004 predicted a total cost of $1.083 billion dollars for an alternative that restricted new construction to be within the existing highway median, including $423 million in construction costs and $253 million in right-of-way acquisition costs. On the other hand, the alternative that placed new lane construction on the shoulders of each travel direction and the alternative that placed new lane construction on the west side of the exiting highway were projected to cost $1.141 billion and $1.413 billion, respectively. The latter two alternatives both had larger expected construction costs, and the west side construction scenario had a substantially larger right-of-way acquisition cost because it would be necessary to acquire high-value commercial real estate adjacent to the existing freeway.

By 2007, the project scope had expanded greatly to include separate truck only lanes, bus rapid transit stations, and commuter rail. The 2007 DEIS capital cost estimates placed the total project cost between $3.5 billion and $4.0 billion. These estimates prompted reductions in the scope of the project, leading to the final reversable managed lane design. The 2011 FEIS reported a projected project cost of between $834 million and $968 million.

The various economic assessments performed also considered several indirect costs and benefits associated with the various design iterations of the project. The 2004 estimates considered the opportunity cost associated with acquiring additional right of way in terms of residential and commercial displacement and localized development stagnation. The project was anticipated to reduce local property tax revenues by $3.3 million to $5.8 million annually due to the acquisition of existing tax-paying parcels. Risk associated with potential soil or water contamination affecting adjacent parcels was also considered. On the other hand, construction activity was forecasted to generate up to 27,700 person-years of work, directly through on-site labor, indirectly through supplier firms, and induced jobs supported by worker spending.

The decision to implement a reversable managed lane strategy was supported by anticipated savings associated with right of way acquisition and construction costs. Traffic observations indicated that about 68% of traffic was in the southbound direction during morning hours, and 71% of traffic was in the northbound direction in the afternoon. These travel patterns create a scenario in which reversable managed lanes that run southbound in the morning and northbound in the afternoon could have a substantial impact on mitigating peak-hour traffic congestion while only requiring about half of the physical space compared to permanent general-purpose lanes in each direction of travel. This results in savings associated with right of way acquisition. Halving the number of constructed lanes also resulted in lower bridge construction costs, which was forecasted to be a large driver of overall construction costs.

Selection Amongst Transportation Alternatives using Lifecycle Analysis

Substantial analytical work was undertaken by the project sponsors to compare the direct financial impacts of the various alternatives proposed for the Northwest Corridor, including predictions of construction costs, right of way acquisition costs, economic impact projections, and anticipated tolling revenues. However, there are many other costs and benefits accrued throughout the lifecycle of a managed lane project that were considered qualitatively, but not necessarily quantitatively. As such, selecting a preferred project alternative is more nuanced than simply comparing the anticipated financial impacts of the alternatives.

Lifecycle Cost Analysis is the practice of considering the various costs and benefits associated with a project throughout the entire lifespan of the project, from design to demolition. Lifecycle Cost Analysis promotes economic, social, and environmental sustainability by considering positive and negative project impacts at each stage of the project (Altaf, et al., 2023). The quantitative consideration of direct costs, direct revenues, and positive and negative externalities throughout the lifecycle of a project results in a more complete understanding of the potential benefits and detriments associated with each project alternative, thereby allowing decision makers to be more well-informed when selecting a preferred alternative.

The research summarized in this report was designed to quantify some of the costs that do not appear in traditional analyses, allowing analysts to disclose some of the additional benefits that come from efficient facility designs, construction, and operations. For example, embedded energy cost associated with concrete are very high (producing Portland cement, delivering concrete mix to the site, and pouring the concrete) and can be reduced significantly when infrastructure can serve two directions of travel with fewer lanes. Similarly, changes in on-road congestion can lead to significant decreases in energy per vehicle-mile of travel. This report shows how some of these cost savings can be integrated into alternatives assessment.

CHAPTER 3. PROJECT LIFECYCLE ASSESSMENT

A managed lane project has several project stages, including planning, design, construction, operation, maintenance, and decommissioning. For each of these stages, there are a multitude of costs and benefits that affect the project's lifecycle costs. For instance, there are direct costs associated with planning and design work, such as staff salaries and benefits, consulting fees, and community engagement expenses. There are direct costs associated with construction, such as the costs of materials, equipment, labor, and fuel. There are also indirect costs associated with energy consumption induced by managed lane construction, such as the energy consumed by the material and equipment production processes. Indirect costs are also associated with worker injury risk and impacts on neighboring communities (e.g., increased traffic congestion, construction noise, etc.). There are various potential benefits associated with the operation phase of a managed lane project resulting from a presumed reduction in traffic congestion, such as travel time savings, fuel efficiency improvements, and reductions in crash risk. If the managed lane incorporates tolling, toll revenue will be another direct benefit, although overhead costs are associated with facilitating the tolling systems. Managed lane maintenance and eventual decommissioning will have implications for traffic congestion and will therefore reduce many of the congestion-related benefits associated with operation. There are also material, equipment, labor, and fuel related costs associated with highway maintenance, as well as many of the indirect costs also associated with construction. After decommissioning, it may be possible to reuse some materials in future projects, which can be considered as a project benefit. A schematic of these various lifecycle costs and benefits is shown in Figure 2.

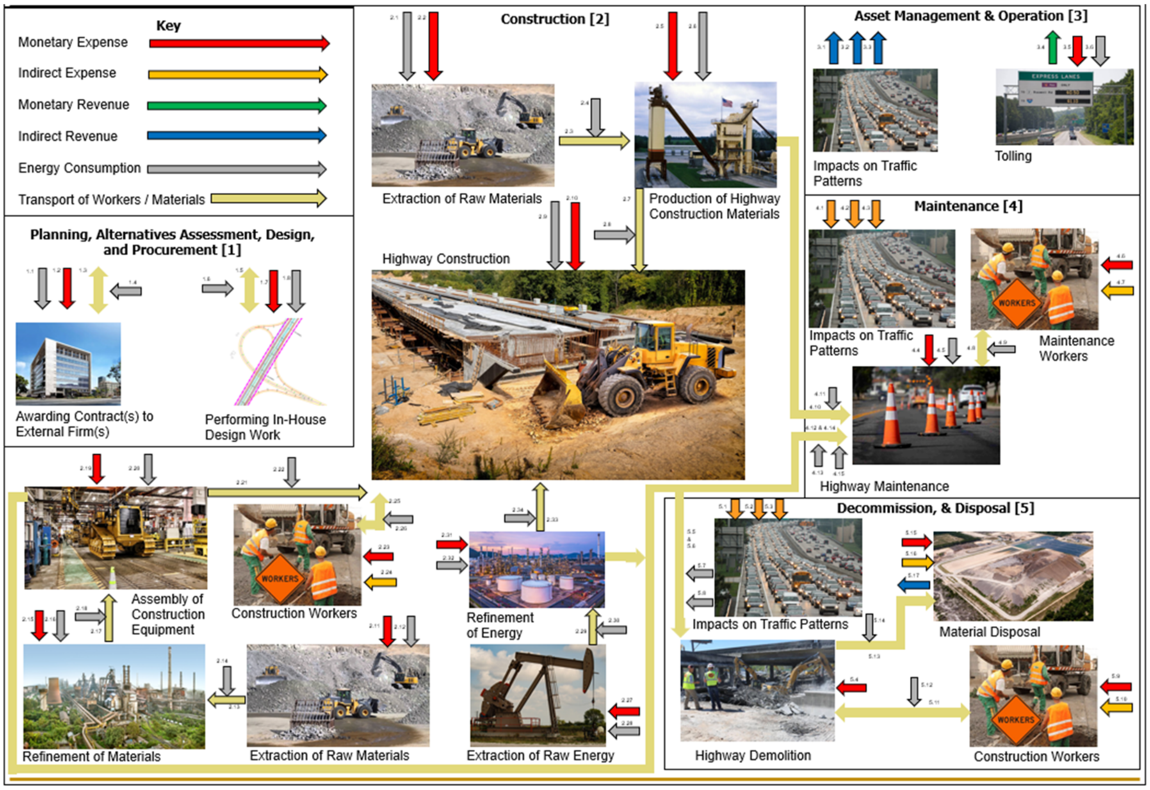

Figure 2: Photo. Lifecycle Costs of Managed Lane Projects

When considering the lifecycle costs of any transportation project, it is important to account for both the direct and indirect costs and benefits associated with the project, throughout all stages of its lifecycle. This necessitates an understanding of monetary and non-monetary costs and benefits associated with project planning, design, construction, operation, maintenance, and decommissioning. This chapter provides a categorized summary of important literature sources, including those describing previously conducted lifecycle economic studies, cost benefit analysis methodologies, construction and logistics, energy efficiency modeling, and assessment of operational performance and safety.

LIFECYCLE ECONOMICS STUDIES

A variety of previous studies that have performed lifecycle economic analyses of highway projects. Cassady et al. (2020) performed cost-benefit analyses for seven toll lane projects throughout the United States, considering factors such as travel time, construction costs, and maintenance. Sisiopiku et al. (2009), performed a cost-benefit analysis for different managed lane scenarios to reduce interstate highway traffic congestion in Birmingham, Alabama for three scenarios: 1) no change, 2) conversion of one general-purpose lane to an HOV lane, and 3) construction of an additional HOV lane. The study found that the construction of an additional lane as an HOV lane would provide the greatest economic returns for commuters over a 20-year period, despite the higher costs associated with construction. Similarly, Rathbone (2017) compared the strategies of widening urban freeways with implementing reversible lanes using movable barriers to address congestion and found that reversible lanes are significantly cheaper to implement, quicker to construct, and can more easily handle uncertainties, such as higher autonomous vehicle usage and mobility as a service in the future.

In contrast, Sundeen (2022) performed a case study analysis of the economic feasibility of reversible lanes in Gothenburg, Sweden, finding that reversible lanes were not an effective method of congestion reduction on their major roadways. Sundeen discusses multiple ways to model traffic behavior, as well as the limitations associated with each method. Their study also concluded that reversible lanes were not feasible for many of their major corridors, due to spatial and economic factors.

Additional papers and resources provide valuable insights relating to various stages of a highway's lifecycle. For instance, Irfan et al. (2011), Georgia Department of

Transportation (2021), and Antoine et al. (2019) describe costs and durations associated with the planning, design, and material procurement phases of a highway project, respectively.

OPERATIONAL COST BENEFIT ANALYSIS METHODS

Cassady, et al. (2020), Sisiopiku, et al. (2009), and Rathbone (2017) each describe relevant modeling tools and methods for estimating highway lifecycle costs. A variety of other sources in this literature review provide more detailed information pertaining to specific components of a highway's lifecycle. Cohen et al. (2015) offers a structured approach for monetizing travel time variability and delay impacts using the FHWA's Work Zone Road User Costs methodology. Cohen et al. (2015) also provides standardized equations for calculating passenger and freight vehicle delay costs, including adjustments for time-related vehicle depreciation and freight inventory losses. Culotta, et al. (2019) found that drivers value travel time consistency about as much as they value the actual travel time savings.

Laval et al. (2015) investigated ways to optimize traffic flow and revenue using innovative toll pricing. Their study discusses congestion pricing techniques, from fixed to dynamic tolls incorporating factors such as time of day and real time pricing. The authors emphasize that dynamic strategies are highly effective in reducing delays and achieving system optimization (Laval et al., 2015). Further, using household income data, Khoeini and Guensler (2014) found that drivers from all income brackets use HOT lanes, and not just drivers from high-income households.

Billings and Gerrick (n.d.) discuss the costs and benefits associated with highway decommissioning and removal by examining a case study in Milwaukee, Wisconsin. The elevated 0.8-mile Park East Freeway, originally built in 1971, would have required an estimated $100 million in repairs by the late 1990s. Instead, officials pursued facility demolition at a cost of approximately $25 million, achieving a 75% construction cost savings. Prior to removal, the freeway carried around 54,000 vehicles per day and functioned as a physical barrier between downtown Milwaukee and its surrounding neighborhoods. The removal of this facility spurred redevelopment efforts and significantly improved urban connectivity (Billings and Gerrick, n.d.).

CONSTRUCTION AND LOGISTICS

A variety of articles in the literature identify and quantify construction cost elements, including the costs of equipment, materials, and labor. Millson and Wilemon discusses the processes used to manufacture construction equipment (Milson and Wilemon, 2006). Meanwhile, Cheng et al. (2010) examined heavy equipment supply chains. After the manufacturing process, construction equipment must be transported to project sites, typically using cargo ships, rail, or long-haul trucking. This process is coordinated between manufacturers, contractors, architects/engineers, and other key personnel involved with the project. Construction equipment is typically repaired by the manufacturer or dealership from which it was acquired. The supply chain costs associated with equipment use in these lifecycle stages are not typically integrated into analyses, as many construction projects are performed by different firms of varying sizes, which also leads to difficulties with consistency and efficiency (Cheng et al., 2010). Antoine et al. (2019) provides additional details on material procurement.

The Georgia Department of Transportation (2020) emphasizes that pipelines are the most cost-effective method for moving large volumes of oil and gas, offering significant savings on transportation costs compared to other modes. Pipelines allow for continuous, high-volume transport with low operational expenses, helping to lower the delivered cost of refined fuels and making them a critical economic input across multiple industries (Georgia Department of Transportation, 2020).

The U.S. Bureau of Transportation Statistics notes that the FHWA's National Highway Construction Cost Index surged by 70.2% from Q4 2020 through Q1 2024, marking the sharpest cost escalation since 2003 (Bureau of Transportation Statistics, 2023). This increase reflects higher prices for labor, materials, and fuel; all of which contribute to the direct cost of construction. Likewise, the U.S. Bureau of Labor Statistics provides wage statistics for various highway construction related jobs (Bureau of Transportation Statistics, 2024).

ENERGY USE AND ENERGY EFFICIENCY

A transportation system consumes energy during operation and maintenance; however, energy is also used in every stage of a transportation project's life. This includes energy use associated with components that are used to construct a project. The energy use associated with extraction of raw materials, processing of materials, manufacture of components, transportation of materials and components, and final disposal of materials is known as embodied energy. Modeling the embodied energy associated with a highway's lifecycle is necessary for tabulating the full cost of a highway. Chen and Huang (2019) assessed energy consumption during pavement construction, revealing substantial differences between construction materials and processes. For continuously reinforced concrete pavement, about 94% of total energy consumption occurs during the manufacturing phase, primarily for cement and reinforcing steel, from raw material extraction to placement. In contrast, approximately 48% of asphalt pavement energy use stems from mixing and drying aggregates, while 40% of energy use attributable to bitumen production (Chen and Huang, 2019). Likewise, Liu and Peng (2018) evaluated energy consumption patterns across construction, operation, and maintenance phases. The literature review results indicated that a reasonable ratio of energy use during these phases is approximately 5:10:3 (construction: operation: maintenance).

The U.S. Bureau of Transportation Statistics reports that traffic congestion significantly increases fuel consumption among commuters (Bureau of Transportation Statistics, 2012). According to the Bureau of Transportation Statistics findings, the average commuter experiences 34 hours of delay annually due to congestion and consumes an added 14 gallons of fuel as a direct result. Meanwhile, Monsere, et al. (1982) identified relationships between pavement roughness and fuel consumption.

The U.S. Energy Information Administration describes the typical oil refining processes, as well as the associated energy consumption, and the California Air Resources Board describes the refining process for natural gas (Energy Information Administration, 2023, and California Air Resources Board, 2021). Shuai et al. (2022) reports that pipelines, the dominant method for crude oil and natural gas movement, consume 200- 400 Btu/ton-mile and use less than 1% of the transported fuel's energy per 1,000 miles. Marine shipping, particularly ocean tankers, are extremely energy-efficient overall, consuming just 40 - 50 Btu/ton-mile, followed by inland barges at 220 - 250 Btu/ton-mile. Rail, which is increasingly used for transporting crude oil and remains the most common shipping method for coal, uses 250 - 300 Btu/ton-mile, which is more efficient than trucking, but slightly less efficient than pipelines (for oil) or barges (for oil or coal).

Similarly, Frey (2005) found that shifting fuel transport from trucks to more efficient modes, such as rail or pipeline, can reduce greenhouse gas emissions by 60% to 75%, depending on the specific fuel and distance. These reductions are driven by lower fuel consumption per ton-mile and more efficient combustion technologies associated with these modes (Frey, 2005).

Velumani and Kalidinadi (2012) evaluated the embodied energy contributions from both human labor and transportation during a 16-month masonry construction project, finding that transportation-related energy use (primarily from diesel-fuelled delivery of blocks, cement, and sand) accounted for 70% of on-site construction energy. Human labor (i.e., resources needed to support human labor) contributed another 29% to embodied energy (Velumani and Kalidinadi, 2012).

OPERATIONAL PERFORMANCE AND SAFETY

Understanding the benefits of managed lanes is critical for calculating the overall costs and benefits of a highway's lifecycle. Figueroa-Medina et al. found that dynamic toll lanes with algorithm-controlled pricing compared favourably against general toll lanes in terms of congestion reduction and improved reliability (Figueroa-Medina et al., 2021).

Dey et al. (2011) explored the advantages of reversible lane operations in arterial roadways, primarily related to infrastructure capacity, traffic safety, and economic development in the Washington D.C. region. Reversible lanes achieve peak roadway efficiencies by providing direct allocation based on peak travel times, which reduced congestion in a cost-effective manner, without physical development of new or expanded infrastructure capacity, which is especially beneficial in densely settled urban cores where eminent domain costs for procurement of occupied land may be prohibitive (Dey et al., 2011).

Lifecycle analysis also requires the quantification of risks and safety benefits associated with the various stages of a highway's lifecycle. The U.S. Federal Highway Administration examined the safety of several types of managed lane, showing that HOT lanes are the safest, with 10-30% fewer crashes than general-purpose lanes. These authors indicate that the safety improvements are explained by controlled access and fewer lane changes (Federal Highway Administration, 2016a). Wen et al. (2021) employed advanced machine learning techniques, specifically Light Gradient Boosting Machine (LightGBM) and SHAP (SHapley Additive exPlanations), to further assess the impact of various risk factors on several types of roadway segment crashes. By examining crash data from Texas between 2015 and 2017, the researchers identified significant predictors for total crashes, run-off-road crashes, and rear-end collisions (Wen et al., 2021). Luan et al. identifies key factors in crash risk such as road lighting, time of crash, speed, alcohol involvement, and driver demographics (Luan et al., 2024).

Gupta et al. (2020) noted that traffic management strategies such as variable speed limits (VSL) have demonstrated substantial effectiveness in improving work zone safety. In Wyoming, VSL systems reduced total crashes by 34.4% and rear-end crashes by 65.2%. Georgia experienced similar benefits, with a 29.2% reduction in total crashes and a 35.2% reduction in rear-end crashes following VSL implementation (Gupta et al., 2020). Meanwhile, Mohan and Gautam (2002) indicated that the average direct cost of a work zone crash is approximately $3,687, with a median cost of $687. These costs vary as a function of crash type and severity, both of which can be affected by facility design

(Mohan and Gautam, 2002) and operating conditions. Mahlberg et al. (2022) found that lane width has been identified as a key risk factor in work zones. Research shows that lane widths narrower than 11 feet in construction zones are associated with reduced highway capacity and higher crash rates (Mahlberg et al., 2022). Narrower lanes create tighter operating spaces for vehicles, increasing the likelihood of collisions, especially in congested conditions.

RISK MANAGEMENT

Project risk involves any events or conditions that, if they occur, would have an unanticipated impact on the project (Federal Highway Administration, 2016a). The Federal Highway Administration provides recommendations for the identification, analysis, mitigation, and monitoring of project risks. First, agencies should identify potential project risks and the potential consequences of those risks. For example, traffic on a newly constructed toll road may be lower than anticipated, resulting in reduced toll revenues, which would have implications on project financing. Agencies should then qualitatively assess the various potential risks by considering the probability of that risk occurring and the magnitude of potential impact should each risk occur. For risks that have a high likelihood of occurring and/or would have large potential impacts, the Federal Highway Administration recommends that agencies should take steps to mitigate those risks, transfer the risk to a third-party, and/or avoiding the risk entirely by adjusting the project scope. If it is not possible to sufficiently mitigate, transfer, or avoid the risk, agencies should be ready to respond to the risk. Throughout the life of the project, agencies should continuously monitor project risks. Over time, some project risks may disappear, and new project risks may become apparent.

When planning large infrastructure projects, agencies will sometimes consider engaging in a public-private partnership. In a public-private partnership, agencies will share project risks and rewards with one or more private sector firms (Burke and Demirag, 2018). In design-build partnerships, an agency will typically delegate design and construction responsibilities to a firm in exchange for agreed upon lump-sum payments. In this arrangement, the private firm would take on the risk associated with construction cost overruns or construction delays. In the case of toll road construction, agencies may also consider outsourcing operation and maintenance responsibilities to a private firm. In this arrangement, the private firm would collect a portion of the toll revenue for an agreed upon duration of time, and the agency would absolve itself of risks related to maintenance cost overruns or unanticipated drops in traffic and toll revenue.

LIFECYCLE ASSESSMENT SUMMARY

This research effort will produce a spreadsheet-based modelling tool that can compute lifecycle costs and benefits for highway managed lane projects, across each lifecycle stage. The information contained within the Literature Review and Annotated Bibliography prepared for this project provided an extensive base of knowledge that served as a foundation for the design of the analytical spreadsheet (organized by project lifecycle element) and the component content within each lifecycle element.

In comparison to existing literature, the research team is creating a particularly in-depth model of the costs and benefits associated with the operation phase of a managed lane project. By leveraging modelling tools such as PTV VISSIM™ and the US Environmental Protection Agency's MOtor Vehicle Emissions Simulator (MOVES), it is possible to achieve a detailed prediction of on-road travel time and energy consumption impacts resulting from differing design scenarios. On the other hand, due to data limitations it was not possible to integrate many of the insights relating to construction and logistics, particularly those relating to lifecycle costs and energy consumption of construction materials.

CHAPTER 4. ENERGY USE AND EMISSIONS MODELING

The United States Environmental Protection Agency developed MOtor Vehicle Emission Simulator (MOVES) to model energy consumed by on-road vehicles as a function of vehicle operating conditions, and the emission rates associated with the predicted energy use under those operating conditions (U.S. Environmental Protection Agency, 2022). MOVES must be employed to model energy consumption rates for on-road sources for any federal project, which includes any planning activities and impact assessments that involve federal resources or approvals (U.S. Environmental Protection Agency, 2024). MOVES emission rates are modal in nature, modeled as a function of vehicle modal acceleration and deceleration, better representing emissions as a function of instantaneous (1HZ) speed and acceleration (Guensler, 2018), so that average speeds were no longer driving the emission rate development process (Guensler, 1994). Hence, MOVES also supports the use of high-resolution vehicle activity input data, such as the use of second-by-second vehicle activity (U.S. Environmental Protection Agency, 2025).

In any case study modeled with the spreadsheet-based system, MOVES can used in combination with PTV VISSIM™ to model baseline fleet energy consumption and emission rates on each transportation link and across different scenarios, thereby allowing for the estimation of total fuel consumption under differing traffic patterns, as well as the estimation of fuel consumption throughout other phases of the project lifecycle, such as material procurement.

MOVES APPLICATIONS

The MOVES model serves as the regulatory standard for estimating on-road energy use and emissions (U.S. Environmental Protection Agency, 2024). Unlike its predecessor, the MOBILE model, MOVES utilizes a modal-based approach that calculates energy use and emission rates as a function of instantaneous vehicle activity, specifically vehicle-specific power (VSP) for light-duty vehicles and scaled tractive power (STP) for heavy-duty vehicles. MOVES is designed to process high-resolution input data (providing energy use and emission rates for modal activity as a function of instantaneous speed and acceleration). However, the model's internal complexity makes it computationally prohibitive for modeling large-scale or dynamic roadway networks (Lu et al., 2025). For a typical regional network comprising over 100,000 roadway links, performing individual MOVES runs to account for hourly variations in fleet composition, temperature, and humidity could take years on a standard personal computer. This computational bottleneck often forces researchers to simplify their analyses, potentially sacrificing the high-resolution benefits the regulatory model was designed to provide (Lu et al., 2025, and Liu et al. 2019).

To address these limitations, the Georgia Tech research team utilizes MOVES-Matrix 5, a high-performance modeling system that pre-calculates trillions of emission rates using supercomputing clusters. While the latest published documentation details the architecture for MOVES-Matrix 4.0 (Lu et al., 2025) and 3.0 (Lu et al., 2024), this study employs data generated from the EPA's MOVES 5.0.0 model. It is important to note that MOVES 5.0.1 was released in October 2025, after the commencement of this research; therefore, the energy use and emission rates utilized here are derived from the 5.0.0

version. Despite the update, MOVES-Matrix 5 retains the same conceptual design and high-performance computing (HPC) architecture as its predecessors (Lu et al., 2025, Liu et al., 2019, Guensler et al., 2018, and Guensler et al., 2016).

The scale of the MOVES-Matrix generation process is tremendous. To develop a complete database for a single modeling region, the team prepares and executes 181,818 unique MOVES run on the Partnership for an Advanced Computing Environment (PACE) clusters. These runs cover every possible combination of input variables, including 26 calendar years (2015 to 2060), three fuel months (summer, winter, transition), 111 temperature bins (0 to 110°F), and 21 humidity levels (0% to 100%) (Lu et al., 2025). Each run populates a multi-dimensional sub-matrix containing energy and emission rates for 13 vehicle source types and 31 model years. The resulting database contains more than 5.8 trillion records, providing a comprehensive lookup table for any conceivable operating scenario.

A defining feature of MOVES-Matrix 5 is that it generates the exact same results as the regulatory MOVES model without any "optimization," "adjustment," or approximation. The system is a library of completed MOVES runs; hence, querying the matrix returns the exact same energy use or emission rate that MOVES calculates in a single run for the same conditions. Verification tests comparing MOVES-Matrix 4.0 against MOVES 4.0.1 batch runs confirmed that the outputs are identical, with negligible internal rounding errors less than 0.0005% (Lu et al., 2025). This architecture allows researchers to bypass the cumbersome MOVES Graphical User Interface (GUI) entirely, instead using scripts (e.g., Python or SQL) to query the database and assemble fleet emission rates 200 times faster than standard model execution (Lu et al., 2025, and Liu et al., 2019).

The system's versatility has enabled a broad spectrum of applications in transportation and environmental research. In regional planning, MOVES-Matrix has been integrated with travel demand models (Xu et al., 2018c) and with microscopic simulation results to evaluate specific traffic strategies (Xu et al., 2016a). The tools have also been used to assess the environmental benefits of median bus lanes (Kim et al., 2019) and the conversion of High-Occupancy Vehicle (HOV) lanes to High-Occupancy Toll (HOT) lanes (Xu et al., 2017). The matrix data can also be used to model individual vehicles (Guensler et al., 2017; Kall 2008). The system also supports high-speed roadway link screening for regional air quality analysis (Kim et al., 2020), allowing planners to assess the specific impacts of changes in traffic volume and speed across entire metropolitan areas without computational delays.

MOVES-Matrix is also instrumental in microscale air quality and dispersion modeling. It serves as a high-speed emission engine for dispersion models like AERMOD, RLINE, and RLINEXT (Lu et al., 2023, and Guensler et al., 2021). AERMOD is a microscale air pollutant dispersion model that allows users to model the dispersion of pollutants through a study area, accounting for transportation network geometry, vehicle emissions, meteorological factors, and the presence of obstructions such as highway noise barriers (Guensler, 2021). Though it was beyond the scope of this study, AERMOD could be used in combination with PTV VISSIM™ and MOVES to model the anticipated downwind impacts of traffic emissions across different scenarios, allowing for the accounting of lifecycle costs and benefits associated with differing pollutant concentrations. The high-resolution link inputs can directly support distributed computing approaches for sub-regional and corridor level dispersion modeling (Kim et al., 2021, and Liu et al., 2017). This capability is essential for investigating the temporal and spatial aggregation of on-road operating conditions and their subsequent impacts on downwind pollutant exposure (Lu et al., 2019, and Lu et al., 2020).

Furthermore, the system facilitates detailed energy and fleet analysis. Existing studies have utilized MOVES-Matrix to assess transit services (Fan et al., 2024a, Fan et al., 2023, Li et al., 2016a, and Li et al., 2016b) and to evaluate "eco-driving" strategies for transit fleets (Xu et al., 2016b, and Xu et al., 2018b). It also supports life-cycle modeling efforts (Liu et al., 2016) and comparison of alternative transportation modes (Li et al., 2018). The model can be further integrated with engine start, soak, evaporative, and truck hoteling emissions (Xu et al., 2018a). Recent applications have expanded to assess the impact of ambient temperature on fuel consumption (Fan et al., 2024b) and the energy use of emerging vehicle technologies, including hybrid, plug-in hybrid, and battery electric vehicles (Dai et al., 2022, and Dai et al., 2023). Most recently, the system was also applied to the 2021 US Vehicle Inventory and Use Survey (VIUS) data to improve commercial truck fleet composition modeling (Xu et al., 2025).

Given the immense scale of the MOVES-Matrix database (comprising trillions of pre-calculated emission and energy use rates across combinations of calendar year, fuel month, ambient temperature, relative humidity, vehicle source type, model year, and operating mode), it is neither necessary nor desirable to deploy the full matrix for every applied analysis. Instead, this study extracts a policy- and context-relevant subset of MOVES-Matrix outputs tailored to the analytical needs of a spreadsheet-based implementation. Specifically, emission and energy rates were selected for calendar year 2025, model year 2025, summer fuel conditions (July), ambient temperature of 87.3°F, and relative humidity of 53.8% (representative summertime morning peak-hour operating conditions for Georgia). By constraining the dimensionality of the MOVES-Matrix query space to these conditions, the resulting rate tables preserve full regulatory fidelity while enabling transparent, link-level energy and emissions calculations within a spreadsheet environment designed for scenario testing and stakeholder use.

Building on these MOVES-Matrix-derived rates, a suite of interconnected spreadsheets was developed to perform link-level energy and emissions calculations in a computationally efficient, yet methodologically rigorous manner. First, driving cycles are preprocessed into operating mode (OpMode) bin distributions by vehicle class, converting second-by-second speed and acceleration traces into time fractions in each OpMode bin. These bin distributions are then integrated with PTV VISSIM™ link-level outputs, including traffic volume, link length, speed, and managed-lane designation, to construct a vehicle activity table for each roadway link. For each link, an assigned driving cycle is used to scale OpMode bin allocations based on vehicle-seconds traveled, which are subsequently multiplied by the corresponding MOVES-Matrix energy use and emission rates. This approach replaces second-by-second trace processing with bin-based calculations, substantially reducing computational burden while retaining the modal structure of MOVES. The framework supports simultaneous calculation of energy use and multiple pollutants across light-, medium-, and heavy-duty vehicle classes, while maintaining consistent assumptions across calendar year, model year, and environmental conditions.

Fleet composition within the spreadsheet framework is represented using three MOVES source types: Source Type 21 (passenger cars), Source Type 32 (light commercial trucks), and Source Type 62 (combination long-haul trucks), corresponding to light-duty, medium-duty, and heavy-duty vehicle classes, respectively. These source types were selected based on their relative contributions to vehicle miles traveled as documented in fleet composition data provided by the Georgia Department of Natural Resources (DNR) for statewide emissions modeling. Within each source type, a single regulatory class was selected to represent the dominant vehicle population. Regulatory class selection was based on the sample vehicle population data ("samplevehiclepopulation" table) embedded in the MOVES5 database, which defines default fleet compositions (and is not user-customizable). For Source Type 21, only regulatory class 20 (light-duty vehicles) is defined. For Source Type 32, regulatory class 30 (light-duty trucks) was selected, and for Source Type 62, regulatory class 47 (Class 7 and 8 Trucks with gross vehicle weight ratings of more than 33,000 pounds) was selected, each corresponding to the largest population share within the respective source type. MOVES automatically weights all output rates using the default "samplevehiclepopulation" table (hard-coded and cannot be modified), and the team mathematically reversed this adjustment. The output rates were divided by the corresponding fleet fractions to isolate the actual emission rates for each specific regulatory class. This approach ensures internal consistency with MOVES default fleet assumptions while maintaining a tractable and policy-relevant vehicle classification scheme for spreadsheet-based analysis.

MOVES INTEGRATION LIMITATIONS IN THE SPREADSHEET TOOL

Building on the MOVES-Matrix framework described in the preceding section (which enables rapid access to MOVES-consistent energy and emission rates across a wide range of operating and environmental conditions), the research team proposed the implementation of a spreadsheet-based modeling tool to operationalize these rates for rapid corridor-level analysis under a limited number of scenarios.

Within the scope of work for this project, the research team proposed the development of a spreadsheet-based modeling tool to predict corridor-level travel time, energy use, and on-road emissions using MOVES-consistent methodologies. The original intent of this approach was to create a rapid, sketch-level analysis framework that could be executed quickly and transparently, allowing users to observe how link-level vehicle activity data are transformed into corridor-level performance metrics across various vehicle classes. A key motivation for this approach was to provide an accessible modeling environment in which transportation planners and engineers could directly inspect intermediate calculations, assumptions, and vehicle activity processing steps rather than relying on an opaque modeling system (MOVES is sometimes referred to as a black box).

As development progressed, it became clear that implementing MOVES-based energy and emissions modeling within a spreadsheet environment was substantially more complex and resource-intensive than originally anticipated. At each model iteration, and with the introduction of each additional user option (e.g., alternative calendar years, combinations of fleet mix, model years, and regulatory class groups, selection of driving cycles, or specification of environmental conditions), the size of the spreadsheets (and consequently the associated processing time) increased geometrically. To create a stable and functional modeling process, the research team was required to partition the workflow into multiple spreadsheets and to restrict user selections to a limited and carefully curated set of modeling options. These restrictions included fixed calendar and model years, constrained combinations of fleet composition and regulatory classes, selection from a predefined set of representative driving cycles (rather than MOVES-weighted operating mode distributions), and the use of single-point ambient temperature and relative humidity assumptions. These design decisions were made to preserve computational feasibility and file stability while maintaining consistency with MOVES-derived energy and emission rates.

Despite these constraints, the spreadsheet-based modeling tool successfully demonstrates the mechanics of applying MOVES energy and emission rates to fleet and activity data. The spreadsheets explicitly document how link-level traffic volumes, speeds, facility types, and vehicle class distributions are converted into vehicle activity metrics and subsequently combined with operating mode-specific rates to produce link- and corridor-level prediction of travel time, energy use, and emissions. As such, the tool provides transparency into the modeling process and allows users to trace the propagation of assumptions and inputs through each stage of the calculation framework.

In hindsight, however, the research team believes that the project would have benefited from the direct integration of a Python-based modeling approach that has been developed and applied successfully in prior MOVES-related research efforts using MOVES2014a and MOVES3. The Python approach requires users to execute modeling scripts that query very large, precomputed energy and emission rate arrays derived from MOVES, rather than relying on spreadsheet-based rate lookups. While the intent of the spreadsheet framework was to avoid requiring users to run external code or interact with large lookup datasets, experience gained during this project suggests that it would probably be better to have transportation planners and engineers perform Python-based modeling. The Python approach provides a scripted workflow and avoids having to manage large, interdependent spreadsheet files. Furthermore, the 160 MB spreadsheet files used in the current implementation impose nontrivial data handling costs, delay time associated with recalculations, and version-management burdens. In contrast, the Python-based approach executes substantially faster and avoids the simplifications that were necessary in the spreadsheet framework to control processing time and file size for each scenario run.

Based on these observations, the research team will ultimately recommend retaining the spreadsheet-based travel time worksheets within the overall modeling framework, but populating specific spreadsheet elements using the Python-based implementation demonstrated in prior work. This hybrid approach would preserve the transparency and accessibility of spreadsheet-based travel time estimation, while enabling energy and emissions calculations to fully leverage the flexibility of the underlying MOVES rate structure. Specifically, integrating the Python-based approach would allow users to specify arbitrary fleet compositions, detailed on-road operating conditions, and spatially varying environmental parameters for every link in the modeled network, thereby eliminating the constraints inherent to spreadsheet-based emissions modeling. Documentation and example workflows for the Python implementation of MOVES-Matrix are publicly available at: https://github.com/gti-gatech/moves_training.

CHAPTER 5. MODELING TOOL INTEGRATION

The following sections describe the methodological approach to implement the various direct and indirect costs and benefits associated with a highway project. For modeling purposes, the lifecycle of a highway project has been subdivided into four separate phases: Planning and Design, Construction, and Ongoing Operations. Annual Maintenance is not included in the spreadsheet due to a lack of reliable data on maintenance expenses. However, information on how highway maintenance could be modeled is included within this section. Decommissioning cost (typically the fifth infrastructure cost category) is not included in the spreadsheet, given the rarity of complete removal of a freeway corridor. The costs and benefits associated with each phase are described below.

PLANNING, DESIGN, RIGHT-OF-WAY, AND FINANCING COSTS

The following section describes the costs associated with the planning of a highway project. Direct costs include community outreach, production of the Environmental Impact Statement, design costs, construction contracting costs, and the planner-hours, engineer-hours, and administrator hours used throughout the process.

Planning and Design Costs

The primary costs associated with the planning and design phases of a managed lane project are labor and miscellaneous administrative costs. The research team was able to access an itemized list of various planning and design related costs for the Northwest Corridor project, including the costs associated with permitting, producing various preliminary engineering plans, public outreach, performing traffic studies, and utility relocation, among others. These data were used to create the model’s default assumptions regarding these miscellaneous expenses. These assumptions can be found in Table 18 within Appendix B. Furthermore, administrative labor positions contained within the model include the positions outlined in Table 2. For each of these positions, users may adjust assumptions relating to compensation rates and billable hours. The model’s default assumptions for compensation rates and billable hours can be found in Table 16 within Appendix C.

Table 2: Administrative and Planning Job Classifications Included in the Model

Environmental Transportation Analyst I	Right of Way Specialist Supervisor I
Environmental Transportation Analyst II	Right of Way Specialist Supervisor II
Environmental Transportation Analyst III	Senior Right of Way Manager
Environmental Transportation Specialist I	Training and Development Specialist I
Environmental Transportation Specialist II	Training and Development Specialist II
Environmental Transportation Specialist III	Training and Development Specialist III
Environmental Transportation Specialist IV	Transportation Planning Specialist I
Environmental Compliance Specialist I	Transportation Planning Specialist II
Environmental Compliance Specialist II	Transportation Planning Specialist III
Environmental Compliance Specialist III	Planning Manager I
Environmental Compliance Specialist IV	Transportation Specialist I
Environmental Protection Manager II	Transportation Specialist II
Senior Environmental Protection Manager II	Transportation Specialist III
GDOT Civil Engineer I	Transportation Specialist IV
GDOT Civil Engineer II	Transportation Specialist V
GDOT Civil Engineer III	Transportation Specialist Manager I
GDOT Civil Engineer IV	Transportation Specialist Manager II
GDOT Professional Civil Engineer V	Transportation Specialist Manager III
GDOT Professional Civil Engineer VI	Senior Transportation Specialist Manager I
GDOT Civil Engineering Manager I	Senior Transportation Specialist Manager II
GDOT Civil Engineering Manager II	Transportation Technician I
GDOT Senior Civil Engineering Manager I	Transportation Technician II
GDOT Senior Civil Engineering Manager II	Transportation Technician III
Right of Way Specialist I	Transportation Technician IV
Right of Way Specialist II	
Right of Way Specialist III	

Right of Way Acquisition Costs

Right of way acquisition costs can be one of the most significant elements of managed lane construction in urban areas. The cost of land acquisition is a function of the amount of land required, the land use types, and proximity of the land to nearby amenities.

In developing the case study scenario for this project, the team developed a polygon-based approach for mapping potential right of way requirements using standard lane-width and buffer zone assumption. The research team completed the creation of polygons for the synthetic corridor widening (traditional lane addition) case study. Polygons have been created for lanes, overpass expansion, new ramp gore areas, etc.

The final model will allow users to create entries for parcels. Users will be required to enter the area of the affected portion of each parcel, the current land use of that parcel (e.g., residential, commercial), density of development on and around the parcel (rural, suburban, or urban), and proximity of that parcel to the economic center of the nearest metropolitan area. These user inputs allow the model to make more reasonable assumptions regarding the land value of those parcels. As with other components of the model, users will be able to adjust these assumptions should they have access to land value data that is more relevant to the context of the specific managed lane project being modeled.

For very large and complicated managed lane projects with reversible lanes, the research team is relying on insights gained from various Northwest Corridor planning, design, and financing documents to create the model's default assumptions. The research team has also used mapping software to create polygons that overlay the current footprint of the Northwest Corridor, as shown in Figure 3. These polygons will help the research team estimate the current land area of the Northwest Corridor. Likewise, the research team has accessed parcel level data for the areas immediately adjacent to the Northwest Corridor through the Atlanta regional Commission, as depicted in Figure 4.

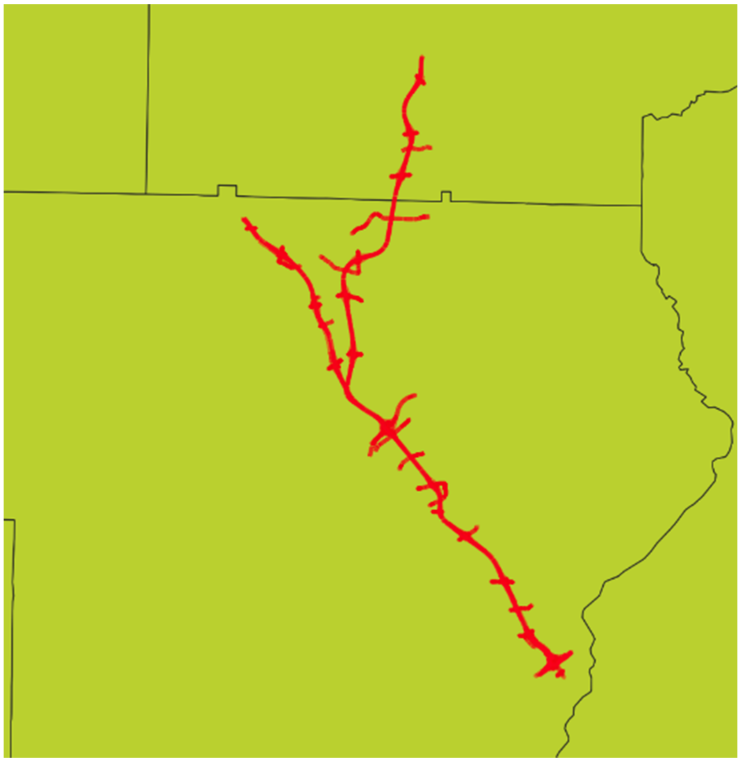

Figure 3: Map. Northwest Corridor Polygons

Figure 4: Map. Northwest Corridor Adjacent Parcels

Financing Costs

Financing related costs are heavily reliant on the types of federal funding available. For instance, approximately one-third of the Northwest Corridor project was funded by a federal loan through the Transportation Infrastructure Finance and Innovation Act (TIFIA), with additional funding appropriated through the State Transportation Improvement Plan and state motor fuel taxes. Future policy changes could affect the availability of these funding sources for managed lane projects and/or make new funding sources available for managed lane projects. Furthermore, the decision to engage in a public-private-partnership arrangement would have a substantial impact on project financing, with the scale of the impact being dependent on the structuring of the partnership agreement. The research team has relied on Northwest Corridor project documentation to formulate assumptions regarding the cost of bonds, debt service, contingency, and other miscellaneous financial expenses.

The modeling tool allows users to include financing costs as a simple line-item add-on to construction costs (where financing is a cost and toll revenues are a benefit). However, the research team believes that the development of an alternative big-picture social benefits calculator is warranted; one that accounts for the massive opportunity cost benefits of using private finance and freeing-up public gas tax dollars for other projects.

The research team started developing a spreadsheet-based modeling tool that would calculate 60-year lifecycle opportunity costs for the integration of private financing (with calculation rows for each out-year). The team plans to continue to explore this option, bringing in additional literature input associated with variable return on transportation investment over time (lower returns over the short term that become greater over the long term).

Inflation Rates

A managed lane project's lifecycle typically spans multiple decades. Project financial forecasting usually occurs early in the planning process, but it may take several years to complete the planning and design phases. In that time, inflation and shifting market conditions would affect the cost of construction materials, equipment, and labor. Likewise, any potential tolling revenues associated with the project would not be accrued until construction is completed, which may be a decade later than the time at which the financial forecasts were created. Due to the temporal nature of project revenues and expenses, it is necessary to account for inflation rates.

As of 2026, the Bureau of Labor Statistics consumer price index reports an inflation rate of 2.7%. However, this value may vary substantially by cost category. For instance, Figure 5 and Figure 6 show the producer price indices for asphalt and steel, respectively.

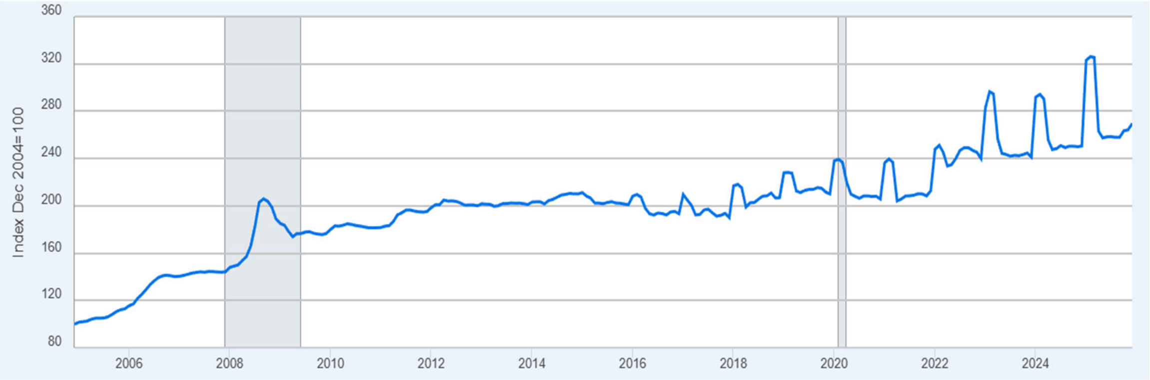

Figure 5. Graph. Producer Price Index: Asphalt Paving Mixture and Block Manufacturing: Asphalt and Tar Paving Mixture (Excluding Liquid), including Bitumen or Asphalt Concrete, Asphalt Paving Cement (U.S. Bureau of Labor Statistics, 2026a)

Figure 6. Graph. Producer Price Index: Metals and Metal Products: Iron and Steel (U.S. Bureau of Labor Statistics, 2026b)

These charts demonstrate the potential for differences in inflation rates and price volatility between cost categories. Between 2010 and 2020, asphalt maintained a relatively stable price. In the same period, steel experienced much more price variation. In the years following 2020, both items experienced increased rates of inflation, but while asphalt prices continue to trend higher, steel prices have generally declined since 2022. As such, material selection may have a substantial impact on financial risks related to inflation. Table 1Table 3 shows the annualized three-year inflation rates by cost category, spanning from December 1, 2022, to December 1, 2025.

Table 3. Annualized 3-year Inflation Rates by Cost Category

Cost Category	Annualized 3-year Inflation Rate
Asphalt	3.7%
Concrete	4.0%
Tolling / ITS Systems	-3.6%
Pipe	-8.9%
Steel and Metal	0.1%
Traffic Control	3.4%
Fuel	-10.5%
Wages (construction)	4.0%
Wages (engineer)	6.2%

Sources: Bureau of Labor Statistics (2026a, 2026b, 2026c, 2026d, 2026e, 2026f, 2026g, 2026h), and Energy Information Administration (2026).

It is also necessary to consider the rate at which land value appreciates or depreciates over time. For the purposes of this analysis, land value will be defined as the value of a parcel of land minus the replacement cost of any structure(s) or improvements occupying that parcel of land (Davis and Heathcote, 2007). Using this methodology, Davis, Larson, Oliner, and Shui have tracked the rate in which land value has changed between 2012 and 2019 across over 10,000 census tracts in the United States (Davis et al., 2021), finding that the appreciation rate of land value is correlated with the population of the metropolitan area in which the parcel is located and the distance between the parcel and the central business district. Land values increased at the greatest rate for parcels near the center of the metropolitan area and increased at the lowest rate in metropolitan areas with fewer than 500,000 housing units. These data are shown in Figure 7.

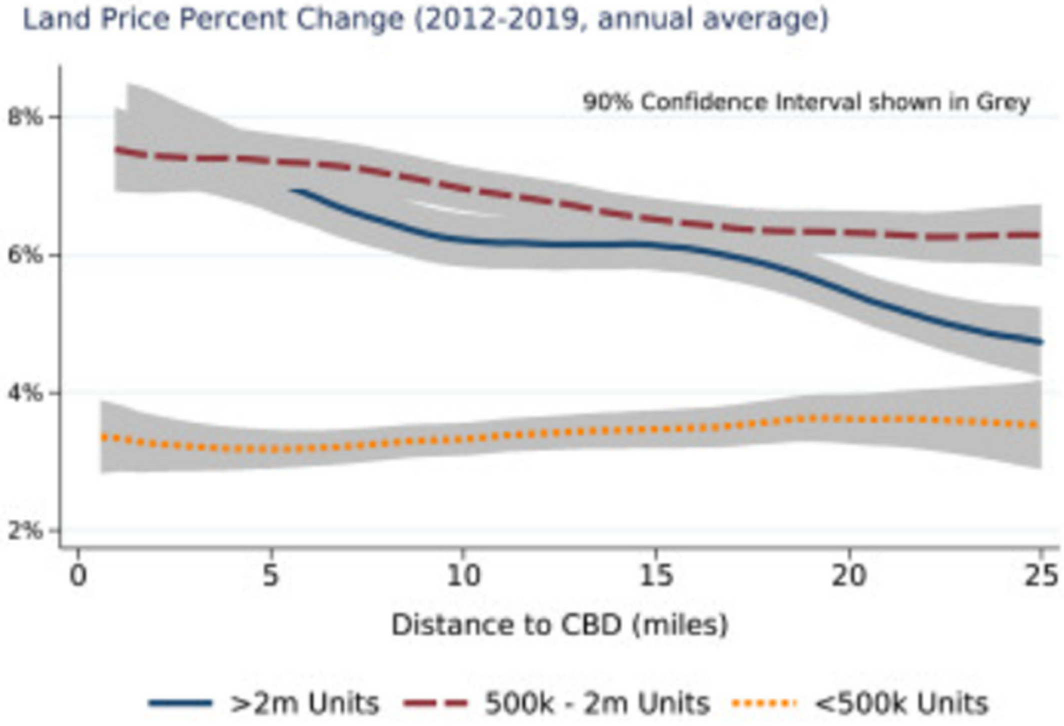

Figure 7. Graph. Annualized increases in land value (2012-2019) by metropolitan area population and distance to central business district (Davis et al., 2021)

The Northwest Corridor project affected parcels of land ranging between 10 and 28 miles from downtown Atlanta. As such, the annualized land value inflation rate for these parcels could be expected to be between 4.5% and 6.5%, depending on the parcel's location.

Time Value of Money

Costs and benefits accrued by new managed lane construction are dispersed throughout the lifespan of the project. For analysis purposes, these costs and benefits are converted into present values. For direct monetary costs, such as those associated with construction and maintenance, standard net present value calculations will be employed to convert future costs into present-day dollars using a 3.5% discount rate (Bernhard, 1992). The total net present values of recurring expenses would then be converted into an equivalent annualized cost over the lifespan of the project (Bray et al., 2022).

CONSTRUCTION COSTS

The following subsection describes the costs associated with the construction of a highway project. The direct costs associated with highway construction include the cost of materials, equipment, and labor. Additionally, there are indirect costs associated with highway construction, such as the cost of energy consumed throughout the construction process.

The user interface of the construction cost estimation model has been structured to allow users to enter one or more "links." For each link, users enter the length of the link in lane-feet and classify the link as a Highway Travel Lane, Highway Bridge/Overpass, Arterial Travel Lane, or Arterial Bridge. Four primary components were considered in modeling construction costs: material costs, equipment costs, labor costs, and administrative costs. The methodology for calculating each of these costs is outlined in the following subsections.

Construction Materials Costs

AASHTOWare Project Estimation (AASHTOWare) is a web-based cost estimation software designed to standardize cost estimation procedure for engineering firms (American Association of State Highway and Transportation Officials, n.d.a). To estimate the unit price of a particular pay item, AASHTOWare considers the bid-cost of that item in previous projects within the state. Users have the option to refine this calculation further with the inclusion of any number of optional parameters (e.g., only considering projects in rural settings, on mountainous terrain, constructed during the winter, etc.) (Reichard and Guensler, 2024). AASHTOWare requires users to input quantities of specific pay items (e.g., Item no. 413-0750: TACK COAT). However, the research team did not have access to sufficiently detailed material quantity information for the Northwest Corridor project; as such, the AASHTOWare Project Cost Estimator has not been formally integrated into the spreadsheet-based model. Nonetheless, the spreadsheet is structured to easily integrate AASHTOWare data, should the user have access to that data.

Material costs were modeled based largely on resources provided by the Georgia Department of Transportation from the construction of the I-75/I/575 Northwest Corridor managed lane expansion project, including Schedule of Values documents from various stages of construction. The Schedule of Values documentation includes line items for Bonding and Insurance, Mobilization, Traffic Control, Clear and Grub, Demolition, Erosion Control, Project Aesthetics, Earthwork Grading Complete, Aggregate Bases, Concrete Pavement, Bituminous Pavement, Other Roadway Work, Storm Drainage Systems, Retaining Walls, Traffic Barrier Walls, Bridge Foundations, Bridge Substructures, Bridge Superstructures, Bridge Other Work, Railroad Work, Soundwalls, ITS Systems, Tolling Systems, CEI Fees, Design Engineering Fees, Utility Adjustments, and associated arterial road construction. There are lump sum costs associated with each line item. However, the research team did not have access to a list of specific materials used, and in some cases the research team lacked information on the precise quantity of materials used.

The Georgia Department of Transportation maintains a Qualified Product List (QPL), containing approved sources for a variety of roadway construction items (Georgia

Department of Transportation, 2025). The items contained within the QPL have been vetted to ensure compliance with various relevant regulatory standards (e.g., MUTCD, AASHTO, etc.), as well as to ensure sufficient quality and reliability. Generally, contractors working on Georgia Department of Transportation sponsored projects are expected to adhere to the QPL, unless a specific waiver has been granted. A total of 172 materials are covered by the Georgia Department of Transportation QPL, including aggregate materials, asphalt, concrete, erosion control items, ITS systems, pipe, steel and metal, traffic control materials, etc. For each of these materials, a list of approved suppliers and approved products is provided, as well as the address of the supplier and any relevant material specifications. The median number of unique suppliers for each type of material is five. Concrete Sand Type II has the greatest number of unique suppliers (102), while twenty items have exactly one approved supplier.

Using the QPL in combination with the Schedule of Values documentation, it is possible to deduce the locations of material suppliers for the Northwest Corridor project. By knowing the locations of the material suppliers, it is possible to estimate the cost of fuel consumed by delivering materials to the job site. For materials on the QPL that have multiple approved suppliers, the average of the distances to each supplier was used for the purpose of calculating material transport energy costs. For entries on the Schedule of Values that corresponded to multiple QPL items (e.g., “Traffic Control”), the average of the distances to each item was used for calculation purposes.

The number of deliveries required for each type of material is a function of the quantity of the material required for the project and the quantity of material that can be delivered by one vehicle. For instance, the schedule of values documentation indicates that 10,189 tons of bituminous pavement are required per lane-mile of highway construction. A standard tri-axle truck can transport approximately 20 tons of bituminous pavement per delivery. Therefore, one lane-mile of highway construction is assumed to require 509.5 deliveries of bituminous pavement material. Table 14 in Appendix A contains more information on the default construction cost related assumptions within the model.

MOVES-Matrix energy use and emission rate data for the Atlanta Metropolitan Area in the state of Georgia were used in this study to estimate material delivery vehicle energy consumption rates on a per-mile basis. These analyses assumed that vehicles would primarily travel on the freeway road type, at an average speed of 65 miles per hour (off-peak with respect to congestion), and at a temperature of 60 degrees Fahrenheit. These assumptions reflect the median operating condition for most road material delivery vehicles, particularly those that deliver materials from out-of-state. The assumption of a consistent speed necessarily ignores the potential effects of traffic congestion, as well as the unique operating conditions of first mile and last-mile delivery. As such, these assumptions will result in a slight underestimation of energy consumption. Accuracy generally increases as delivery distance increases and freeway travel becomes a greater portion of overall trip length.

Depending on the user’s input for link type (i.e., Highway Travel Lane, Highway Bridge/Overpass, Arterial Travel Lane, or Arterial Bridge), differing subsets of line items from the Schedule of Values documentation have been used for construction material cost calculation purposes. For example, the Bridge Foundations, Bridge Substructures, Bridge Superstructures, and Bridge Other Work items were excluded from consideration for

Highway Travel Lane and Arterial Travel Lane links but were included in calculations for Highway Bridge/Overpass links.

Construction Equipment Costs

The material costs described in the previous section are rooted in contractor bid-based pricing data. As such, it is assumed that the capital costs of acquiring and operating the various types of construction equipment necessary for a managed lane project are priced into the contractor's bid values for each material. Nevertheless, it is necessary to account for the energy consumed by the construction equipment throughout the project. The research team did not have access to data specific to the construction of the Northwest Corridor and therefore has based the construction energy consumption modeling on existing literature. Wang et al. (2021) provides estimates for the energy consumption of various roadway construction vehicles per lane-mile of roadway constructed, as shown Table 4 (Wang, et al., 2021).

Table 4: Energy Consumption of Roadway Construction Equipment per Lane-mile of Roadway Constructed

Construction Equipment Type	Energy Consumption (gallons of diesel fuel per lane-mile)
Paver	891.3
Double-Wheel Roller	544.1
Single-Wheel Roller	212.5
Tire Roller	383.5
Asphalt Spreader	191.7
Crawler Bulldozer	766.7
Grader	2,374.0
Roller	2,839.4
Vibratory Roller	2,388.0

Construction Labor Costs

The construction material costs described previously are based on historic contractor bid-based pricing data. Thus, it is generally assumed that the direct costs associated with construction labor are priced into the contractor's bid values for each material. Furthermore, the research team had access to bid-based costs for various construction positions, as shown in Table 5.

Table 5. Bid-Based Construction Employee Expenses per Lane-Mile

Position	Bid-Based Employee Expenses per Lane-Mile	Hours per Lane-Mile
ATMS 7 Sign Inspector	$41,802.36	382
Bridge Inspector	$81,123.31	764
CEI Manager	$41,486.49	271
Contract Support Specialist	$41,503.38	639
Field Tech	$73,608.53	1060
Inspector Aid	$76,418.92	1274
Inspector I	$90,110.64	1274
Inspector II	$84,172.30	1021
Lab Manager Project Coordinator	$18,783.78	271
Lead Office Engineer	$51,586.99	348
Office Engineer	$44,188.34	382
Project Liaison Manager	$63,459.04	354
Project Manager	$95,820.95	764
Senior Inspector	$78,641.89	764
Testing Manager	$29,455.24	254

These bid-based construction employee expenses per lane-mile are included as default values in the construction cost estimation model. The user may adjust these values should they have access to data that better reflects the context of the managed lane project being modeled.

The calculation of costs associated with the risk of injury or death to construction workers and drivers was beyond the scope of this modeling tool; however, these costs can be estimated and integrated when more reliable data are made available. There were 321 work zone fatal crashes on the interstate highway system in 2022, approximately 30% of which involved commercial vehicles (Federal Highway Administration, 2025). There is a lack of reliable data regarding the number of interstate work zones occurring annually or the vehicle-miles of exposure to work zones, but the Federal Highway Administration estimates that one work zone fatality occurs for every $112,000,000 in roadway construction expenditures, including both interstate and non-interstate work zone fatalities and construction expenditures (Federal Highway Administration, 2025). For economic analysis purposes, the Unites States Department of Transportation values a statistical life at $13,700,000 (United States Department of Transportation, 2025). Likewise, the KABCO injury classification scale could be used in combination with reliable frequency and exposure data to evaluate non-fatal injuries (Reichard et al., 2023).

FACILITY OPERATION TRAVEL TIME SAVINGS AND ENERGY USE

The construction of new and modified facilities generally leads to congestion reduction, increased operating speeds, and traveler/freight travel time savings. These travel time savings provide direct economic benefits ($/hour) based upon the users' value of time, and the travel time savings almost always lead to additional savings in the form of reduced fuel consumption. The spreadsheet structure tracks vehicle activity on each link in the modeled or monitored transportation system. Any reliable data source can be employed as the source of the basic input data, provided that the minimum variables are carried into the analysis that describe fleet composition, traffic flows (vehicle/hour), and on-road operating conditions (speed/acceleration profiles, or an average speed for which the profiles will be provided by the model). Another direct impact of managed lane facility operation is often the collection of toll revenues.

There are also several indirect costs and benefits typically associated with highway operation, including reduced crash risks incurred by highway users and reductions in local air pollutant concentrations and noise impacts (although noise levels can sometimes increase with improved vehicle speeds and elevated flyover designs). The costs and benefits associated with some of these factors are influenced by the context in which the highway was built (design and adjacent land use characteristics). Each of these factors is discussed in the following subsections.

Ongoing Operations - Travel Time Computation per Scenario

Travel time is computed within the spreadsheet framework using model-predicted link-by-link traffic flows and speeds (taken from a travel demand model, simulation model, or observational data, etc.) that are carried in spreadsheet rows. Scenario-based travel on each link could be compared to facility design speeds, free flow travel speeds, or engineering throughput efficiency speeds that are slightly above facility capacity. While the research team recommends using an engineering capacity 45-mph baseline for managed lanes and general-purpose lanes to calculate travel time cost savings across scenarios, users can select an assessment speed by facility type (freeway managed lane, freeway general-purpose lane, ramps, and arterials).

Ongoing Operations - Tolling Revenue

The research framework does not include a method for forecasting toll revenues, because more information on toll pricing would need to be integrated into each scenario. The model does track modeled vehicle activity on general-purpose lanes vs. managed lanes.

So, if fixed toll rate is known, it is relatively simple to calculate corridor tolls based using managed lane traffic volume x toll rate. However, variable rates are a function of traffic volume and congestion on adjacent general-purpose lanes. Dynamic-priced toll lanes charge higher toll rates when congestion increases on the general-purpose lanes. The increase in toll price reduces the number of drivers in the congested lanes what will desire to move to the less congested facility. Proper pricing ensures that demand never exceeds the capacity of the managed lane. The variable prices help maintain free-flow conditions in the toll lane at the expense of additional congestion in adjacent general-purpose lanes. The modeling framework is structured such that if incremental analyses were performed, say every 5 minutes, the variable rate tolling algorithm implemented in a travel demand or simulation model could be introduced to track toll revenues for each iteration given the observed traffic volumes on managed lanes and the toll rate for that time increment.

For the purposes of the case study, the research team is basing toll revenues upon the insights described in the Northwest Corridor Financial Plan (Georgia Department of Transportation, 2014), some of which are shown in Table 6, Table 7, and Figure 8. Table 6 shows anticipated toll revenue scenarios (in 2011 dollars) for the Northwest Corridor in 2016, 2020, 2030, and 2040 (Georgia Department of Transportation, 2014). Table 7 shows the 2014 projected cumulative toll revenue by year from fiscal year 2019 to fiscal year 2053. The data in Table 7 assume an annual inflation rate of 2.5% and assumes varying toll lane traffic volumes by year. Figure 8 illustrates the forecasted tolling revenue by fiscal year (Georgia Department of Transportation 2014).

Table 6: Northwest Corridor Toll Revenue Scenarios

Time of Day	Max Toll Revenue ($2011)	Max Toll Revenue per-Mile ($2011)	Operational Toll Revenue ($2011)	Operational Toll Revenue per-Mile
2016 AM Peak	$13,084	$0.55	$11,809	$0.35
2016 AM Transition	$9,806	$0.45	$8,843	$0.32
2016 AM Shoulder	$5,983	$0.35	$4,448	$0.16
2016 PM Peak	$14,766	$0.55	$11,127	$0.26
2016 PM Transition	$9,109	$0.45	$7,181	$0.23
2016 PM Shoulder	$13,615	$0.40	$10,320	$0.19
2020 AM Peak	$18,225	$0.60	$16,592	$0.40
2020 AM Transition	$12,495	$0.45	$11,720	$0.36
2020 AM Shoulder	$9,049	$0.35	$6,779	$0.18
2020 PM Peak	$19,745	$0.60	$14,722	$0.30
2020 PM Transition	$12,238	$0.45	$9,868	$0.26
2020 PM Shoulder	$18,343	$0.40	$13,209	$0.19
2030 AM Peak	$28,269	$0.75	$25,283	$0.50
2030 AM Transition	$16,232	$0.55	$15,912	$0.48
2030 AM Shoulder	$14,441	$0.40	$13,454	$0.30
2030 PM Peak	$29,107	$0.75	$22,147	$0.41
2030 PM Transition	$17,938	$0.55	$15,492	$0.36
2030 PM Shoulder	$27,216	$0.45	$21,596	$0.26
2040 AM Peak	$45,257	$1.05	$40,153	$0.70
2040 AM Transition	$26,266	$0.75	$26,264	$0.70
2040 AM Shoulder	$26,061	$0.40	$26,061	$0.40
2040 PM Peak	$45,688	$1.05	$23,969	$0.56
2040 PM Transition	$28,551	$0.75	$26,440	$0.56
2040 PM Shoulder	$43,953	$0.70	$36,760	$0.40

Table 7: 2014 Forecasted Cumulative Tolling Revenue by Fiscal Year

Fiscal Year	Cumulative Toll Revenue (2011 Dollars, 2.5% Annual Inflation Rate)
2019	$7,600,900
2020	$15,778,000
2021	$20,498,800
2022	$24,272,700
2023	$27,132,000
2024	$29,115,000
2025	$31,242,700
2026	$33,525,700
2027	$35,975,500
2028	$38,604,000
2029	$41,424,500
2030	$44,450,800
2031	$47,831,800
2032	$51,604,000
2033	$55,787,300
2034	$60,063,600
2035	$64,667,700
2036	$69,624,700
2037	$74,961,700
2038	$80,707,700
2039	$86,894,300
2040	$93,555,000
2041	$100,275,700
2042	$107,030,600
2043	$113,954,200
2044	$120,674,600
2045	$127,106,100
2046	$133,233,300
2047	$139,157,600
2048	$145,215,400
2049	$151,383,400
2050	$157,660,000
2051	$163,699,300
2052	$169,473,900
2053	$175,452,200

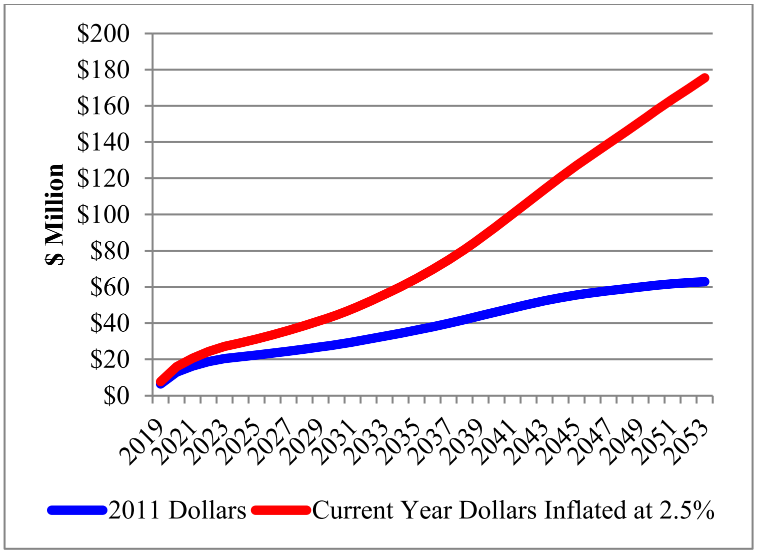

Figure 8: Graph. 2014 Northwest Corridor Cumulative Toll Revenue Forecast

Ongoing Operations - Energy Consumption and Pollutant Mass Emissions

Hourly energy use for each link and the mass of pollutant emissions generated on each transportation link are modeled using MOVES energy use and emission rates as a function of energy use for the observed operating conditions. Calculations for each link require the tracking of vehicle activity (vehicles per hour), fleet composition (mix of vehicle classes), on-road operating conditions (speed/acceleration activity that induces engine load), and environmental conditions (temperature, humidity, etc.). The MOVES model can predict energy use and emissions for any fleet and any operating condition. However, when modelers consider every combination of fleet composition, operating condition, pollutant type, fuel specification, inspection and maintenance program, temperature, humidity, etc., the number of unique combinations in a matrix of outputs exceeds nine billion cells. While the MOVES-Matrix model does allow users to link any scenario (any combination of MOVES inputs) with a scenario using Python scripts

(Guensler, et al., 2021; Liu, et al, 2018; Guensler, et al., 2018; xu, et al., 2016) the level of complexity was initially thought by the research team to be overkill for comparative scenario analysis and beyond the scope of this project. To simplify implementation within the spreadsheet framework, the modeling team first developed an assumed vehicle fleet that can be varied across limited dimensions by users.

The regional fuel specifications and inspection and maintenance program assumptions are fixed across all scenarios (using regional default analyses for regional modeling work conducted by the Atlanta Regional Commission and Department of Natural Resources). The vehicle class distributions employed by the Georgia Department of Natural Resources (DNR) and Atlanta Regional Commission (ARC) in modeling for regional planning are shown in Table 8 below. To facilitate spreadsheet calculations, the research team has collapsed these 13 vehicle classes into three categories (light-duty automobiles, medium-duty trucks, and heavy-duty trucks), also seen in the same table. The assignment of vehicles to general-purpose lanes across these three aggregated classes (LDVs, MDTs, and HDTs), summed from the table below, can be seen in Table 9. Because Express Lanes in Georgia do not permit commercial vehicle use, users can also select 100% LDVs for assignment to managed lanes. Hence, the users can apply two fleets in the analytical spreadsheet: 1) the metro area default fleet, or 2) a 100% light-duty vehicle fleet.

Table 8: Department of Natural Resources and Atlanta Regional Commission Fleet Composition and Modeling Tool Vehicle Class Assignment

MOVES ID (sourceTypeID)	MOVES Vehicle Class (sourceTypeName)	Activity Fraction (sourceTypeFraction)	Vehicle Class Assignment
11	Motorcycle	0.02836115	LDV
21	Passenger Car	0.35914832	LDV
31	Passenger Truck	0.52006361	LDV
32	Light Commercial Truck	0.05380505	MDT
41	Other Buses	0.00017208	HDV
42	Transit Bus	0.00024583	HDV
43	School Bus	0.00243376	HDV
51	Refuse Truck	0.00006574	HDV
52	Single Unit Short-haul Truck	0.02752990	HDV
53	Single Unit Long-haul Truck	0.00175723	HDV
54	Motor Home	0.00228626	HDV
61	Combination Short-haul Truck	0.00217154	HDV
62	Combination Long-haul Truck	0.00195952	HDV
NA	Total	1.00000000	NA

Table 9: Department of Natural Resources and Atlanta Regional Commission Fleet Composition and GT Model Class Assignment

Vehicle Class Assignment	Percent Activity General-Purpose Lanes	Percent Activity Express Lanes
LDV	90.8%	100.0%
MDT	5.4%	0.0%
HDT	3.9%	0.0%
Total	100.0%	100.0%

Vehicle age distributions, and technology subtype distributions within MOVES source types (vehicle classes), are fixed to match Atlanta regional distributions. The model employs the Atlanta summer fuel composition and includes the effects of the Metro Area inspection and maintenance program. Default MOVES temperature (87.3F) and humidity (53.8%) remain fixed across scenarios and cannot be changed by the user. Given the difficulty of properly weighting the VSP parameters that are employed in calculating VSP across different vehicle classes (A,B,C,M, and m), the current spreadsheet model assumes that all light-duty vehicles are MOVES Class 21, all medium-duty trucks are MOVES Class 32, and all heavy-duty vehicles are MOVES Class 62. The research team may modify this assumption in the next model release after performing model sensitivity analyses to assess the assumption impact on modal energy use and emission rates across scenarios.

As noted earlier, the Georgia Tech research team can implement MOVES-matrix using Python scripts to model any complex fleet composition and on-road scenario, but the spreadsheet is purposefully limited to ensure a reasonable analytical processing time given that second by second vehicle activity is allowed to be employed in the spreadsheet. This spreadsheet tool can be further enhanced to assess more complicated scenarios that may affect fleet composition or vehicle age distributions, but the current tool proves useful for a comparison across similar fleet composition scenarios.

Ongoing Traffic Noise Impacts and Pollutant Concentration Costs

Integration of outputs from the Traffic Noise Model (TNM) and the USEPA's AERMOD microscale dispersion model was beyond the scope of the project. However, the model is purposefully structured for such integration. The same link-and-node structure employed in the spreadsheet model for energy consumption modeling (as a function of fleet composition, on-road operating conditions, and ambient environmental conditions) tracks the variables that are needed to predict sound pressure levels (Decibels) and pollutant concentrations at any point in space surrounding the project. The roadway geometry characteristics, traffic volumes, vehicle fleet composition, and speed/acceleration profiles can be pulled for use in preparing the spatial and activity inputs for running the TNM and AERMOD.

Annual Crash Risk Costs and Impacts of Design Intervention

Although the integration of crash risk reduction across scenarios was beyond the scope of this project, the spreadsheet structure does provide vehicle fleet composition, traffic volumes, and on-road operating conditions for each link in the transportation network. Users can add additional worksheets to the model to track the integration of crash modification factors for specific intervention measures that affect one or more links in the system and may differ across scenarios (which are tracked in separate spreadsheets). If the user were also to add a table for monetary values per crash event, and a distribution of monetary values associated with crash severity, the tracking of economic benefits associated with safety interventions can be readily integrated.

ANNUAL MAINTENANCE COSTS

There are several direct costs associated with highway maintenance, such as the cost of labor, materials, and equipment. Likewise, there are many indirect impacts associated with the disruption of normal traffic patterns caused by maintenance activity, such as the value of time lost by drivers, impacts on energy use, impacts on crash risk (for drivers and for maintenance workers), and potential impacts on tolling revenue. The research team has not had access to any Georgia Department of Transportation resources regarding typical highway maintenance frequency, duration, scope, labor requirements, or materials and equipment involved in maintenance activities. This is because at-risk projects are not required to disclose actual maintenance costs, or even what the maintenance costs are likely to be (maintenance costs are paid from the toll revenues and are not reported to the sponsor). Thus, the research team has been unable to formulate reliable default assumptions for many critical calculation components. Due to a lack of data on typical Georgia highway maintenance frequencies, scopes, and impacts, these costs are not included in the current version of the spreadsheet-based model.

For analysis purposes, highway maintenance projects could be classified as either minor maintenance or major maintenance. Major maintenance encompasses any maintenance activity that requires the closure of one or more travel lanes (e.g., pavement repair, bridge repair, etc.) Minor maintenance encompasses maintenance that is performed without the closure of any travel lanes (e.g., mowing). Standard net present value calculations would be employed to convert future maintenance costs into present-day dollars using a 3.5% discount rate (Bernhard, 1992). The total net present values would then be converted into an equivalent annual cost to estimate annualized cost over the lifespan of the project (Bray et al., 2022). The model would allow users to enter assumptions regarding the anticipated frequency of minor and major maintenance activities, as well as the anticipated highway design lifespan, with default assumptions based on historic data from Georgia's highways.

Maintenance material and equipment cost estimations largely resemble the material and equipment calculations performed for initial project construction. As with construction, it is important to consider the direct monetary cost of materials and equipment, as well as energy consumed throughout the production and transportation of those materials and equipment to the job site. It is important to note that the construction material cost model relies on bid-based data, and it is therefore assumed that direct costs associated with equipment are priced into the material bids. That same assumption will not be applicable to the maintenance calculations, as highway maintenance will be performed by the

Georgia Department of Transportation itself. Thus, the research team would incorporate equipment capital costs into the model.

Similarly, the construction labor cost estimation components of the model also rely on bid-based data, which would not be applicable to maintenance work done in-house. Instead, assumptions regarding maintenance worker compensation rates will be derived from the salaries and reimbursements data for fiscal year 25 made available by the Georgia Department of Audits and Accounts (Georgia Department of Audits and Accounts, 2025).

Maintenance activity consumes energy directly through material transportation and equipment operation, but the greater energy consumption impacts will be caused by increased congestion induced by maintenance activity. Minor maintenance may contribute somewhat to traffic congestion, particularly if the maintenance work is accompanied by a speed limit reduction. Major maintenance involving the closure of one or more lane(s) will certainly have a drastic impact on traffic patterns in the area. Users can simulate the effects of minor and major maintenance activity using PTV VISSIM™, which would potentially allow them to quantify the travel time loss and marginal energy consumption increases caused by the maintenance activity. However, the research team was not able to undertake the simulation of maintenance activities for this project.

SUMMARY OF MODELING TOOL INTEGRATION

The managed lane lifecycle cost analysis model consists of several components, each of which models a separate portion of a managed lane's lifecycle. These components include planning and design costs, right of way acquisition costs, financing costs, construction material costs, construction equipment costs, construction labor costs, travel time impacts, toll revenue, on-road energy consumption, and maintenance costs. These modeling components leverage information and data from the Georgia Department of Transportation, academic literature, and an assortment of existing modeling software, including PTV VISSIM™ and MOVES.

CHAPTER 6. SPREADSHEET MODEL STRUCTURE

The methodologies outlined in the previous chapter are implemented within a spreadsheet modeling framework. Model integration is structured around the infrastructure network, where each set of calculations associated with the modeling framework are performed for each link in the final constructed network. The roadway link and node structure can be tailored around the different roadway classifications (e.g., around individual general-purpose links, managed lane links, ramps, and connecting arterials), and then broken into sub-segments as needed to track specific design elements associated with significantly different design criteria (e.g., number of lanes) or operating characteristics (e.g., weaving segments where congestion may form at a much higher rate). Differences in link construction costs can be estimated, when differences in link design and required bills of materials are available for each segment. In cases where corridor-level construction costs and bills of materials are tracked, the research team has proposed a mechanism for allocating these costs to system links (allocating average per-mile values by roadway classification). The spreadsheet modeling structure supports the integration of activity-based travel demand model outputs or microsimulation model results and allows analysts to assess differences in travel time, fleet composition, on-road operating conditions, energy consumption, and pollutant emissions across alternatives. That is, when a regional planning agency predicts link speeds and travel times for a scenario, these outputs can be loaded into the spreadsheet on a link-by-link basis to estimate the impacts. Later in this report, the research team will demonstrate how the link-based structure for roadway segments allows these costs to be tracked, and how simulation model outputs to be used in predicting energy consumption as a function of simulated operating conditions.

SPREADSHEET MODELING APPROACH

The network link-and-node structure employed throughout the modeling framework allow users to track differences in transportation link performance, construction cost, and operating costs across design and operation scenarios. Once the link and node structure is established in the primary spreadsheet, these data feed into three parallel processes (all of which employ the same physical network row-by-row in the spreadsheet). The first model estimates the costs for design, construction, and maintenance of infrastructure associated with each transportation link. The second spreadsheet model integrates outputs from travel demand models, simulation models, or monitored vehicle activity to predict roadway operating conditions on each link, and calculates ongoing user travel time, energy consumption, and emissions generation.

LINK-AND-NODE NETWORK

The transportation link-and-node structure in the spreadsheet model is designed to accept inputs from travel demand models (such as the Atlanta Regional Commission's Activity-based Model, or ABM), traffic simulation models (such as PTV VISSIM™), or map-based network structures (such as Open Street Map or ArcGIS). The spreadsheet model is designed to carry variables that are required for estimating design and construction costs as well as ongoing facility performance and operating costs. Facility design-oriented costs and construction costs require tracking facility characteristics, such as number of lanes, lane width, etc., to which bills of materials can be linked. Ongoing facility travel-time costs/savings/savings, energy use, and emissions require tracking of facility operations and performance characteristics, such as vehicle fleet composition, vehicle speed and acceleration profiles, and environmental conditions, for which MOVES energy use and emission rates can be linked. The variables employed in the link-and-node structure are described later in the report.

CONSTRUCTION COST MODELING

The design, construction, and maintenance components of the model are contained within one spreadsheet, with calculations based on the link and node input data. Link length, link type (Highway Travel Lane, Highway Bridge/Overpass, Arterial Travel Lane, or Arterial Bridge), and link construction year are the three- primary input variables. Outputs include total administrative cost, total material cost, and total fuel cost. Additionally, the model estimates total energy consumption in kilojoules and gallons of diesel fuel, as well as total CO_2, CO, NO_x, VOC, PM_{10}, and $PM_{2.5}$ emissions.

Each of these calculations relies on various numerical assumptions that may be adjusted by the user. For example, per-mile material quantities and costs are based on the material costs associated with the Northwest Corridor project. As such, the model by default assumes the use of approximately 10,000 tons of bituminous pavement per lane-mile at a cost of approximately $1,000,000 per lane-mile. Users can adjust these rates should they have access to data that is more relevant to their context.

Construction material energy consumption costs are calculated as a function of material quantities and material delivery distance. Each category of materials is associated with a DistancePerDelivery and QuantityPerDelivery variable. Delivery distances are based on the average distance between Georgia Department of Transportation approved material suppliers and the location of the Northwest Corridor project, and delivery quantities are based on various logistical factors including material size and weight. DistancePerDelivery and QuantityPerDelivery can be manually adjusted by the user if they have better information regarding the project location, locations of specific material suppliers to be used, and/or delivery logistics that may be unique to that project. Finally, users may also adjust the per-gallon cost of diesel fuel, which is set as $3.000 by default.

Construction and maintenance labor costs are a function of salary or hourly wages, benefit structures, and hours worked per lane-mile by job title. The spreadsheet contains associated labor variables for the construction-related positions outlined in Table 10. For each of these positions, users may adjust assumptions relating to compensation rates and billable hours.

Table 10: Construction Job Classifications Included in the Model

Equipment Operator I	General Trades Tech Supervisor
General Trades Technician I	Highway Maintenance Tech. Supervisor
General Trades Technician II	Heavy Equipment Operator I
General Trades Technician III	Heavy Equipment Operator II

TRAVEL TIME, ENERGY AND EMISSIONS MODELING

The overall spreadsheet structure for cost and benefits assessment is structured around the physical network, so that physical infrastructure and on-road vehicle activity can be processed in parallel. The network physical structure contains information about each link, including, facility type, number of lanes, link length, traffic volume, operating speeds, etc. In travel time and energy/emissions modeling, time spent on each link is a critical variable, which is derived from link distance and operating speeds. Modeled or monitored vehicle activity data from any desired source can also be tracked within the modeling framework and used in travel time, energy, and emissions modeling. Other required data include fleet composition (vehicle class and model year mix), on-road operating conditions (typically a second-by-second driving cycle, or average speed and facility type for which MOVES assumes driving cycle conditions to address engine load associated with speed and acceleration), and environmental conditions (e.g., temperature and humidity). Roadway grade can also be integrated into the energy and emissions analysis supported by MOVES energy use and emission rates given that road grade is simply another acceleration component against gravity.

The approach employed within the modeling framework includes three spreadsheets. The first spreadsheet processes second-by-second driving cycle (speed vs. time patterns used with MOVES to assess vehicle load and resulting energy use and emissions) to create Operating Mode bin distributions to which energy use and emission rates are assigned for each vehicle class (source type) and model year. Because the first spreadsheet is so large, and because each of the 109 MOVES-related driving cycle needs to be run for each of the 13 MOVES vehicle classes (source types), the first spreadsheet is processed 13 times (once per vehicle class), and the results are transferred into a second project spreadsheet "MOVES Duty Cycle VSP and OpMode Bin Outputs." This second spreadsheet summarizes the number of seconds on each cycle that each vehicle class spends in each of the 23 MOVES Operating Mode Bins. Because different vehicle classes employ different VSP parameters, each Operating Mode Bin distribution is different for each driving cycle, vehicle class, and regulatory technology group. The third spreadsheet is the "MOVES Duty Cycle VSP and OpMode Bin Processor" which accepts the processed driving cycle results from the second spreadsheet. This third worksheet calculates all energy use and emissions results across the 23 MOVES

Operating Mode Bin assignments. Because MOVES assigns a single energy use and emission rate value to each Operating Mode Bin by vehicle class, only 23 calculations are needed for each vehicle class operating on a roadway link.

- MOVES Duty Cycle VSP and OpMode Bin Processor - This first spreadsheet takes any second-by-second driving cycle (speed vs. time pattern used by MOVES to assess vehicle load and resulting energy use and emissions) and generate the Operating Mode bin distributions to which energy use and emission rates are assigned for each vehicle class (MOVES source type) and model year. The spreadsheet processes each second of activity for a vehicle source type and regulatory class, calculates vehicle specific power (VSP), and assigns the second of activity to an Operating Mode Bin. MOVES allows a user to assign any driving cycle to a transportation link, where engine load and energy use and emissions can be calculated for each vehicle class and model year on that link. However, the research team found that processing the second-by-second duty-cycles for the 109 driving cycles inflated the spreadsheet to about 150Mb, impeding calculation processing times. Inflating this spreadsheet to process individual driving cycles for 7,500 transportation links was simply not possible.
- MOVES Duty Cycle VSP and OpMode Bin Outputs - This second spreadsheet hosts the outputs from 13 different vehicle class runs across all 109 MOVES-related driving cycles from the MOVES Duty Cycle VSP and OpMode Bin Processor spreadsheet. Each run is performed one at a time for the 13 vehicle classes, and results are copied into this worksheet in vehicle class order. A second worksheet in the same file, sorts the outputs so that they can be carried

into the third worksheet with 13 vehicle classes per cycle, rather than 109 cycles per vehicle class.

- MOVES5 Bin Distribution Energy Processor - This third spreadsheet calculates travel time, energy use, and emissions per hour for every link in the modeled transportation system. Each link is tracked in the spreadsheet and carries the basic data required for travel time along the link (link length and average speed), as well as the fleet composition and operating conditions required for hourly MOVES modeling of energy and emissions per link. The spreadsheet currently handles 7,500 transportation links, with separate fleets assigned to general-purpose lanes and managed lanes, and with the capability of assigning many different driving cycles to these links. Users enter basic model output information from a travel demand or microsimulation model, assumptions about fleet composition, and the model predicts fleet vehicle-hours, energy use, and emissions.

Each of the three spreadsheets, and the variables and procedures undertaken in each worksheet within each spreadsheet, are described in more detail in Appendix D. However, every spreadsheet shares some common structural elements:

- The first worksheet in each spreadsheet is the results worksheet, summarizing the final outputs of the spreadsheet.
- The final worksheet in each spreadsheet is a model information worksheet that describes the changes made since the previous version of the model.
- All spreadsheet models are named Version 3.0. Initial spreadsheet structures were first designed for individual vehicles and individual roadway links. As

modeling progressed, the team had to modify the approaches significantly because the spreadsheets became too large and unwieldy as they were expanded to fleets and corridors (the energy modeling spreadsheet had to be broken into three components along the way).

- Users only enter data into worksheet cells that are highlighted in yellow. All other cells are either inputs from the MOVES (typically in other colored cells) or are calculated by the model.
- The xLookup function was used extensively within the spreadsheets to obtain model variables within a worksheet from cells in other worksheets.
- To ensure continuity within each spreadsheet, none of the spreadsheet models include cell references to other Excel files. If a new driving cycle is desired within the analytical process, users must modify the driving cycle processor, copy the results into the outputs excel file, and then integrate the driving cycle data into the bin processor spreadsheet.

CHAPTER 7. MODELING TOOL USE-CASE EXAMPLES

The spreadsheet-based lifecycle cost estimation model is designed so that it can be applied to the assessment of a variety of project types. This chapter describes four potential model use cases, including very large and complicated corridor-level projects that include the integration of Express Lanes, smaller design-build projects where bills of materials are generally available, the analysis of transportation control measures (TCMs) designed to change vehicle activity or individual travel behavior, and potential use in policy-oriented regulatory analyses. The four potential use cases for model applications presented in this chapter include: 1) a managed lane corridor expansion on I-75 (with modifications to and connectivity with existing managed lanes); 2) a more traditional at-grade highway conversion to access-controlled freeway; 3) a corridor-level traffic signal coordination project as a TCM example; and 4) a policy-oriented assessment under the National Environmental Policy Act to develop a categorical exclusion for HOV-to-HOT lane conversions. The research team elected to undertake one of the more complicated analyses for this report. The detailed case study implementation presented in Chapter 8 assesses the I-75/I-575 Northwest Corridor expansion project, where a reversible Express Lanes system was added to existing general-purpose-lane infrastructure.

MANAGED LANE CORRIDOR EXPANSION

In January 2026, the Georgia state government announced plans to allocate $1.8 billion dollars towards improvements to the existing I-75 managed lane corridor in Henry County, Georgia. Currently, the corridor includes two reversible Express Lanes with an approximate total length of 24 lane-miles that connect the I-75/I-575 interchange in the north with County Road 155 in McDonough to the south. These reversible lanes are typically open to southbound traffic in the morning (inbound) and northbound traffic in the evening (outbound), to facilitate commuter traffic to and from Atlanta. The proposed expansion would add an additional two Express Lanes (approximately 24 additional lane-miles) and remove the reversible functionality of the Express Lanes in favor of two permanent northbound Express Lanes and two permanent southbound Express Lanes. The following subsections provide further detail on how an agency would be best able to make use of the model to estimate the costs associated with such an extensive and complicated project. The spreadsheet-based lifecycle cost estimation model is designed to be applicable to this type of project.

Planning, Design, and Construction Cost Modeling

The planning, design, and construction component of the spreadsheet-based cost estimation model allows users to estimate costs associated with those respective phases of the project. The cost estimation model is based on the lane-miles of highway travel lanes, construction of highway bridges and overpasses, addition/modification of arterial travel lanes, and construction of arterial bridges and overpasses included in the project This component of the model contains several tabs that allow users to enter various data and assumptions relating to the project.

Parcel Data Entry

The Parcel Entry tab prompts users to enter information regarding any parcels of land that may need to be acquired to complete the project. Costs are calculated on a parcel-by-parcel basis, and the user may partition the managed lane corridor into as many or as few parcels as they deem necessary. Columns in which the user is expected to enter information are highlighted in green, and columns in which the user is not expected to enter information are colored gray.

The ParcelID column allows users to assign a name, numeric code, or other form of identification to each parcel. By default, the spreadsheet is populated with 1,000 parcel IDs, and users may adjust these IDs as they see fit. Another column is provided for parcel Acquisition Year, in which users enter the year in which the parcel of land was acquired or will be acquired (used in calculations that account for the impacts of inflation on land values). The Parcel Distance to Downtown Central Business District (miles), Parcel Area (in acres), and Parcel Type (Urban Residential, Urban Commercial, Suburban Residential, Suburban Commercial, Rural Residential, Rural Commercial, or Undeveloped) columns are used in estimating parcel values. The calculations based upon parcel characteristics are rooted in published reports and academic literature but can be overwritten by the user when better research data are available. The Parcel Acquisition Cost (user entry) column is an optional user entry column that allows users to directly enter the cost of acquiring each parcel as each parcel is acquired. If the user enters a value in this column, it will override the estimated parcel value produced by the model. The final Parcel Acquisition Cost Estimate column provides the calculated parcel values based upon all of the relevant inputs.

Link Data Entry

The Link Entry tab prompts users to enter information regarding the length and design of the managed lane corridor. Costs are calculated on a link-by-link basis, and the user may partition the managed lane corridor into as many or as few links as they deem necessary. Where possible, the designation of roadway links in the system construction estimates should match with the links in the transportation network that will be employed in vehicle activity modeling (although sometimes the modeled transportation links will be broken into sub-elements for improved cost estimation). The columns in which the user is expected to enter information are highlighted in green, and columns in which the user is not expected to enter information are colored gray.

The LinkID column allows users to assign a name, numeric code, or other form of identification to each link (populated with 1000 default link IDs that can be changed by the user). The Construction Completion Year column prompts users to enter the year in which construction work for the managed lane corridor finishes or is expected to finish (used for inflation calculations). The Link Length (lane-feet) and Link Length (lane-miles) columns ask users to enter the length of each link (users can use either of these two columns to define the length of each link). The length data are critical because the values are used in nearly every calculation within the planning, design, and construction component of the spreadsheet-based model. The Link Type column requires users to denote whether the link is a highway travel lane, highway bridge/overpass, arterial travel lane, or arterial bridge/overpass. This entry is used to calculate costs associated with construction materials and construction energy consumption. These four facility types are used throughout the modeling system for calculation of cost, energy use, and emissions.

The remaining columns in the planning spreadsheet contain model outputs. The Total Link Costs (in present day dollars) column reports the monetary expenses associated with planning, design, and construction work for each link. Likewise, the Administrative Costs, Material Costs, and Fuel Costs tabs report the costs associated with each respective project development expense type (on-road energy use is handled separately in the on-road vehicle activity and energy use calculation elements). The sum of these three columns is equal to the total project development cost. The Total Fuel Consumption (in gallons of fuel) and Total Energy Use (in kJ) columns report the expected energy consumption associated with construction activity. These estimates account for energy consumed by construction equipment as well as energy consumed by the transportation of materials to the construction site. Similarly, total emissions in grams for carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx), volatile organic compounds (VOC), and particulate matter emissions (PM_{10} and $PM_{2.5}$) are reported in separate columns for materials transport and construction activity. Separate spreadsheet columns are provided for each element described above, so that the user can see the elements that contribute to the total energy use and emissions by category.

Materials Cost Assumptions

The Material Cost Assumptions tab contains many of the underlying assumptions that affect the material cost calculations within this model component. These cells are populated with default assumptions rooted in data from previous Georgia Department of Transportation projects and academic literature. However, the user may adjust these assumptions to better reflect the specific conditions of the managed lane project in question, should they have access to more accurate data. Columns in which the user is expected to enter information are highlighted in green, and columns in which the user is not expected to enter information are colored gray.

The Material Category column contains a list of material types that would likely be used in a managed lane highway project. The full list of included material types is shown in

Appendix A of this report. The Quantity Units column contains the units associated with each material type (e.g., tons, linear feet, cubic yards, each, gallons, hours, etc.). The Unit Cost column lists the anticipated cost of each material type on a per-unit basis. These cells are currently populated with default values based on material costs for the Northwest Corridor managed lane project. This information is used to calculate link material costs. The user may adjust these default entries if they have access to more accurate unit cost data for the specific project in question.

Users enter data into the Quantity per Highway Lane-Mile, Quantity per Highway Bridge/Overpass Lane-Mile, Quantity per Arterial Lane-Mile, and Quantity per Arterial Bridge/Overpass Lane-Mile columns for their project, representing the anticipated quantities of each material type that will be used on a per-lane-mile basis. This information is used to calculate link material costs, as well as energy consumption associated with material delivery. These cells are currently populated with default values based on material quantities for the Northwest Corridor managed lane project (forthcoming in Chapter 8), but users can change these default entries for their specific projects.

The Material Delivery Distance (Miles) column contains the expected distance a delivery vehicle would have to travel to deliver each material type from its respective production facility to the job site. This information is used to calculate costs associated with material delivery. These cells are currently populated with default assumptions based on the production locations of items included on the Georgia Department of Transportation Qualified Products List relative to the Northwest Corridor managed lane project area. In cases where there are multiple qualified vendors for a particular material type, the average of each vendor's distance is used. Users may adjust these assumptions if material vendors for the specific project in question are known.

The Quantity per Delivery column lists the anticipated quantity of each material that could be delivered in a single shipment to the job site. This information is used to calculate costs associated with material delivery. These cells are currently populated with default assumptions based on various academic and industry sources. The user may adjust these assumptions if they have access to more accurate information for the specific project in question.

The Material Delivery Energy Consumption Rate (kJ/mi) column lists the anticipated energy efficiency of material delivery vehicles, on a kilojoule-per-mile basis. This information is used to calculate material delivery costs. These cells are currently populated with default assumptions based on academic literature and the Environmental Protection Agency's Motor Vehicle Emissions Simulator (MOVES) model. Users may adjust these values if they have access to data that more accurately relates to the specific project in question. The Cost of Fuel ($ per Gallon of Diesel) column lists the anticipated cost of diesel fuel. This value is used to calculate material delivery costs. The cells are currently populated with default assumptions based on the cost of diesel fuel in January 2026. Users may adjust these assumptions to better reflect the anticipated cost of diesel fuel during construction.

The Annual Inflation Rate column contains the anticipated rate of inflation associated with each material type. This information is used to convert between net present value and anticipated future material expenses. This column is currently populated with default assumptions based on data collected by the United States Bureau of Labor Statistics and the United States Federal Reserve. Users may adjust these assumptions if they have access to more accurate inflation rates for each material type.

The remaining columns contained within the Material Cost Assumptions tab contain various calculations that are based on these material assumptions. These calculations include fuel use costs per delivery, per highway lane-mile, per highway bridge/overpass lane-mile, per arterial lane-mile, and per arterial bridge/overpass lane-mile. Material delivery energy consumption in kJ and gallons of fuel are also reported for deliveries and each of the four facility-type categories. Material delivery emissions calculations are output in specific spreadsheet columns for CO_2, CO, NOx, VOC, PM_{10}, and $PM_{2.5}$ for deliveries and each of the four facility-type categories.

Equipment Cost Assumptions

The Equipment Cost Assumptions tab contains assumptions regarding the energy consumption of various construction equipment. Columns in which the user is expected to enter information are highlighted in green, and columns in which the user is not expected to enter information are colored gray.

The Equipment Type column lists the various types of construction equipment that are expected to be used for the construction of a managed lane project. The Fuel Consumption (in gallons per lane-mile) column lists the anticipated fuel consumption of each type of construction equipment on a gallon-of-diesel-per-lane-mile basis. These cells are currently populated with default assumptions based on academic literature. Users may adjust these assumptions if they have more accurate information pertaining to the fuel efficiency of the construction equipment used for the specific project in question. Similarly, the Cost of Fuel column (in dollars per gallon) lists the anticipated cost of diesel fuel. This value is used to calculate material delivery costs. The cells are currently populated with default assumptions based on the cost of diesel fuel in January 2026. Users may adjust these assumptions to better reflect the anticipated cost of diesel fuel during construction. The remaining columns contained within the Equipment Cost Assumptions tab contain various calculations that are based on the assumptions described above. These calculations are output in specific spreadsheet tabs that provide the results for fuel use (gallons and $), energy use (kJ/lane-mile), and emissions of CO_2, CO, NOx, VOC, PM10, and PM2.5 (grams/lane-mile).

Administrative Cost Assumptions

The Administrative Cost Assumptions tab contains assumptions regarding costs associated with various administrative activities. Columns in which the user is expected to enter information are highlighted in green, and columns in which the user is not expected to enter information are colored gray.

The Expense Category column contains the list of various administrative costs expected to be associated with a managed lane construction project (a full list of these expenses is included in Appendix B of this report), and the Units column contains the unit associated with each expense category. The Bid Total per Lane-Mile column contains the expected costs of each administrative activity on a per-lane-mile basis. These cells are currently populated with default assumptions based on the expenses associated with the Northwest Corridor managed lane project, but users can adjust these assumptions if they have access to more accurate expense data for each expense category.

GDOT Employee Cost Assumptions

The GDOT Employee Cost Assumptions tab contains assumptions regarding costs associated with labor performed by Georgia Department of Transportation employees. Columns in which the user is expected to enter information are highlighted in green, and columns in which the user is not expected to enter information are colored gray.

The Position column contains a list of employee job titles at the Georgia Department of Transportation that are expected to perform planning, design, and/or administrative work for a managed lane project (a full list of these positions can be found in Appendix C of this document), and the adjacent Annual Salary column contains the expected salaries associated with each position. The Hourly Wages column contains the anticipated hourly wages associated with each position (annual salary divided by a 40-hour work week and 52 work-weeks per year). These cells are currently populated with assumptions based on publicly available Georgia Department of Transportation salary data, but users can adjust these assumptions if they have access to more accurate data. The Overhead Rate column lists the expected overhead rate associated with each position (currently populated with assumptions based on industry sources), but users can update these assumptions if they have access to more accurate overhead rate information.

The Billable Hours Per Lane-Mile column contains a list of billable hours associated with each position on a per-lane-mile basis, again currently populated with default assumptions based on industry sources that users can update if they have access to more accurate billable hour information. Finally, the Employee Cost Per Lane-Mile column contains the anticipated costs associated with each position on a per-lane-mile basis.

These cells are calculated as a function of hourly wage, overhead rate, and billable hours per-lane-mile.

Contractor Cost Assumptions

The Contractor Cost Assumptions tab contains assumptions regarding costs associated with labor performed by contractors for a managed lane project. Columns in which the user is expected to enter information are highlighted in green, and columns in which the user is not expected to enter information are colored gray.

The Position column contains a list of contractor job titles. The Bid-Based Total per Lane-Mile column contains estimated costs associated with each position on a per-lane-mile basis. These cells are currently populated with assumptions based on contractor expenses for the Northwest Corridor project, but users can adjust these assumptions if they have access to more accurate contractor cost information.

AASHTOWare Database

The AASHTOWare Database tab contains data sourced from the AASHTOWare Project Cost Estimator model. This tab is not currently used by the spreadsheet-based model. However, the integration of AASHTOWare into this model would yield more accurate material expense data. As such, the user may optionally use this tab to calculate material costs, replacing the Material Costs column on the Link Entry tab. Columns in which the user is expected to enter information are highlighted in green, and columns in which the user is not expected to enter information are colored gray.

The GDOT Pay Item Index Code column contains a list of every material reference code listed in the Georgia Department of Transportation Pay Item Index. These reference codes are used by the AASHTOWare Project Cost Estimator to calculate material expenses. The Units column contains the unit associated with each item listed on the Georgia Department of Transportation Pay Item Index (e.g., tons, hours, cubic yards, etc.). The Item Description column contains the name of each item included on the Georgia Department of Transportation Pay Item Index, and the Unit Cost column contains the unit cost of each item on the Georgia Department of Transportation Pay Item Index, as calculated by the AASHTOWare Project Cost Estimator. These cells are currently populated with AASHTOWare outputs for each item (in instances where there is insufficient data for AASHTOWare to calculate a unit price, the cell has been left blank). Users may adjust these values if they have more up-to-date material price data.

The Quantity per Lane-Mile column contains a list of quantities for each item included on the Georgia Department of Transportation Pay Item Index, on a per-lane-mile basis. Users may enter values based on the material quantities used for the managed lane project in question. The Material Cost column calculates the cost of each material on a per-lane-mile basis, as a function of material unit costs and material quantities per lane-mile. Users may use these values in combination with the link lengths listed on the Link Entry tab to produce more accurate material cost estimates per link.

Vehicle Activity and Energy Use Modeling

For very large complex networks, a PTV VISSIM™ microscopic model instance can be created in which every roadway, lane, ramp, right turn channel, left turn bay, etc. is represented as a links in the simulation domain. Vehicles flow into the system from “parking lots,” cruise from link-to-link, interacting with traffic signal controls and other vehicles within the domain, as each vehicle makes its way from its network origin location to its network departure location (also represented as parking lots). The lion's share of the modeling work associated with any simulation project is the development of the physical model designed to represent the transportation infrastructure system in the microscopic model, and efforts required to QA/QC the network and simulation performance.

In larger networks, microscopic simulation can include the integration of travel demand model outputs to establish the origin-destination boundary conditions for the simulation domain, defining the traffic flows into and out of the simulation. Vehicles enter the PTV VISSIM™ -modeled network at the demand-model-predicted boundary entry edge and exit the PTV VISSIM™-modeled network at the demand-model-predicted boundary exit edge. PTV VISSIM™ takes control of every vehicle within the simulation process, using car following theory and a variety of driver and vehicle behavior algorithms (described in more detail in Chapter 8), predicting the interactions of every vehicle with traffic signal timing and with other vehicles as they move through the simulation to their desired destination point. PTV VISSIM™ retains the flow and speed data for every link in the simulation for use in traffic flow and energy consumption analysis for any simulated project alternative.

The spreadsheet modeling tool tracks vehicle activity for each link in the modeled highway network (whether this comes from PTV VISSIM™ or from a travel demand model) and then calculates use and emissions for each link as a function of vehicle fleet composition and on-road operating conditions for each link (discussed in Chapter 6). To perform these calculations, the model requires inputs for link length, traffic volume, fleet composition (vehicle source type and model year distributions), and specific on-road operating conditions (e.g., assigned driving cycles or average speeds). By accepting outputs directly from regional travel demand models, such as the Atlanta Regional Commission's Activity-Based Model (ABM), or microscopic simulation tools like PTV VISSIM™, the framework seamlessly translates predicted link speeds and traffic flows into actionable operational data.

As described in Chapter 6, the spreadsheet-based modeling tool divides the energy use and emissions calculation workload across three interconnected spreadsheets (to manage the computational complexity associated with using MOVES modeling methods). The third and final spreadsheet in that process ("MOVES5 Bin Distribution Energy Processor") brings the physical network and vehicle activity data together. This spreadsheet applies the pre-processed OpMode bin distributions and MOVES-derived emission rates to the specific traffic volumes, speeds, and fleet compositions assigned to each roadway link. Capable of processing up to 7,500 individual transportation links, this final processor calculates the total travel time, energy use, and emissions per hour for the entire corridor, enabling the planners to rapidly compare the operational performance of various facility designs and fleet scenarios.

AT-GRADE TO CONTROLLED ACCESS HIGHWAY CONVERSION

In January 2026, the state of Georgia also announced plans to allocate $200 million towards the conversion of a portion of Georgia State Route 316 from an at-grade highway to an access-controlled freeway. The upgrades would be applied to an approximately 33-mile-long corridor, connecting the SR-10/SR-316 interchange in Lawrenceville and the SR-20/SR-316 interchange in Athens. Nearly all construction activities will concentrate on the removal of existing at-grade signalized intersections and the installation of grade-separated interchanges.

Once again, the spreadsheet-based lifecycle cost estimation model can be used to model the lifecycle costs associated with traditional highway improvements or the conversion of major signalized corridors to limited access highways. The application of the tools to a more traditional case study is considerably less complicated than the I-75 Express Lanes system described earlier. The same general modeling approach is employed with this proposed conversion project as described in the previous section, so each subsection describing data input requirements will not be repeated here.

Planning, Design, and Construction Cost Modeling

The Planning, Design, and Construction component of the model also requires users to create a link-and-node representation of the project. Users must enter the lane-mileage associated with each link, as well as the type of link (highway travel lane, highway bridge/overpass, arterial travel lane, or arterial bridge/overpass). Similarly, users must enter the area of any land parcels that must be acquired to complete the project, as well as the parcel's current land use and the distance from that parcel to downtown Athens.

To use the Planning, Design, and Construction component of the model, it is preferable to have a bill of materials and their corresponding Georgia Department of Transportation Pay Item Index codes, thus allowing the user to use data sourced from AASHTOWare Project Cost Estimator. However, in the absence of a complete bill of materials, the model will still be able to predict material costs on a per-lane-mile basis using historic expense data from the Northwest Corridor (NWC) managed lanes expansion project (as will be discussed in Chapter 8).

Vehicle Activity and Energy Use Modeling

To use the operations component of the model, it will be necessary to perform PTV VISSIM^{TM} analyses of traffic patterns pre-construction, during construction, and post-construction. It is only possible to calculate travel time savings after first modeling baseline travel times for a no-build scenario. If assessing across project alternatives, similar construction and post-construction scenario analyses would be performed for each alternative design. Baseline and future condition assessment supports the marginal costs and benefits comparisons against the no-build alternative (and across alternatives). Note that construction activity will likely result in increased traffic on adjacent arterial roads, and post-construction traffic patterns will likely divert traffic away from adjacent arterials and onto State Route 316. Changes in traffic patterns can be predicted by monitoring fleet activity via license plate reading systems as described in previous SRTA before-and-after assessments (Guensler, et al, 2022a, 2022b; Khoeini and Guensler, 2014).

ASSESSMENT OF CORRIDOR-LEVEL TRAFFIC SIGNAL COORDINATION

The coordination of traffic signal timing to provide “green wave” progression (where vehicles arrive at each consecutive traffic signal on its green phase) has been known for more than 25 years as one of the most cost-effective transportation control measures, significantly reducing traffic delay, fuel consumption, and vehicle emissions (Unal, et al., 2003; Rakha, et al., 2000; Hallmark, et al., 2000; Guensler, 1998; Kahng, et al., 1982). Traffic signal timing allows platoons of vehicles on a major arterial to travel through multiple intersections without stopping. The reduction in energy use on the mainline is much greater than the increase in delay-related emissions for traffic on lower-capacity arterials crossing the primary arterial (Kwak, et al., 2012; Stevanovic, et al., 2012). Where major arterials meet, future traffic signal coordination can be expanded across multiple corridors using AI to optimize flows, minimize delays, and reduce energy use (Wu, et al., 2025). Alshayeb, et al. (2022) summarized the results from more than 60 technical papers related to the impacts of traffic signal timing, finding fuel and emissions savings that range from 2% to 48% depending on methodology. The evidence in the literature is consistent that signal timing optimization provides cost-effective energy savings.

Planning, Design, and Construction Cost Modeling

Traffic signal coordination is a relatively low capital cost approach to increasing effective capacity of complex arterial networks. Costs include planning, capital equipment, communications, and operations and maintenance. Costs for corridor traffic signal coordination can vary significantly by corridor and intersection complexity, corridor length, required data transmission (e.g., edge computing traffic count data transmitted by cellular vs. live video feeds to a traffic management center that may require fiber installation), and whether adaptive signal control is employed. While most traffic signal corridors already include hardware, upgrades to more advanced controller cabinets and replacement of traffic signal hardware, upgrading pedestrian push buttons, and updating signage to ADA design standards can be quite costly. Adaptive signal control, which can significantly improve arterial performance by changing traffic signal cycles to respond to real-time traffic demand, also requires the integration of traffic detection hardware and potentially the integration of proprietary software. The spreadsheet-based lifecycle cost estimation model is designed specifically to assess the monetary costs associated with corridor components based either on real costs provided by the agency (and/or estimated costs provided by AASHTOWare integration) with upstream embodied energy costs coming from the literature. With respect to quantifying operational benefits, modeling now needs to account for the vehicle activity on the corridor and the resulting operating conditions on each link in the corridor traffic signal network that will be used in energy and emissions modeling.

Vehicle Activity and Energy Use Modeling

Traffic signal coordination is traditionally modeled using microscopic simulation modeling tools such as PTV VISSIM™. As discussed earlier, a travel demand model can also be used in conjunction with the PTV VISSIM™ model, where the travel demand model provides vehicle origin-destination pairs, defining where trips enter and depart the microsimulation domain.

The PTV VISSIM™ modeling approach allows modelers to integrate complicated traffic signal timing plans and to integrate adaptive signal control, where detection of vehicles in the system can be used to automatically change signal timing to improve overall system efficiency. Because the link-by-link PTV VISSIM™ simulation results can feed directly into the modeling tool along with simulated speed-acceleration profiles for individual vehicles, the spreadsheet-based lifecycle cost estimation model is perfectly suited to such analyses. As was described earlier, the tracking of vehicle activity and operating conditions on a link-by-link basis makes the spreadsheet-based modeling tool ideal for such assessments.

The spreadsheet-based tool can be employed to assess the cost-effectiveness of traffic signal coordination projects (or other transportation control measures for which before and after traffic volumes and operating condition data are modeled or monitored). Capital and operating expenditures to coordinate traffic signals on major arterial corridors (especially complex corridors) can be significant. The public is often made aware of these costs through traditional or social media outlets because these projects are included in transportation plans and costs are itemized in transportation improvement programs. However, the benefits for traffic signal coordination are much more diffuse, with each traveler receiving small travel time and fuel savings. Most users are likely to notice small improvements to their daily travel experience along signal-coordinated corridors, while some travelers that cut across the coordinated mainline will potentially experience slight increases in travel time. The collective benefits to individual users over the entire year become much more significant but are difficult for travelers to conceptualize. Collectively, across all users, the user benefits of coordinated signal timing far exceed project costs, and the return on investment far outpaces most other transportation control measure investment alternatives. The spreadsheet calculator allows analysts to quantify system-wide travel time and fuel savings and compare these savings to the capital and ongoing operating expenses (to maintain equipment, process data, and continually enhance optimization algorithms) implemented on the corridor. Hence, the calculator can be used to quantify the return on investment of corridor signal coordination and compare this return to other transportation strategies designed to improve system efficiency.

Because the spreadsheet-based modeling tool carries link-by-link predictions of vehicle activity (traffic volumes) and the operating conditions on each link (average speeds from

PTV VISSIM™ or the travel demand model), energy use and emissions are directly predicted within the model. The research team has demonstrated in previous work that PTV VISSIM™ can retain the speed/acceleration profile of every vehicle-trip modeled (model run time is significantly increased to support the write functions in PTV VISSIM™), such that energy use and emissions calculations could be performed using the second-by-second data for every vehicle in the modeled system. Although the current version of the tool is not configured to assess the energy impacts of each individual vehicle using second-by-second data, because the spreadsheet calculation process becomes unwieldy, the features and calculation functions are actually integrated in the cycle processing spreadsheet (and actually used as a teaching tool in the Corridor Impact Assessment CE4803 undergraduate course at Georgia Tech). As will be discussed in other sections of this report, the team will recommend that existing Python code be adapted to feed the spreadsheet calculator the values needed for each specific fleet and modeled transportation link, where the user specifies the distribution of vehicle classes, model year distributions within each source type, and on-road operating conditions for each combination. This will reduce the size and complexity of the spreadsheet itself, allowing calculations for what-if scenarios to process much more quickly.

DEVELOPMENT OF CATEGORICAL EXCLUSIONS UNDER NEPA

The National Environmental Policy Act (NEPA) requires the preparation of an Environmental Impact Statement (EIS) whenever a federal project has a significant impact on the human environment. Full EIS preparation is a costly endeavor, requiring modeling and documentation of all reasonably foreseeable impacts. Some types of projects, such as heavy rail capacity expansion, automatically proceed to the preparation of an EIS because there is no doubt that a significant impact will arise. Whenever there is a question as to whether a major project is likely to have a significant impact, an Environmental Assessment (EA) is typically prepared to assess the impacts, and the lead agency either publishes a Finding of No Significant Impact, allowing the project to proceed without an EIS, or finds that there are significant impacts that warrant the preparation of a full EIS. Fortunately, the majority of transportation projects (i.e., the huge number of smaller or routine transportation projects) are demonstrated to have no significant impact on the environment and are able to proceed without the preparation of a full EIS. When a pattern exists for a class of routinely assessed transportation projects consistently being demonstrated to have no significant impact, a Categorical Exclusion (CE) can be developed under 23 CFR 771.117 for that project type. The CE allows future projects of the same nature to be implemented without the need for preparation of an EA or EIS, providing that pre-defined boundaries or specific limiting conditions are in place to ensure that extraordinary circumstances will not result in a significant project-specific impact.

Historically, CEs have been developed for routine projects that have been previously assessed multiple times, and in multiple locations. For example, categorical exclusions have been established for classes of projects such as traffic signal modernization and optimization, highway lighting retrofits, construction of bicycle lanes and pedestrian facilities within existing roadways, highway rest area rehabilitation, highway safety improvements (e.g., barrier installation), pavement rehabilitation, adoption of carpooling incentives, etc. The USDOT regulations limit the adoption of categorical exclusions to projects and project classes that will not have a reasonably foreseeable significant impact on the human environment, specifically excluding certain types of major roadway capacity expansion projects in 23 CFR 771.115(a) and excluding from CE consideration projects that will induce significant impacts on planned growth or land use, will have a significant impact on travel patterns, or will have a significant impact on air quality or noise impacts (23 CFR 771.117(a)). In defining a new CE, these analytical determinations must be made based upon agency expertise and supported by evidence in the regulatory adoption process under the Administrative Procedure Act (APA).

On three previous occasions, the United States Department of Transportation has approved project-specific CEs for individual managed lane projects for the Washington State SR 167 HOT Lanes, Minnesota's I-394 MnPASS Express Lanes, and Georgia's I-85 Express Lanes. General evidence cited for approval of these case-study CEs includes the predicted reduced congestion, improved flow stability, and reduced idle and acceleration activity (stop-and-go conditions) that lead to lower energy use and emissions, and that although peak-period vehicle throughput may increase slightly, changes in emissions are typically small in magnitude and geographically limited, and often offset by adjacent facility congestion relief. The detailed before-and-after analyses for the I-85 conversion conducted by the Georgia Institute of Technology (long after the USDOT CE approval) provide the most compelling evidence-based upon monitored pre-and-post facility opening data, that the Atlanta I-85 HOV-to-HOT conversion did not yield any significant increase in emissions or air quality impacts, with observed changes primarily reflecting operational redistribution of traffic (Guensler, et al., 2022a, 2022b). Taken collectively, the analyses of these three HOV-to-HOT conversions support FHWA's position that such conversions do not reach a level of significance that would require the preparation of an EA or EIS under NEPA. Given the findings from these previous case studies, a compelling case can be made for the development of a category-wide CE for HOV-to-HOT conversions. The agency would only need to perform and document additional analyses that establish project boundary conditions under which the agency can be assured that extraordinary circumstances will not exist (i.e., no significant impacts will arise). Once the USDOT integrates documentation demonstrating why they are assured that no significant impacts will arise, and the proposed CE and properly processed under the rulemaking provisions of the USDOT and the APA (draft proposal, response to comments, final approval), any future HOV-to-HOT project that falls within these boundary conditions will be able to proceed under the new CE (no EA/EIS required). The spreadsheet-based tool developed by the research team and presented in this report can be employed to assess a variety of conversion projects and establish such boundary conditions.

Planning, Design, and Construction Cost Modeling

The development of a CE for HOV-to-HOT conversions under NEPA does not require an assessment of planning, design, and construction costs. The only relevant aspect of the analysis is whether this type of project will yield a significant impact on the human environment. Hence, all of the analytical work focuses on the operational assessment side to assess changes in vehicle activity and environmental impacts.

Vehicle Activity and Energy Use Modeling

As outlined in the three previous examples for application of the spreadsheet-based modeling tool, any potential conversion scenarios can be assessed within the spreadsheet-based modeling tool. Given the empirical before-and-after findings for the I-85 project, it would make sense to first affirm the projections that supported the CEs for the Washington State SR 167 HOT Lanes and Minnesota's I-394 MnPASS Express Lanes. The researchers could then turn their attention to performing sensitivity analysis for a set of before-and-after scenarios for the I-85 project, using an activity-based travel demand model as an input to the process, to establish whether general-purpose lanes must be congested beyond a certain severity and/or whether the HOV lanes need to reach flow breakdown on a regular basis (as was the case pre-construction on I-85) as a condition of finding that the conversion will have no significant impact on travel patterns and emissions. Alternatively, the research may find that these lanes do not have to be congested at all as a pre-condition for conversion (i.e., no significant impacts will result from the conversion with or without the presence of congestion).

SUMMARY OF MODEL USE-CASE EXAMPLES

This chapter summarizes four real-world transportation applications for which the spreadsheet-based lifecycle cost estimation model is a suitable tool for assessing potential changes in before-and-after savings in user travel time and energy use. In reverse order, the chapter showed how the modeling tool could be applied in a policy-oriented scenario to demonstrate that a specific project type (HOV carpool lane conversion to high-occupancy toll lanes) could be shown to have no significant impact on energy use, pollutant mass emissions, and downwind pollutant concentrations, to support the development of a categorical exclusion under NEPA. Another proposed case study presented in this chapter was for the implementation of corridor and network traffic signal coordination, as an example of a transportation control measure for which microscopic PTV VISSIM™ traffic simulation model outputs can be derived and applied.

The chapter also discussed how the modeling tool could be applied to traditional design-build projects, where project alternatives can be assessed in parallel or in sequence, and where bills of materials are generally readily accessible. Finally, the chapter presented the proposed assessment of the $1.8 billion improvement of the I-75 (South) reversible Express Lane corridor in Henry County, Georgia, as a good example of how the modeling tool can be implemented for very complex networks.

To further demonstrate how the modeling tool can be implemented for these huge projects, the next chapter in this report shows how the model could have been applied to the I-75/I-575 Northwest Corridor expansion project, a project that employs the private partner "at-risk development" approach (and includes reversible Express Lanes). In Chapter 8, the research team will show how the spreadsheet-based modeling tool could have been applied to the reversible Express Lane project final design (using data from the current post-build system) and to a hypothetical alternative design that would have involved building two additional non-reversible general-purpose lanes in each direction on the corridor. In the NWC case study chapter that follows, complex modeling can involve the simulation of the corridor before-and-after modification using the PTV VISSIM™ microscopic simulation tool, and/or the Atlanta Regional Commission's activity-based travel demand model (ABM), providing link-level traffic flows with speed-acceleration profiles or average speed data.

CHAPTER 8. PTV VISSIM™ CASE STUDY DEVELOPMENT

A major component of this research project was to demonstrate the application of the lifecycle assessment modeling framework for a managed lane project. The Metro Atlanta Georgia Northwest Corridor (NWC) was selected for this case study. The research team developed a microscopic traffic simulation model for the NWC under two scenarios: 1) the baseline current system with reversible managed lanes and 2) a synthetic corridor in which the reversible managed lanes are replaced with additional permanent general-purpose lanes in each direction of travel. This case study chapter allows users to see how traffic simulation models (and/or travel demand model outputs) can be employed in the analytical framework and how the modeling tool identifies and includes costs and benefits that are directly attributable to the construction of reversible managed lanes versus traditional capacity expansion. The baseline scenario with reversible Express Lanes and the Synthetic Corridor scenario with two additional general-purpose lanes in each direction were both modeled in PTV VISSIM™. The research team anticipates that a supplemental chapter showing comparative PTV VISSIM™ outputs for these two scenarios will be released as a supplement to this report in May 2026.

In this chapter, the software's traffic modeling capabilities are described, emphasizing specific details of features useful to the project: dynamic traffic assignment, managed lane facilities, and output metrics. Also described is the process of modeling the NWC, which includes the upgrade process between versions of PTV VISSIM™, the limitations of the process, and the upgraded model's performance metrics. Following is a description of the synthetic corridor model, its development, and its performance metrics.

Overview of PTV VISSIM™ Capabilities

PTV VISSIM™ is a microscopic traffic simulation software used by transportation engineers and planners to model individual vehicles' movements and interactions across a roadway network under different operating conditions (Xu et al, 2016). The roadway model represents roads as objects called links, but additional network objects include signal heads, detectors, stop signs, and desired speed decisions. To model traffic across the network, users can define vehicle inputs at specific locations and then create vehicle routing decisions at different points in the network or provide turn volume ratios at each intersection (Fellendorf and Vortisch, 2010). With this information, the program can simulate vehicles at the desired frequency (usually 10 Hz) and track simulated vehicle second-by-second trajectories through the network to calculate detailed information on vehicle and system performance, including speeds, travel times, volumes, delay, and queue length at selected locations. Among microscopic traffic simulation models, PTV VISSIM™ stands out for its ability to replicate observed traffic conditions realistically and consistently (Fellendorf and Vortisch, 2010, and Al-Msari et al., 2024). PTV VISSIM™ is applicable to a variety of problems: identifying bottlenecks (Halkias et al., 2007), analyzing signal control strategies (Stevanovic et al., 2008, and Rou et al., 2024), studying operational impacts during construction, estimating vehicle emission modeling (Abou-Senna and Radwan, 2013; Xu et al., 2016, and Manjunatha et al., 2022) and more (Fellendorf and Vortisch, 2010).

The original Vissim model was developed in Dr. Hans Hubschneider's dissertation, which described the concept of assembling road networks from predefined components (Hubschneider, 1983). This academic foundation later transformed into the release of

PTV VISSIM™ 1.00 as a commercial traffic simulation tool by PTV Group in 1993 (Vortisch, 2014). The model has been in continuous development for more than 30 years, with the current version being PTV VISSIM™ 2025.

PTV VISSIM™ models travel behavior in detail based on three interconnected blocks: 1) infrastructure, which defines physical road and rail networks and fixed elements such as detectors and signs; 2) traffic demand and vehicle flow, which specifies vehicle characteristics, origin-destination flows, routing, and public transport services; and 3) traffic control, which governs intersections, priority rules, and signal operations. These three blocks interact continuously during simulation and create model outputs. The outputs include vehicle animations, traffic control states, and traffic operation dynamics and statistics (Fellendorf and Vortisch, 2010). Users have the option to define routing via static assignment (user-defined) or dynamic assignment (computer-defined). The latter option uses iterated simulations that allow modeled vehicles to choose different routes based on the costs incurred during previous iterations (Boodhoo, 2025). Furthermore, for advanced research applications, PTV VISSIM™ allows for external control and automation through its Component Object Model (COM) and Event-Based Scripts interface, enabling users to run scripts (e.g., Python, MATLAB) for iterative simulations or custom algorithm testing (PTV Group, 2025).

Dynamic Traffic Assignment

PTV VISSIM™ users can define traffic assignment manually and intersection-by-intersection with static route choices. However, another method, known as dynamic traffic assignment (DTA), allows simulated vehicles to choose their routes dynamically through the network based on origin-destination (O-D) pairs and network travel times.

The simulation is run for multiple iterations, allowing vehicles to learn from previous iterations, so the model gradually converges into an equilibrium state in which each vehicle has found its optimal route.

DTA is particularly appropriate for large and complex networks such as the NWC, where multiple reasonable route choices exist. It is also suitable for models where route choice behavior itself is a critical component. DTA is commonly used to evaluate operational and policy interventions that influence traveler decisions, including toll pricing strategies, managed lane facilities, and changes in signal timing or traffic control. Because vehicle routes are not fixed, the model can reflect adaptive responses to congestion and pricing across competing corridors.

The implementation of DTA requires several components not present in a model using static assignment. First, the user must define traffic analysis zones between which vehicles can travel. The user must also place parking lots on the roadway links to represent each zone's entry and exit locations. Second, the user must define the number of vehicles traveling between each pair of zones, which may vary over time. This information is stored in O-D matrices. Third, the user must create nodes at all intersections, entrances, and exits. Using the links, parking lots, and nodes, the software creates a set of link segments (also known as edges), from which it then constructs all the feasible paths between the O-D pairs. Finally, the user specifies the parameters for dynamic assignment, including convergence criteria and cost-function weights, that govern route-selection behavior.

The DTA procedure is implemented through an iterative simulation process. At each iteration, path travel times and costs are quantified and then smoothed to reduce stochastic variability. These updated costs are used to revise route choice probabilities during subsequent iterations until convergence is achieved, at which point route flows stabilize across the network. This iterative structure allows the DTA framework to approximate network equilibrium while preserving the detailed, second-by-second vehicle interactions.

Managed Lane Facilities

In PTV VISSIM™, managed lanes such as high-occupancy lanes, high-occupancy toll lanes, and express lanes are represented as special-purpose lanes. On these facilities, vehicle access is governed by operational rules including tolls, vehicle occupancy, and time-of-day restrictions. In PTV VISSIM™, managed lanes are modeled with lane-level decisions, rather than with path-level decision, meaning that tolls and access rules influence lane selection probabilities instead of directly altering route choice within the dynamic traffic assignment process.

PTV VISSIM™ implements managed lanes through the definition of network objects called managed lane facilities, which encapsulate both decision models and pricing models. Each managed lane facility includes a decision model that specifies the probability of a vehicle selecting the managed lane based on a utility formulation. The utility of the managed lane is defined as a linear function of toll cost, travel time savings relative to the general-purpose lanes, and a base utility term. The utility of the general-purpose alternative is normalized to zero, and the probability of choosing the managed lane is computed using a logit binary-choice-based utility model. The relative magnitudes of the toll cost coefficient and the travel time coefficient govern travelers' sensitivity to monetary cost versus time savings (which requires embedding user value of time features).

Output Metrics

PTV VISSIM™ provides a comprehensive set of output metrics that support detailed operational analysis at multiple spatial and temporal scales. These outputs can be broadly categorized by data resolution, analysis object, and output format, allowing the analyst to tailor performance measures to the objectives of a given study.

PTV VISSIM™ outputs are available at both raw and aggregated data resolutions. Raw data are collected at the individual vehicle or pedestrian level and are recorded at high temporal resolution, typically at one-tenth-second or second-by-second intervals. Examples include vehicle records, vehicle travel time records, pedestrian records, and node raw data. These outputs preserve detailed vehicle trajectories and are well suited for post-processing applications such as emissions modeling, energy use estimation, and behavioral analysis.

In contrast, aggregated data are computed during the simulation run and reported at higher spatial levels, including across links, nodes, routes, vehicle classes, or the entire network. Common aggregated metrics include average speed, average delay, total travel time, queue length, and network-level performance indicators. Aggregated outputs are typically used for corridor-level performance evaluation, scenario comparison, and summary reporting.

PTV VISSIM™ output metrics can also be classified based on the analysis object to which they apply. At the vehicle level, outputs include vehicle identification, position, speed, acceleration, travel time, delay, waiting time, number of stops, and lane-changing behavior. These metrics provide the most detailed representation of system operations and form the basis for downstream analyses that require second-by-second vehicle activity.

At the link level, outputs include traffic volume, average speed, density, delay, queue length, and congestion duration. Link-level metrics are commonly used to evaluate roadway segment performance, identify bottlenecks, and quantify congestion patterns.

At the node or intersection level, outputs describe operational conditions such as delay, queue formation, and throughput, supporting the assessment of intersection control strategies and operational efficiency.

BASELINE MODEL DEVELOPMENT

This section describes a PTV VISSIM™ model of the NWC used as the baseline scenario in the project, the origins of the model, the updates required for the model, and the performance metrics the model can provide.

Origin of the Baseline Model

The baseline simulation model originated from prior research conducted by Georgia Tech doctoral student Ron Boodhoo (Boodhoo, 2025). Developed in PTV VISSIM™ 9, this model was used to evaluate the impact of the NWC express lanes on system-level travel time and route choice behavior. The model analyzed weekday morning peak-hour operations spanning from 4 am to 11 am on the NWC following the implementation of the managed lane facility. Also, the model has been applied to evaluate total travel time and routing behavior under varying toll rate scenarios.

The structure of this original model provided an appropriate foundation for the present analysis for several reasons. First, the model was specifically designed to analyze managed-lane operational performance. The underlying structure of the model was well-suited for examining traffic distribution and lane usage behavior under managed lane operations. Second, the model explicitly represents the unique geometric and operational design of the NWC-managed lanes, including barrier separation, left-side managed-lane access points, and restricted access to general-purpose lane exits. These features are critical for accurately capturing managed-lane usage patterns and cannot be readily approximated with simplified network representations. Third, the spatial scale and level of detail of the model make it suitable as a baseline for system-level operational and energy analysis. The previous network encompassed the full managed lane corridor and its interacting arterial system, allowing for the capture of corridor-wide impacts rather than isolated segment effects. Finally, travel demand inputs for the model were derived from the Atlanta Regional Commission's activity-based travel demand model, ensuring consistency with regionally accepted forecasting practices. This demand foundation supports the use of the model as a credible baseline for comparative scenario analysis.

Description of the Starting Configuration Model

The original NWC PTV VISSIM™ network model included 7,838 links, 237 parking lots, and 482 nodes. The network also consists of 29.7 miles of managed lanes, which are represented by sequences of links, as shown in Table 11. This level of detail allows the model to capture both freeway operations and interactions with the surrounding arterial network.

There were several inherited assumptions in the PTV VISSIM™ model, including driver behavioral characteristics, signal control, and dynamic assignment. Regarding driver behavior characteristics, the starting point model employed a stochastic, time-step-based microscopic traffic simulation framework. Longitudinal vehicle movement is governed by a psycho-physical car-following model, and lateral movement is governed by a rule-based lane-changing algorithm. Driver heterogeneity is represented using PTV VISSIM™'s default behavioral parameter distributions. The calibration philosophy adopted in the original model emphasized structural realism over extensive parameter tuning. Because detailed calibration is highly location-specific and data-intensive, the model intentionally avoided excessive parameter adjustment beyond commonly adopted values reported in the literature.

Signal control within the network was configured to represent the busiest three-hour peak period. In the fall of 2025, real-world signal timing data were obtained from Cobb County, Cherokee County, and the City of Marietta, and ring-barrier control logic was implemented at signalized intersections.

Table 11: Northwest Corridor Managed Lane Links in PTV VISSIM™

Section Name	Destination Link	Destination Position	Consecutive PTV VISSIM™ Links
Hickory Grove to Roswell Road (right)	3029	13.412	553, 10845, 554, 10872, 579, 10840, 556, 10858, 561, 10838, 565, 10849, 566, 10852, 567, 10832
Hickory Grove to Roswell (left)	13050039	27.287	553, 10845, 554, 10872, 579, 10840, 556, 10858, 561, 10838, 565, 10849, 566, 10852, 567, 10875, 588, 10854
Hickory Grove to I-285 W	50240060	34.467	553, 10845, 554, 10872, 579, 10840, 556, 10858, 561, 10838, 565, 10849, 566, 10855, 570, 10861, 572, 10864, 573, 10929, 617, 10930, 618, 10863, 575, 10865, 576, 10866, 577, 10868, 589, 10891, 592, 10869, 569, 10887
Hickory Grove to I-285 E	50240037	51.752	553, 10845, 554, 10872, 579, 10840, 556, 10858, 561, 10838, 565, 10849, 566, 10855, 570, 10861, 572, 10864, 573, 10929, 617, 10930, 618, 10863, 575, 10865, 576, 10866, 577, 10868, 589, 10871, 574, 10890
Big Shanty Road to Roswell Road (left)	3029	34.034	553, 10845, 554, 10872, 579, 10840, 556, 10858, 561, 10838, 565, 10849, 566, 10852, 567, 10832
Big Shanty Road to Roswell Road (right)	13050039	109.97	553, 10845, 554, 10872, 579, 10840, 556, 10858, 561, 10838, 565, 10849, 566, 10852, 567, 10875, 588, 10854
Sixes Road to I-285 W	50240060	189.955	10892, 548, 10833, 551, 10834, 552, 10835, 550, 10836, 549, 10837, 564, 10848, 565, 10849, 566, 10855, 570, 10861, 572, 10864, 573, 10929, 617, 10930, 618, 10863, 575, 10865, 576, 10866, 577, 10868, 589, 10891, 592, 10869, 569, 569, 10887
Sixes Road to I-285 E	50240037	105.21	10892, 548, 10833, 551, 10834, 552, 10835, 550, 10836, 549, 10837, 564, 10848, 565, 10849, 566, 10855, 570, 10861, 572, 10864, 573, 10929, 617, 10930, 618, 10863, 575, 10865, 576, 10866, 577, 1089, 1089, 10868, 589, 1089, 1089, 10871, 574, 10890
Sixes Road to Roswell Road (left)	3029	46.744	10892, 548, 10833, 551, 10834, 552, 10835, 550, 10836, 549, 10837, 564, 10848, 565, 10849, 566, 10852, 567, 10832
Sixes Road to Roswell Road (right)	13050039	73.343	10892, 548, 10833, 551, 10834, 552, 10835, 550, 10836, 549, 10837, 564, 10848, 565, 10849, 566, 10852, 567, 10875, 588, 10854

The embedded dynamic traffic assignment model was used to represent route choice behavior. In the pre-managed lane scenarios, the model achieved convergence at approximately eighty percent, with travel time variations within fifteen percent. Managed lane scenarios converged at approximately seventy-five percent, with similar travel time variation thresholds. Convergence testing was restricted to nineteen iterations to balance computational efficiency with stability of results.

Baseline Model Update Process

The original simulation model by Boodhoo (2025) was developed using PTV VISSIM™ 9, which was released in 2016 and operates in a Windows 10 environment. Because Windows 10 and PTV VISSIM™ 9 are no longer actively supported, the research team updated the original model to work with PTV VISSIM™ 2023 Service Pack 13 to ensure long-term usability, reproducibility, and compatibility. In addition to this software update, the project also adjusted the model to fit the project's needs. The changes made to the original model are explained here.

Version-Related Updates

At each modeled traffic signal, the software allows the user to define the type of signal control procedure. Between PTV VISSIM™ 9 and PTV VISSIM™ 2023, PTV Group reworked the Ring Barrier Controller (RBC) procedure to improve simulation start-up performance and internal timing consistency. The 162 signal controllers using the legacy procedure type in the original model were flagged during model loading and execution, preventing the accurate modeling of traffic flows at intersections. The signal controllers can be automatically updated from the legacy "Ring Barrier Controller (old)," to the current "Ring Barrier Controller" through an option in the Signal Controllers list.

However, some parameters were lost during this initial step and 98 of the signal controllers had to be manually updated.

There are four types of errors that had to be manually solved when converting “Ring Barrier Controller (old)” signals to the “Ring Barrier Controller” signals. First, multiple controllers generated warnings indicating invalid start-up conditions, including cases in which no signal group was designated to initiate the simulation. To resolve this issue, non-conflicting signal groups were explicitly designated as start-up groups within each affected signal controller which were mainly either signal group numbers 2 and 6 or numbers 4 and 8. Second, several controllers produced warnings such as “Pattern one: no signal group in the sequence is marked as coordinated.” These warnings occurred when coordination patterns were defined without explicitly identifying the coordinated signal group. For patterns intended to operate in coordinated mode, coordinated signal groups were explicitly identified within the appropriate barrier group. Third, warnings indicated that the sum of split values did not match the defined cycle length for one or more rings, including messages such as “Sum of splits must equal cycle length” and “Split value inconsistency.” These issues were resolved by adjusting split values so that the total split duration within each ring matched the defined cycle length. Fourth, the frequency had to be specified to ten hertz to ensure consistent handling of signal timing parameters specified with decimal precision.

The software allows the user to place network objects called Desired Speed Decisions on links to model the speed choices of vehicles. Between PTV VISSIM™ 9 and PTV VISSIM™ 2023, PTV Group reworked Desired Speed Decisions to enforce a minimum distance upstream of the nearest connector. Otherwise, simulated vehicles do not have enough time to change their speed before reaching that connector. In the original model, nine of these objects were too close to the nearest connector; these were moved further upstream to address this issue. Desired Speed Decisions 120062, 120063, 160276, 160277, 160278, 160961, 160962, and 160963 were moved 10 ft upstream, while Desired Speed Decision 130008 was moved 20 ft upstream.

After the upgrade from PTV VISSIM™ 9 to VISSIM™ 2023, additional errors were encountered related to DTA. On the initial run, PTV VISSIM™ reported an error stating that no path file exists and that parking lots have no paths. The model contained two issues that prevented the software from generating paths. First, the original model specified a vehicle class (labeled 6013000) that contained only vehicle types not used in DTA. The Vehicle Classes menu was used to edit vehicle class 6013000 to include Vehicle Type 100. Second, PTV VISSIM™ 2023 could not assign a path from Parking Lot 3973 to Zone 14. In the original model, no links existed such that a vehicle could travel between those two points. A connector was added to model the missing left-turn movement from Paces Ferry Rd NW southbound to W Paces Ferry Rd NW eastbound. After resolving these two issues, the Edges menu was used to create a new graph. After these updates, the iterative simulation process of dynamic traffic assignment was able to proceed.

The model displayed one additional warning regarding managed lanes during the upgrade process. This warning appears when a Managed Lanes (ML) routing decision includes only an ML route but no corresponding General-Purpose (GP) route. PTV VISSIM™ expects both options because ML decisions typically represent a choice between GP and ML. For example, if there is no GP lane at a specific location, then all vehicles are forced into the ML, meaning there is no actual decision to make. In the case of the NWC, the network design intentionally has no GP alternative at those problem points; therefore, this warning was ignored.

Model-Related Adjustments

The first adjustment to the model was related to route assignment. Although now updated to work with PTV VISSIM™ 2023, the original model contains zones and O-D matrices that did not align with the values derived from the ARC's activity-based model using path-retention (Zhao, 2021; Zhao, et al., 2019). As a result, the converged simulation results in unrealistic traffic flows, such as insufficient volumes on the interstate and major arterial corridors, with demand displaced onto local roads.

The original PTV VISSIM™ microsimulation model was based on the 75,000-link ABM® Travel Demand Model provided by the Atlanta Regional Commission, while the travel demand data were based on the ABM 2020 model that had 150,000 links. This discrepancy required a matching reconciliation process between the network to prepare an O-D matrix for the PTV VISSIM™ input. The prior effort to transform travel demand into PTV VISSIM™ input O-D matrices used coordinate-based node matching, assuming nodes located within a horizontal distance of less than 10 feet. However, this criterion produced unrealistic demand assignments due to geometry differences between the network and partial network coverage.

To address these deficiencies, a new O-D reconstruction pipeline was developed. The revised pipeline operates in two stages. In the first stage, each trip's path retention link sequence is traversed to identify network entry time and entry and exit links relative to the PTV VISSIM™ subnetwork. Period-specific link travel times are accumulated from the ABM departure point to the entry link, yielding an accurate PTV VISSIM™ network entry timestamp for each trip segment. A single ABM path retention trip may produce multiple PTV VISSIM™ segments if the trip transits the corridor more than once.

The second stage matches the zone and produces the O-D matrices. Entry and exit links were matched to PTV VISSIM™ zones using a three-tier association table: 1) direct match to existing PTV VISSIM™ 'parking lots' that serve as entry/exit for the zones, 2) match through newly added high-demand parking lots, and 3) nearest parking lot fallback within a 0.88-mile distance threshold. Demand is aggregated at 5-minute intervals, and intrazonal O-D pairs are set to zero.

The second adjustment to the model was related to Link Behavior Types. Each link in a PTV VISSIM™ model has an attribute called Link Behavior Type, which determines individual vehicle decisions. In the original model, each link was coded with one of six types, which are all described in Table 12.

Table 12. Link Behavior Types available in PTV VISSIM™

Number	Name	Description
1	Urban (motorized)	Arterial, collector, local, and service roads
3	Freeway (free lane selection)	Freeways
10	Ramp (faster diffusion)	Some ramps, which act like arterial roads
38	Ramp	Most ramps, which act like freeways
200	VISUM Junction Editor	Default type for links generated by an editing software

In a later stage of analysis, this project uses Link Behavior Types to tie link outputs to different road classes. Because more than 2,500 of the nearly 8,000 links were initially coded with Type 200, these were reassigned to one of the four other road types tied to real road classes. Type 200 links representing the through-lanes of I-75, I-575, and I-285 were reclassified as Type 3 freeways. Type 200 links representing the through-lanes of all other roads were reclassified as Type 1 urban roads. Type 200 links representing on- and off-ramps at freeway exits that already contained Type 10 ramps were similarly reclassified as Type 10 ramps. All other on- and off-ramps that connected Type 3 freeways to Type 1 urban roads were reclassified as Type 38 ramps. Finally, each Link Behavior Type was also reset to its default parameters. The PTV Group highly advises against changing the parameters, which were changed in the original model. For example, the acceleration for Type 3 freeways was slower than that for Type 1 urban roads, causing simulated vehicles to perform very slow at zipper merges, becoming sources of unrealistic congestion. These Link Behavior Types were reset to remedy this problem.

Baseline Model Performance

Although the baseline model does not achieve full convergence under the strictest criteria, it is considered operationally stable for the purposes of this study. During simulation runs, a limited number of warnings were observed. One category of warnings indicates that a small number of vehicles from specific demand matrices could not be placed in the network (e.g., “vehicles from the matrix could not be placed in the network”). These warnings are commonly associated with dynamic assignment volume initialization and incremental loading procedures. PTV VISSIM™ allows demand volumes to be introduced gradually using dynamic assignment volume increments, in which traffic demand is scaled upward over multiple runs until full demand is reached. For large-scale networks such as the Northwest Corridor, achieving higher convergence levels is computationally challenging, and the number of convergence runs was constrained by available processing resources. These warnings are therefore not unexpected and can be further reduced through refinement of volume increment parameters and additional convergence runs.

A second category of warnings occurs when vehicles are removed from the network after exceeding the maximum allowable waiting time for lane changing. In such cases, vehicles remain queued while attempting to execute a lane change and are subsequently removed once the predefined waiting threshold is exceeded. This behavior reflects parameter settings related to lane-changing patience and can be mitigated through adjustment of waiting-time and lane-changing parameters.

Dynamic traffic assignment convergence was evaluated based on path-level travel time consistency, with convergence defined as at least 75% of all paths exhibiting travel time differences of 15% or less between successive iterations. The number of iterations required to reach this convergence level varied depending on simulation run length and modeling settings. When the evaluation interval was set to 3,600 seconds and the total simulation duration was set to 7,200 seconds, the travel time convergence criterion was satisfied in fewer than ten iterations. Under these conditions, the model was therefore judged to operate in a stable manner for the purposes of performance evaluation.

Overall, while additional parameter refinement could further improve convergence and reduce the frequency of warnings, the baseline model demonstrates stable and consistent operational behavior. The observed warnings are well understood, limited in scope, and do not materially affect the interpretation of corridor-level or route-level performance results presented in this study. The baseline model was simulated with an initial warm-up period of 30 minutes to allow traffic conditions to stabilize. The simulation start time was set to 6:30 AM, and performance metrics were collected for the period spanning 7 AM to 8 AM, representing the weekday AM peak hour. Traffic volumes are concentrated on southbound I-75 routes approaching the system split, reflecting expected weekday morning peak commuting patterns. Average travel times increase systematically with route length and downstream congestion effects, particularly on I-575 southbound routes, which experience longer travel times due to higher congestion levels and extended distances.

SYNTHETIC CORRIDOR MODELING

This section describes a PTV VISSIM™ model of the synthetic corridor used as a comparison scenario in the project, the model's development process, and the performance metrics the model can provide.

Synthetic Corridor Description

The popularity of PTV VISSIM™ comes from its ability to model traffic conditions under different scenarios via Scenario Management. Because this project is focused on identifying the costs and benefits of constructing a reversible managed lane along the Northwest Corridor, PTV VISSIM™ can model the operational costs for two scenarios: the baseline corridor and a synthetic corridor. The baseline corridor has a reversible managed-lane facility that runs as one lane along I-75 from Hickory Grove to the merge point, one lane along I-575 from Sixes to merge point, and two lanes along I-75/I-575 from the merge point to Akers Mill. As an alternative to the integration of reversible managed lanes, the synthetic corridor adds permanent general-purpose lanes on both sides of the corresponding corridors (in total, two inbound and two outbound).

Synthetic Corridor Development Process

To create the synthetic corridor, the PTV VISSIM™ model was placed under the software’s Scenario Management program. This allowed both the baseline and synthetic corridors to be stored in the same file. Any edits made to the baseline corridor (such as changes to the O-D matrix or Link Behavior Types) were reflected in the synthetic corridor, but edits made to the synthetic corridor stayed within the synthetic “Scenario”. To create this new scenario, two new general-purpose lanes (one per direction) were added to the right side of each freeway link running parallel to a managed lane facility. Entry and exit ramps were moved to connect to the new rightmost lanes. The managed lanes were deleted.

Synthetic Corridor Performance

The synthetic corridor model was evaluated using the same simulation framework as the baseline scenario to ensure consistency in performance comparison. An initial warm-up period of approximately 30 minutes was applied, with the simulation starting at 6:30 am and performance measures collected for the weekday AM peak period from 7 am to 8 am. Dynamic traffic assignment convergence for the synthetic corridor was assessed using the same criteria as the baseline model, requiring 75% of all paths to maintain a travel time difference of 15% or less between successive iterations. Under these conditions, the synthetic corridor model exhibited similar convergence behavior, typically stabilizing within five to six iterations.

Traffic volumes are distributed across both northbound and southbound routes, with notable volumes observed on I-575 southbound routes approaching the system split. Average travel times increase with route length and reflect congestion effects along longer corridor segments, particularly on I-575 southbound routes. Overall, the synthetic corridor results exhibit internally consistent relationships between traffic volumes, travel times, and distances traveled, providing a stable operational basis for comparison with the baseline managed-lane scenario.

CHAPTER 9. PTV VISSIM™ CASE STUDY RESULTS

This chapter summarizes the I-75/I-575 Northwest Corridor comparative case study results for the Baseline Reversible Express Lanes Scenario vs. the Alterative General-Purpose-Lane Expansion Scenario. This comparative assessment demonstrates a potential use case for the spreadsheet-based model and provides valuable insights into managed-lane investment decisions.

BASELINE REVERSIBLE LANES VS. ALTERNATIVE SCENARIO

First, the research team modeled the Northwest Corridor as it currently exists, with reversible, grade-separated express lanes to assist traffic flow, which is referred to as the baseline reversible Express Lanes scenario. Similarly, as described in the previous chapter, the research team modeled traffic conditions on the Northwest Corridor with one additional general-purpose lane per direction (two each for I-75 and I-575), replacing the reversible managed lanes that are currently in place. The comparison of these two scenarios allows the costs and benefits of new managed lane construction to be quantified relative to the construction of new general-purpose lane construction.

Modeled Planning, Design, and Construction Costs

Using the Planning, Design, and Construction component of the spreadsheet-based model, combined with design documentation from the Northwest Corridor managed lane project, it is possible to model the costs associated with planning, design, and construction for the baseline scenario. With a few assumptions, it is also possible to model these costs for the synthetic scenario.

The baseline scenario contains approximately 29.7 miles of reversible express lanes. South of the I-75-575 interchange, there are two reversible lanes. These two lanes diverge at the interchange, leaving just one reversible managed lane along the length of I-575 and one reversible managed lane along the portion of I-75 north of the interchange. The synthetic scenario assumes one additional general-purpose lane in each direction along the entire length of I-75 and one additional general-purpose lane along the entire length of I-575, for a total of approximately 51 lane-miles. However, these additional general-purpose lanes are not grade-separated from the rest of the highway, thereby greatly reducing the length of highway bridge/overpass lane-miles in the project. It is also assumed that the synthetic scenario will have no tolling equipment costs and greatly reduced ITS material costs. It is assumed that all right-of-way acquisition costs and all administrative costs remain constant between the two scenarios. Table 13 reports the modeled planning, design, and construction costs for each scenario.

Table 13: Modeled Planning, Design, and Construction Costs: Baseline Scenario vs. Synthetic Scenario

	Baseline Scenario	Synthetic Scenario
Total Planning, Design, and Construction Cost ($ 2026)	$653,814,847.58	$853,607,492.71
ROW Acquisition Cost ($ 2026)	$64,523,641.43	$64,523,641.43
Administrative Cost ($ 2026)	$157,331,759.91	$157,331,759.91
Construction Material Cost ($ 2026)	$422,962,218.06	$619,844,281.22
Fuel Consumption Cost ($ 2026)	$8,997,228.17	$11,907,810.15
Embodied CO_2 Emissions (tons)	7,715.58 tons	11,161.59 tons
Embodied CO Emissions (tons)	11.14 tons	16.12 tons
Embodied NO_x Emissions (tons)	44.09 tons	62.09 tons
Embodied VOC Emissions (tons)	1.69 tons	2.38 tons
Embodied PM_{10} Emissions (tons)	1.26 tons	1.78 tons
Embodied $PM_{2.5}$ Emissions (tons)	1.16 tons	1.63 tons

As shown in Table 13, the baseline scenario results in approximately $200 million in savings throughout the planning, design, and construction process. These savings are almost entirely due to reduced construction material expenses resulting from constructing fewer lane-miles of highway.

Modeled On-Road Travel Time and Energy Use

For each scenario, the research team performed PTV VISSIM™ model runs for the 7:00 AM to 8:00 AM morning rush hour on a typical day. Both simulations run successfully. Figure 9 and Figure 10 show visualizations of network travel speeds and vehicle volumes throughout the model network, respectively.

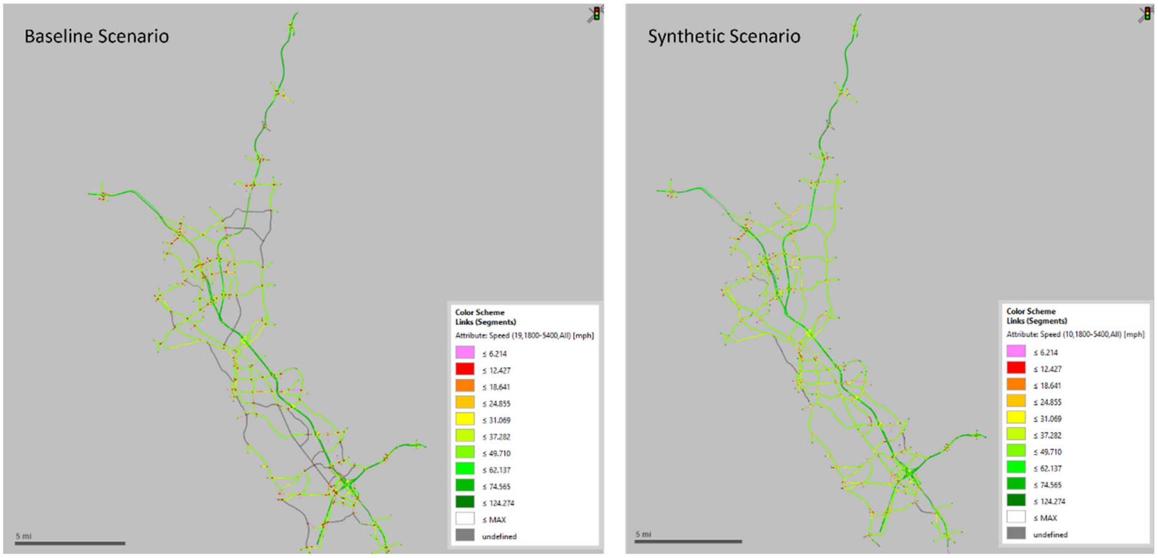

Figure 9: Map. Modeled Network Travel Speeds:
Baseline Scenario vs. Synthetic Scenario

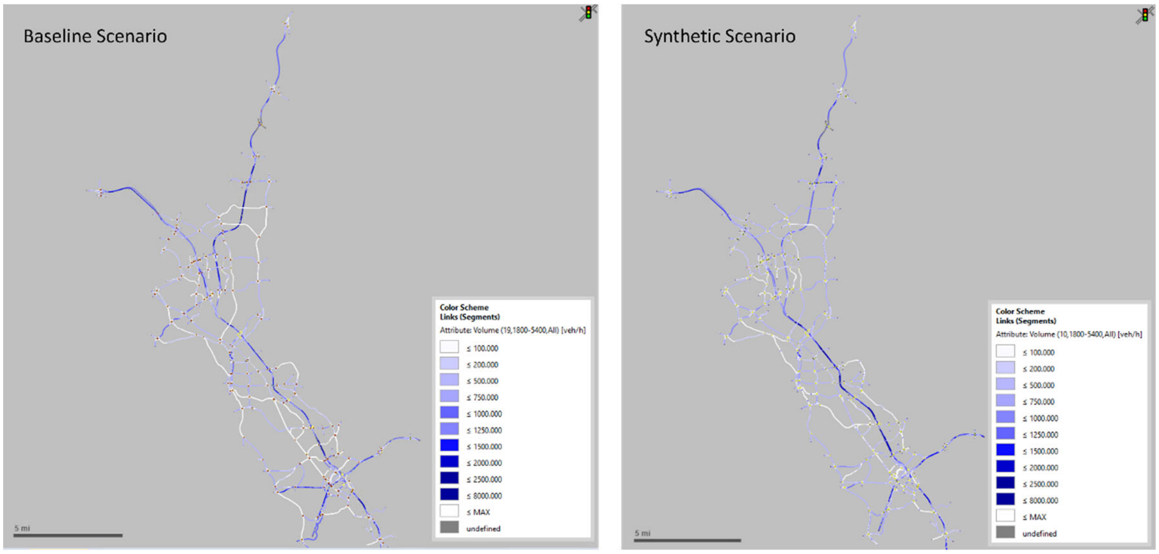

Figure 10: Map. Modeled Network Vehicle Volumes:
Baseline Scenario vs. Synthetic Scenario

In preparing the final analyses for this report, the research team noted that the latest PTV VISSIM™ runs for the baseline reversible Express Lane System lanes system are showing four choke points that do not exist in the real world. The travel time comparison across the two scenarios currently shows that GP lane scenario performs better than the reversible lanes (vehicle-hours) due to the presence of these choke points; however, the research team is certain that these scenarios should show comparable congestion levels. The research team did not have time to verify the coding of the slip ramps and driver behavior elements in the PTV VISSIM™ network before the project report was due. Hence, the research team is not reporting the comparative results from the travel time, energy, and emissions spreadsheet component of the modeling tool in this report. The team plans to publish an amended report when the coding issues in the baseline scenario network are repaired.

On-road operating conditions constitute a critical component of lifecycle cost analysis, as differences in network performance between scenarios compound significantly over time. However, the reversible managed lane scenario also offers toll revenue which also provides a recurring financial advantage. Operating under an assumed average toll rate of $0.50 per mile, the managed lane facility generates approximately $2,901 in toll revenue per peak hour. This revenue stream represents a direct financial return on infrastructure investment, partially offsetting the operational cost disadvantage of the managed lane configuration.

CASE STUDY DISCUSSION

There are several sources of uncertainty associated with the results of this case study. First, due to limitations in source data, the modeled traffic volumes are almost certainly lower than the traffic conditions that would be expected in both the baseline and synthetic scenarios. Increased traffic volumes would result in increased congestion, which would result in greater differences in on-road travel times and energy consumption between the two scenarios. Similarly, the daily and annual travel time, energy use, and toll revenue savings are approximated using a peak hour factor, also due to limitations in traffic data. It is likely that users of this model will have access to more reliable traffic data for their project alternative comparisons, and as such, these uncertainties would become less prominent.

The PTV VISSIM™ portion of the model relies on path retention data, which is developed based on the Atlanta Regional Commission's Activity-Based Model. This model can provide anticipated future path-retention data for future years, but these model runs were not available for scenario analyses (it takes about one week of computing time for the ARC to run an instance of the ABM with path retention). For this reason, the research team has elected to only model on-road traffic conditions for the first year of operation in this case study.

It is important to note that this single-year snapshot may not be representative of long-term lifecycle performance. As traffic volumes grow over time, operational differences between the two scenarios are likely to evolve. It is possible that induced demand may arise from the addition of general-purpose lanes, generating new vehicle trips over time and gradually eroding the operational advantages observed in the first year of operation (Duranton and Turner, 2011). In contrast, the managed lane scenario's pricing mechanism provides an inherent demand-management function that can help maintain stable operating conditions as background traffic grows. A full lifecycle assessment incorporating projected traffic growth and future-year network conditions could therefore improve the ability to draw definitive conclusions about the long-term relative performance of the two scenarios.

An additional source of uncertainty arises from the network mismatch between the PTV VISSIM™ microsimulation model and ARC's updated Activity-Based Model. The PTV VISSIM™ network was originally constructed using topology from ARC's 75,000-link ABM, while the travel demand data used to develop the O-D matrices was derived from the updated 150,000-link ABM 2020 model. Because the two networks differed in link definitions, node coordinates, and roadway geometry, the research team could not establish a direct correspondence between ABM trip paths and PTV VISSIM™ network elements. As a result, a portion of the O-D demand may be assigned to approximate entry and exit locations rather than those that precisely reflect the modeled trip paths, which could affect the accuracy of simulated flow distributions on individual links and segments within the corridor.

Finally, there are various uncertainties associated with the assumptions made when modeling the planning, design, and construction costs of the synthetic scenario. The research team assumed that right-of-way and administrative costs would remain constant between the two scenarios, but this wouldn't necessarily be the case. The reversible managed lanes are positioned on the western shoulder of the southbound lanes along the portion of I-75 south of the I-575 interchange. This positioning complicates the project design and results in an increased need for right-of-way acquisition along that portion of the project. In the synthetic scenario, it may have been possible to contain both additional general-purpose lanes to the existing median, thereby reducing design complexity and the need for right of way acquisition. Alternatively, if one or both of the additional general-purpose lanes were constructed on the outside shoulder of the highway (as would have been the case in preliminary designs for the NWC expansion), right of way acquisition costs would have likely increased by a significant margin. These determinations were considered beyond the scope of this case study.

There are also several opportunities for further research. Costs associated with highway maintenance are not accounted for by the spreadsheet-based model due to a lack of reliable data to support these calculations. Highway maintenance has direct material, labor, and equipment costs, but also can have substantial impacts on adjacent traffic flow, particularly if the maintenance results in the closure of travel lane(s). For these considerations to be incorporated into the model, more data is needed on the typical scope and frequency of highway maintenance.

Similarly, costs associated with crash risk and severity crash are not incorporated into the model. Crash risk is affected by travel speed and traffic congestion. More frequent and more severe crashes would result in higher medical expenses, greater damage to personal property, and greater damage to highway infrastructure. Like maintenance, crashes that result in the closure of one or more lanes would substantially impact on-road traffic patterns. Further research is necessary to better quantify the relationships between traffic congestion, travel speed, crash frequency, and crash severity.

CASE STUDY SUMMARY

This chapter describes a case study in which the I-75/I-575 Northwest Corridor's reversible managed lane system is modeled using the spreadsheet-based model and compared with an alternative scenario in which the reversible managed lanes were replaced with an additional general-purpose lane in each direction of travel. The results of this case study highlight some meaningful tradeoffs between the two scenarios across different dimensions of lifecycle cost.

The reversible managed lane scenario demonstrates a substantial advantage in planning, design, and construction costs primarily due to the reduction in total lane-miles constructed. Additionally, the managed lane facility generates an estimated $10.6 million in annual toll revenue, representing a recurring financial return on investment unavailable under the general-purpose lane scenario. In preparing the final analyses for this report, the research team noted that the latest PTV VISSIM™ runs for the baseline reversible Express Lane System lanes system are showing four choke points that do not exist in the real world. The research team believes that proper simulation of the baseline scenario would not show these associated congestion delays, that both scenarios would show relatively comparable congestion levels for the modeled trips, and therefore both scenarios would yield comparable calculated costs for on-road hours of travel, energy use, and emissions. The research team was unable to update the model runs and report these differences and/or similarities at the time this report was submitted. The team plans to publish a supplemental chapter for the report once the problems in the coding of the baseline scenario network are identified and repaired.

This case study illustrates the analytical value of the spreadsheet-based lifecycle cost model developed in this research. By integrating planning, design, and construction costs, on-road operational performance, emissions, and toll revenue into a single framework, the model enables decision-makers to evaluate managed-lane investments across multiple dimensions simultaneously.

CHAPTER 10. CONCLUSIONS

This report summarized the development and implementation of a spreadsheet-based modeling tool for lifecycle economic and energy costs. The modeling framework includes spreadsheet tools for the assessment of lifecycle cost across planning and construction activities, and a spreadsheet basis for linking modeled or monitored travel activity to calculations for travel time and fuel savings across scenarios, as well as emissions changes. The spreadsheet model structure is transparent, in that users can see all of the calculations that are being performed and can make changes to default assumptions that are employed. The methods used to develop the framework and the data that reside in the framework are all outlined in this report and its appendices.

Initially developed for the assessment of Express Lane facility alternative, the tool can be applied to a variety of use-cases. This report described how the model could be applied to alternative design scenarios for Express Lane facilities, traditional design-build conversions of at-grade highways to limited access highways, corridor-level traffic signal coordination, and even how the tool could be used to support a categorical exclusion for HOV-to-HOT facility conversions.

With respect to model elements and data integration, as well as overall model structure, there are a number of model improvements that are recommended. Each section below provides a summary of the most interesting issues encountered by the research team and the activities undertaken to address these issues through the course of the study. This chapter then concludes with some recommendations for further research.

AASHTOWARE PROJECT ESTIMATION INTEGRATION

AASHTOWare Project Estimation (AASHTOWare) is a web-based cradle-to-grave estimation application designed to deliver accurate and reliable transportation construction cost estimates (American Association of State Highway and Transportation Officials n.d.b.). AASHTOWare is currently used by entities in 40 states and the District of Columbia (American Association of State Highway and Transportation Officials, 2022). There is a specially tailored version of AASHTOWare for each state, allowing integration with state DOT reference item indices. For example, AASHTOWare licenses within the state of Georgia can interface with the GDOT Reference Item Index, and data associated with those items (Reichard and Guensler, 2021).

Unfortunately, itemized material reference item index codes and quantities were not available for the Northwest Corridor project because the implementation was an at-risk public-private venture. That is, the private partner is not reimbursed for expenses, and bears the risk associated with project costs and cost overruns. Hence, construction component use and costs were not tracked for public use, nor were actual 'reimbursable' maintenance activities reported to the agency. The team was unable to fully integrate data from the AASHTOWare Project Estimation software into the spreadsheet-based model for the case study. It is anticipated that the inclusion of AASHTOWare data would improve the precision and accuracy of construction material cost estimation.

CALCULATION OF MATERIAL PRODUCTION ENERGY CONSUMPTION

The research team had very limited access to material quantity information for the Northwest Corridor project, which prevented the modeling of energy consumption throughout the full lifecycle of the construction materials. A traditional lifecycle analysis would account for energy consumption throughout all stages of a material's life leading up to construction, including raw material extraction, transportation to refining and/or production facilities, assembly and/or production processes, and transportation to the construction site. Without data on the specific materials used for the construction of the Northwest Corridor, it was not possible to model material's lifecycle energy use, other than transportation from the production facility to the job site. By not accounting for the full lifecycle of these materials, the model underestimates total lifecycle energy consumption for the case study.

TRAVEL TIME, ENERGY, AND EMISSIONS CALCULATIONS

The scope of work proposed by the research team was designed to calculate on-road user vehicle activity and travel time from any travel demand model or microscopic traffic simulation model on a link-by-link basis. A spreadsheet basis was proposed to keep modeling simple and to ensure that calculation processes were transparent to the user community. Energy use and emissions are calculated by integrating MOVES energy and emission rates directly into the spreadsheet model.

As development progressed, it became clear that implementing MOVES-based energy and emissions modeling within a spreadsheet environment was more complicated than anticipated. With each model improvement and introduction of an additional user option (e.g., alternative calendar years, combinations of fleet mix, model years, and regulatory class groups, selection of driving cycles, or specification of environmental conditions), the size of the spreadsheets (and associated processing time) increased geometrically. To create a stable and functional spreadsheet-based modeling process, the research team was forced to break the model into multiple spreadsheets and to restrict user selections to a limited and carefully curated set of modeling options.

The spreadsheet-based modeling tool does successfully demonstrate the mechanics of applying MOVES energy and emission rates to fleet and activity data. Users can trace the propagation of assumptions and inputs through each stage of the calculation framework, explicitly tracking how link-level traffic volumes, speeds, facility types, and vehicle class distributions are converted into vehicle activity metrics and multiplied by energy use and emission rates for the specific operating modes either observed on the road, or predicted by a travel demand or simulation model.

Providing transparency into the modeling process is helpful, but the research team has concluded that this project would benefit from the direct integration of the Python-based modeling approach that has been applied successfully in prior MOVES-related research efforts using MOVES2014a and MOVES3. The Python approach does require users to execute modeling scripts that query very large, precomputed energy and emission rate arrays derived from MOVES, rather than relying on spreadsheet-based rate lookups. However, the team has concluded that transportation analysts can likely handle the program queries better than the complicated spreadsheet modeling. Plus, the Python based approach allows users to specify any input conditions desired, removing the scenario limitations imposed by the spreadsheet structure.

PTV VISSIM™ IMPLEMENTATION

Development of the PTV VISSIM™-based microscopic traffic simulation model for two Northwest Corridor alternatives facilitated a quantitative comparison of operational differences between a reversible managed lane alternative vs. traditional expansion of a facility via the addition of general-purpose lane expansion. PTV VISSIM™ explicitly represents lane-level vehicle behavior, including lane choice decisions, merging, and diverging processes, and interactions at bottleneck locations. These detailed behavioral representations allow link-specific and lane-specific traffic flow characteristics to be modeled, providing critical inputs for traffic flow and vehicle speeds into the estimation of lifecycle costs and benefits.

Despite the strengths of the comparative modeling across alternatives supported by microscopic vehicle activity modeling, the current PTV VISSIM™-based analyses are subject to several limitations. Due to the scale and complexity of the Northwest Corridor network, long-duration simulations and extensive parameter exploration are computationally constrained. Achieving stable model convergence, given the use of the dynamic traffic assignment process, requires substantial computational effort. In addition, toll values within the dynamic assignment framework must be specified by the user as an input to the model and must remain fixed throughout each individual simulation.

The team plans to continue additional NWC simulation model implementation and testing to improve convergence stability within the dynamic traffic assignment framework. Critical modeling parameters, such as convergence criteria, demand input increment settings, and simulation duration, will be systematically varied to identify configurations that allow traffic to fully propagate throughout the network under realistic operating conditions. These efforts will aim to balance computational feasibility with the need to represent corridor-wide traffic dynamics as reasonably as possible, ensuring that modeled vehicle flows reflect stable and realistic network conditions.

Over the longer term, the modeling framework could be extended by leveraging the PTV VISSIM™ Component Object Model (COM) interface to implement dynamic toll pricing logic during dynamic traffic assignment. Such an extension would allow tolls to respond endogenously to congestion levels or managed lane utilization, more closely reflecting real-world operational practices. In addition, the framework could be expanded to evaluate a broader range of operational scenarios, including construction-related lane closures, incident conditions, and long-term demand growth. Incorporating these scenarios would enable a more comprehensive assessment of lifecycle travel time, energy use, and emissions impacts.

BASELINE REVERSIBLE LANES SCENARIO VS. SYNTHETIC CORRIDOR SCENARIO

The model test case study discussed in Chapter 9 compared the construction of a reversible express lane facility on the I-75/I-575 Northwest Corridor with the construction of additional general-purpose travel lanes in each direction. In this case study, the reversible express lane scenario resulted in roughly $200 million dollars in savings over the general-purpose lane alternative, almost entirely attributable to the substantial reduction in lane-mileage needed to complete the project.

Various source data deficiencies impose uncertainty on these results. In practice, users of this model would likely have access to more accurate data and a clearer understanding of specific design details of each alternative, resulting in more accurate model assumptions.

PROPOSED IMPROVEMENTS TO THE NWC PTV VISSIM™ MODEL

Because PTV VISSIM™ includes many behavioral and assignment parameters, simulation outputs exhibit sensitivity to parameter settings. The model in this report prioritized structural realism and consistency with the original model; however, the scale and complexity of the Northwest Corridor network impose practical constraints on extensive parameter exploration. Each simulation run requires considerable computational time, and additional iterations are required to evaluate dynamic traffic assignment convergence. As a result, long-duration simulations and exhaustive parameter sweeps are computationally difficult. Instead, the analysis focuses on selected peak-period segments, including the weekday AM peak, to balance behavioral realism with computational feasibility.

Dynamic traffic assignment in PTV VISSIM™ allows traffic conditions to evolve endogenously through route choice adjustments; however, toll values remain exogenously specified and fixed throughout each simulation. Changes in managed lane usage under dynamic assignment are therefore driven by variations in travel time savings rather than by real-time toll adjustments that respond to congestion levels. This limitation constrains the model’s ability to replicate managed lane pricing strategies observed in practice, in which tolls vary dynamically in response to prevailing traffic conditions.

Future work may address these limitations through several research activities. First, systematic sensitivity analyses may vary key behavioral and assignment parameters to identify parameter ranges that improve convergence stability and reduce warning occurrences. Second, researchers may use the PTV VISSIM™ Component Object Model interface to implement custom control logic that enables dynamically varying toll prices during dynamic assignment, allowing tolls to respond to congestion levels or managed lane utilization. Finally, the analysis may be extended to include additional operational scenarios, such as construction-related lane closures, incident conditions, or long-term demand growth. These extensions would support more comprehensive estimation of lifecycle travel time and energy costs and strengthen the comparative evaluation of managed lane and synthetic corridor alternatives.

ANTICIPATED MODEL IMPLEMENTATION

The model developed in this research project can be employed to support statewide and regional transportation planning and transportation investment decision-making, by allowing users to assess different freeway corridor design and operations within a common framework. The fundamental structure of the analytical framework centers around the tracking of costs and benefits on a link-by-link transportation network basis. The network includes relevant freeway and arterial subnetworks (including ramps and auxiliary lanes) associated with different project alternatives. The data-driven assessment tool allows users to quantify costs associated with design and construction of alternatives by inputting proposed bills of materials and using cost data from AASHTOWare or other sources.

With respect to ongoing on-road operating costs and benefits, the model supports the integration of modeled or monitored vehicle activity data to assess comparative differences in baseline and predicted user travel time, energy use, and emissions associated with on-road operations. The system allows users to assess alternative designs across total costs, as well as on a per-vehicle-mile basis. The spreadsheet structure of the tool also supports the integration of any additional cost elements not currently included in the model, such as associated safety benefits from the implementation of mitigation measures and prediction of noise and pollutant concentration impacts adjacent to the corridor. Because the system is open source, the tool can serve as a foundation for ongoing updates, integration of alternative models, and expansion of capabilities.

By adding lifecycle comparisons across alternatives, this project supports the assessment of long-term transportation investment strategies. The analytical tool can also help streamline the project approval processes, providing useful tools for preparing comparative alternatives assessments for presentation in NEPA-related documents. The modeling tool can also be used by planners to highlight the efficiency benefits of managed lanes projects in stakeholder and community outreach.

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APPENDIX A: HIGHWAY CONSTRUCTION MATERIAL COST DEFAULT ASSUMPTIONS

Table 14 contains the list of default assumptions regarding highway construction materials. For each material, the model assumes a default unit cost, quantity used per lane-mile of construction, delivery distance between the material production facility and the job site, and the quantity of material able to be transported in one delivery. The unit costs and quantities per lane-mile have been derived from the Northwest Corridor schedule of values documentation. The material delivery distances have been derived from the Georgia Department of Transportation Qualified Products List, and the quantity for delivery default assumptions have been derived from a variety of industry sources. Some materials, including Erosion Controls and ITS Systems, have been listed as Lump Sum values on the Northwest Corridor pricing documentation. It was not possible to make data-driven assumptions regarding material quantities for these items.

Table 14: Highway Construction Material Cost Default Assumptions

MATERIAL	Bid-Based Unit Cost	Quantity per-Lane-Mile	Material Delivery Distance (mi)	Quantity per-Delivery
Aggregate Bases	$26.55	15,271 TN	142.74	80
Bituminous Pavement	$99.47	10,189 TN	407.02	20
Bridge Foundations	$404.62	2,059 LF	426.18	800
Bridge Other Work	$3.13	129,378 LB	611.18	48,000
Bridge Substructures	$1,493.84	588 CY	196.86	10
Bridge Superstructures	$78.72	29,054 CY	196.86	10
Clear and Grub and Demolition	$31,906.91	9 AC	N/A	N/A
Concrete Pavement	$136.33	3,717 SY	363.82	45
Earthwork Grading Complete	$22.48	32,839 CY	N/A	N/A
Erosion Controls	$236,486.49	1 LS	399.59	N/A
Fence	$19.34	1,048 LF	188.46	15,000
Flatwork	$31.42	2,957 SY	N/A	N/A
GM Signs	$71.82	294 SY	730.14	500
Guard Rail/Cable Barrier	$200.70	946 LF	630.66	280
ITS Systems	$1,216,216.22	1 LS	1,242.95	N/A
Overhead Signs	$78,888.70	5 EA	788/00	5
Paving Markings	$3.93	12,669 LF	531.79	125,000
Project Aesthetics	$168,918.92	1 LS	959.71	N/A
Railroad Work	$13,513.51	1 LS	N/A	N/A
Retaining Walls	$81.77	24,790 SF	148.31	72
Roadway Lighting	$8,253.99	22 EA	788.00	8
Signals	$48,986.49	1 LS	1,341.27	N/A
Soundwalls	$11.77	102,104 SF	264.83	6,000
Storm Drainage Systems	$207.90	4,225 LF	398.56	200
Tolling Systems	$281,553.88	1 LS	1,242.95	N/A
Traffic Barrier Walls	$83.65	8,077 LF	148.31	40
Traffic Control	$540,540.54	1 LS	887.00	N/A

APPENDIX B: HIGHWAY ADMINISTRATIVE COST DEFAULT ASSUMPTIONS

Table 15 contains the list of default assumptions regarding highway administrative costs. For each expense type, the model assumes a uniform cost per-lane-mile. These assumptions have been derived from available Northwest Corridor Schedule of Values documentation. The user may adjust these default assumptions if they have more relevant data for the specific managed lane project being modeled.

Table 15: Highway Construction Administrative Cost Default Assumptions

COST CATEGORY	Bid-Based Cost Per-Lane-Mile
Aerial Mapping and Field Enhancements	$59,121.62
Arterial Design Services	$87,466.22
BFI	$27,027.03
Bonds	$288,851.35
Construction Engineering	$101,351.35
Corridor Structure Type Study Report	$3,378.38
Cultural Resource Memos	$10,135.14
Ecology Memo	$5,067.57
EMC Util Relocation	$10,405.41
Environment/Public Involvement	$16,891.89
Final Bridge Plans	$371,621.62
Final Roadway Design	$270,270.27
Final Wall Plans	$13,513.51
Finance Fee	$100,337.84
Ga Power Util Relocation	$20,945.95
IMR/IJR/Traffic Memo	$20,270.27
Insurance	$563,175.68
ITS/Tolling Plans	$30,405.41
Landscaping Plans	$10,135.14
Lighting Plans	$5,067.57
Local Water Authority	$52,770.27
Miscellaneous Structures	$30,405.41
Mobilization	$607,094.59
Natural Gas Relocation	$6,925.68
Noise Memo	$20,270.27
Pavement Evaluation	$1,689.19
Permits (401/404, Stream Buffer)	$3,378.38
Power Relocation	$30,405.41
Preliminary Bridge Plans	$84,459.46
Preliminary Engineering	$337,837.84
Preliminary Wall Plans	$16,891.89
Preliminary/ROW Roadway Plans	$422,297.30
Signing/Marking/Signal Plans	$84,459.46
Soil Survey	$16,891.89
Stream Credits	$4,391.89
SUE Investigation	$10,135.14
Telecom Relocation	$19,087.84
Utility Coordination	$6,756.76
Utility Design	$6,756.76
Water/Sewer Relocation	$45,270.27
WFI	$40,540.54

APPENDIX C: GEORGIA DEPARTMENT OF TRANSPORTATION EMPLOYEE COST DEFAULT ASSUMPTIONS

Table 16 contains the list of default assumptions regarding Georgia Department of Transportation employee costs. For each position, the model assumes an hourly wage, overhead rate, and billable hours per-lane-mile of highway construction. These assumptions are derived from the salaries and reimbursements data for fiscal year 25 made available by the Georgia Department of Audits and Accounts (Georgia Department of Audits and Accounts, 2025). The user may adjust these assumptions to better reflect the financial conditions or workload distributions that may be present during the specific managed lane project being modeled.

Table 16: Georgia Department of Transportation Employee Cost Default Assumptions

POSITION	HOURLY WAGE	OVERHEAD RATE	BILLABLE HOURS PER-LANE-MILE
Environmental Compliance Specialist I	$26.44	190%	0
Environmental Compliance Specialist II	$27.95	190%	150
Environmental Compliance Specialist III	$31.00	190%	100
Environmental Compliance Specialist IV	$37.95	190%	50
Environmental Protection Manager II	$44.10	190%	25
Environmental Transportation Analyst I	$36.45	190%	125
Environmental Transportation Analyst II	$41.59	190%	75
Environmental Transportation Analyst III	$47.29	190%	50
Environmental Transportation Specialist I	$22.04	190%	125
Environmental Transportation Specialist II	$24.04	190%	0

Environmental Transportation Specialist III	$27.04	190%	75
Environmental Transportation Specialist IV	$35.24	190%	50
Equipment Operator I	$12.98	190%	150
GDOT Civil Engineer I	$28.85	190%	0
GDOT Civil Engineer II	$32.50	190%	150
GDOT Civil Engineer III	$37.46	190%	150
GDOT Civil Engineer IV	$41.71	190%	100
GDOT Civil Engineering Manager I	$62.50	190%	25
GDOT Civil Engineering Manager II	$67.31	190%	25
GDOT Professional Civil Engineer V	$48.08	190%	75
GDOT Professional Civil Engineer VI	$52.64	190%	50
GDOT Senior Civil Engineering Manager I	$75.12	190%	25
GDOT Senior Civil Engineering Manager II	$83.98	190%	25
General Trades Tech Supervisor	$18.65	190%	25
General Trades Technician I	$12.98	190%	150
General Trades Technician II	$12.98	190%	100
General Trades Technician III	$12.98	190%	75
Highway Maintenance Tech. Supervisor	$24.31	190%	25
Planning Manager I	$40.16	190%	25
Right of Way Specialist I	$26.00	190%	150
Right of Way Specialist II	$28.50	190%	100
Right of Way Specialist III	$31.27	190%	50
Right of Way Specialist Supervisor I	$34.58	190%	25
Right of Way Specialist Supervisor II	$38.46	190%	25
Senior Environmental Protection Manager II	$56.83	190%	25
Senior Right of Way Manager	$47.12	190%	25
Senior Transportation Specialist Manager I	$62.50	190%	25
Senior Transportation Specialist Manager II	$79.33	190%	25
Training and Development Specialist I	$19.81	190%	150
Training and Development Specialist II	$24.04	190%	10
Training and Development Specialist III	$27.48	190%	50
Transportation Planning Specialist I	$24.24	190%	150
Transportation Planning Specialist II	$31.25	190%	100

Transportation Planning Specialist III	$34.38	190%	50
Transportation Specialist I	$28.85	190%	150
Transportation Specialist II	$30.08	190%	150
Transportation Specialist III	$32.88	190%	100
Transportation Specialist IV	$38.46	190%	75
Transportation Specialist Manager I	$44.99	190%	25
Transportation Specialist Manager II	$51.94	190%	25
Transportation Specialist Manager III	$64.90	190%	25
Transportation Specialist V	$43.03	190%	50
Transportation Technician I	$18.04	190%	150
Transportation Technician II	$21.56	190%	100
Transportation Technician III	$22.47	190%	50
Transportation Technician IV	$26.74	190%	50

APPENDIX D: ON-ROAD AND ENERGY EMISSIONS MODELING FRAMEWORK

Three spreadsheets comprise the on-road energy and emissions modeling framework. This appendix describes the modules in each worksheet of the spreadsheet. As described in Chapter 4, all three of the spreadsheets share some common structural elements:

- The first worksheet in each spreadsheet is the Results Worksheet, summarizing the final outputs of the spreadsheet.
- The final worksheet within each spreadsheet contains model information named Version Info Worksheet. This worksheet includes the changes made since the previous version of the model.
- All spreadsheet models are named Version 3.0. Initial spreadsheet structures were first designed for individual vehicles and individual roadway links. As modeling progressed, the team had to modify the approaches significantly because the spreadsheets became too large and unwieldy as they were expanded to fleets and corridors. In fact, the energy modeling spreadsheet had to be broken into three components along the way.
- Users enter data only into yellow-highlighted cells. All other cells are either inputs from the MOVES (typically in other colored cells) or are calculated by the model.
- The XLOOKUP function was used extensively within the spreadsheets to obtain model variables within a worksheet from cells in other worksheets.
- To ensure continuity within each spreadsheet, none of the spreadsheet models include cell references to other Excel files. If a new driving cycle is desired

within the analytical process, users must modify the driving cycle processor, copy the results into the output Excel file, and then integrate the driving cycle data into the bin processor spreadsheet.

The three sections that follow provide more detailed descriptions of the processes and calculations performed within each spreadsheet.

MOVES Duty Cycle VSP and OpMode Bin Processor Spreadsheet

The MOVES Duty Cycle VSP and OpMode Bin Processor takes any second-by-second driving cycle (speed vs. time pattern used by MOVES to assess vehicle load and resulting energy use and emissions) and generates the Operating Mode Bin (OpModeBin) distributions to which energy use and emission rates are assigned for each vehicle class (SourceType) and model year. The spreadsheet processes each second of activity in the duty cycle for an assigned vehicle source type and regulatory class, calculating vehicle specific power (VSP) for each second of operation (using applicable VSP source type physics parameters for that vehicle class and regulatory class), and assigning the second of activity to its corresponding Operating Mode Bin. This separate spreadsheet handles driving cycle calculations, given the complexity of the calculations and the size of the resulting spreadsheet. Processing second-by-second duty cycles for the 109 MOVES-related driving cycles inflated the spreadsheet to approximately 150 MB. The spreadsheet's results worksheet contains the bin distribution assignments for each cycle, calculated for all source types and regulatory classes. Users can run any number of driving cycles, vehicles, and regulatory class combinations as needed. However, to reduce the number of combinations, the research team selected the most common 2025 regulatory class for each of the 13 vehicle classes. The research team ran the model 13 times, once per source type and its assigned regulatory class. The results were then copied into the MOVES Duty Cycle VSP and OpMode Bin Outputs and subsequently transferred to the MOVES5 Bin Distribution Energy Processor for use in calculating energy use and emissions for the general-purpose lane and managed lane fleets employed in this project. The rest of this section describes the calculations in each worksheet, presented in reverse order from the final worksheet to the initial results worksheet.

- Version Info Worksheet - This worksheet contains basic summary information about the spreadsheet. The information includes the spreadsheet name, model version, and version date. The spreadsheet indicates that the model is running for Fulton County fuels for June 2025. The specific temperature and relative humidity for which the emission rates are provided are from the standard regional analysis (87.3F and 53.8% humidity). Note that different fuel programs, inspection and maintenance (I/M) programs, temperature, and humidity settings would require a spreadsheet update to reflect energy use and emission rates. This worksheet also includes a summary of model version updates since the previous release.
- Menu Lookups Worksheet - To ensure consistency, several worksheets utilize predefined dropdown menus. For example, users can select calendar years 2000 to 2050 in five-year increments. In some cases, the program itself selects the best option from a list. For example, the program automatically identifies the optimal driving cycle from a library to best match the average speed of vehicles on a freeway segment. This worksheet contains a library of lookup values and paired data elements, where if the item is selected in the first column, the value can be delivered from the second column. For example, if a user selects a specific vehicle class, the

MOVES numeric value for that source type can be used in internal XLOOKUP functions (e.g., passenger cars are source type 21). Menu items and lookups are provided in this worksheet for:

a. Calendar year of evaluation in five-year increments.
b. Thirteen EPA source types and their source type IDs, from motorcycles to combination long-haul trucks.
c. Three engine technologies (Internal Combustion, Electric, and Fuel Cell).
d. Six fuel types from gasoline to electricity.
e. Fifteen MOVES regulatory class descriptions.
f. Vehicle model years from 1985 to 2050.
g. Twenty MOVES fuel use and emissions categories.
h. Twenty-three on-road MOVES OperatingModeBin (or OpModeBin) IDs (running-exhaust), which allow internal algorithms to assign each second of vehicle activity to its official OpModeBin based upon source type, speed, acceleration, and VSP (calculated within the spreadsheet).
i. One hundred and nine MOVES driving cycles, so the lookup worksheet contains the names of each cycle and their characteristics (total cycle duration, distance traveled on the cycle, and average speed on the cycle). Five placeholders are also included for users to enter lookups for five user-provided cycles.
j. To simplify the implementation of the spreadsheet, the team limited the number of combinations of vehicle source types and regulatory classes. The lookup worksheet contains the assigned pairs.

k. The model currently assigns separate percentages of automobiles, medium-duty trucks, and light-duty trucks to general-purpose lanes and managed lanes. Users can change these percentages in the lookup worksheet (however, users must take care to ensure that the rows total 100%).

Lane Type	Percent LDV	Percent MDV	Percent HDV
General-Purpose Lane	55.0%	35.0%	10.0%
Managed Lane	61.1%	38.9%	0.0%

l. Thirteen VISSIM™ variables exported from the link segment results in VISSIM™ are defined in the lookup worksheet.

m. VISSIM™ link behavior types are cross-referenced to roadway classification (e.g., VISSIM™ links that are coded as Behavior Type 1 are urban arterials). This lookup table assigns VISSIM™ link types and average speeds to the appropriate MOVES driving cycles.

n. VISSIM™ links can either be general-purpose lanes or managed lanes, to which different fleet compositions will apply (e.g., no heavy-duty trucks on the managed lanes). The final lookup in the worksheet maps the VISSIM™ managed-lanes output (TRUE or FALSE) to Managed Lane or General-Purpose Lane.

- Duty Cycle Library Worksheet - A duty cycle, also known as a driving cycle, is a second-by-second representation of on-road driving activity (speed vs. time). Each duty cycle reflects representative/observed patterns of acceleration and deceleration on various roadway classes under various operating conditions. For example, MOVES includes a specific driving cycle that reflects Level of Service E traffic for light-duty vehicles on freeways, and another cycle for medium-duty trucks operating at an average speed of 20 mph on urban arterials. The worksheet contains 109 driving cycles embedded in the MOVES model. For each cycle, the worksheet contains the cycle ID, name, average speed, cycle duration, total cycle distance, and second-by-second speed data from time=0 to the end of the cycle. Driving cycles vary in duration, and the model supports a maximum length of 5,400 seconds (the Excel column limit). Users can add their own duty cycles to the worksheet and update the Menu Lookups Worksheet. Although placeholders are shown for five cycles, there is no limit to the number of cycles that can be added (other than practical run-time limitations of Excel for expanding the spreadsheet).

- MOVES5 VSP Bin Definitions Worksheet - This worksheet contains the definitions of the MOVES operating mode bins that are used in assigning each second of operation on a duty cycle to a VSP operating mode bin. The first column contains the MOVES Bin ID. There are 23 operating mode bins, grouped and numbered into braking, idling, and three groups of coast/cruise operations (low speed, medium speed, and high speed). Every second of vehicle operation is mapped to exactly one operating mode bin based on instantaneous speed, acceleration, and calculated VSP for that specific class. The VSP calculation employs source type physics parameters that represent the load impact of rolling resistance (A), rotational resistance (B), aerodynamic drag coefficient (C), vehicle mass (m), and fixed mass factor (M) representing on-road mass and reference loaded mass (to reflect partially loaded trucks). The equation employed in calculating instantaneous VSP is:

$$\boldsymbol{VSP = \left(\frac{A}{M}\right)v + \left(\frac{B}{M}\right)v^2 + \left(\frac{C}{M}\right)v^3 + \left(\frac{m}{M}\right)(a + g * \sin\theta)v}$$

Vehicle design and engine technologies have changed significantly over time in response to consumer demand for fuel economy and regulatory limits on engine emissions. Hence, there have been changes in the impacts of tire friction, rotational mass of drivetrains, wind resistance factors associated with vehicle shape and frontal area, and reduced vehicle mass in passenger cars (allowed by improvements in driver/passenger protection mechanisms). The VSP parameters (A, B, C, m, and M) for each combination of source type, regulatory class, and model year grouping are contained in the MOVES5 sourceTypePhysics Option Worksheet.

- MOVES5 sourceTypePhysics Option Worksheet - As described above, the MOVES VSP calculation employs source type physics parameters that represent the load impact of rolling resistance, rotational resistance, aerodynamic drag coefficient, and vehicle mass (reference loaded mass and representative on-road mass, to reflect partially loaded trucks). MOVES employs 178 different sets of VSP parameters (A, B, C, m, and M) that correspond to unique combinations of source type and regulatory class (reflecting vehicle certification standards and model-year grouping). To improve spreadsheet performance, the research project modeling approach necessarily limited the combinations of these parameters to the most common (on-road) combination for each of the 13 source types (using the default MOVES fleet composition from the ‘sample vehicle population’ table, as described in Chapter 4); these rows are highlighted in yellow.
- MOVES5 SourceTypePhysics Worksheet - This worksheet functions as a reference (lookup) table, cataloging the 13 most common in-fleet combinations of source type, regulatory class, and model year grouping for each source type described earlier. It

ensures that the correct VSP parameters are applied to each user-entered vehicle class and drive cycle (discussed later), allowing the Cycle VSP Worksheet to calculate VSP for each second of the cycle for the specified source type.

- Cycle VSP Parameters Worksheet - This worksheet identifies and prepares the VSP parameters for each user-provided vehicle class selected in the Cycle Selected worksheet (described later). The first column lists the cycle run (sequential row of cycles assessed), followed by the source-type name and ID, and then the regulatory class (i.e., the source-type regulatory class model year combination described earlier). Using a lookup function, it retrieves the specific VSP parameters (A, B, C, m, and M) for that combination from the MOVES5 SourceTypePhysics Worksheet. This worksheet ensures that the proper VSP parameters for that class are applied to the cycle analyses when the user processes the spreadsheet for various source-types (an iterative process).
- Cycle VSP Worksheet - This worksheet computes the second-by-second VSP values for the user-prescribed duty cycle and vehicle class. The VSP equation described earlier is applied, in which the instantaneous speed (from the Cycle Selected worksheet), acceleration (from the Cycle Acceleration Worksheet), grade (from the Cycle Grade Worksheet), and the five parameters for that row in the Cycle VSP Parameters Worksheet are applied to VSP for that cell. An example of a cell calculation equation is presented below:

```
=IF(‘Cycle Selected’!I69<>””, (((‘Cycle VSP Param’!$F69/'Cycle VSP
Param'!$I69)*('Cycle Selected'!I69*0.44704)^1)+(('Cycle VSP
Param'!$G69/'Cycle VSP Param'!$I69)*('Cycle
Selected'!I69*0.44704)^2)+(('Cycle VSP Param'!$H69/'Cycle VSP
Param'!$I69)*('Cycle Selected'!I69*0.44704)^3)+(('Cycle VSP
Param'!$J69/'Cycle VSP Param'!$I69)*(('Cycle
Accel'!I69*0.44704)+(9.81*SIN(ATAN(0.01*'Cycle Grade'!I69))))*('Cycle
Selected'!I69*0.44704))),"")
```

- Cycle OpModeBin Worksheet - This worksheet assigns each second of vehicle operation to a specific MOVES Operating Mode Bin based on the VSP values calculated in the previous worksheet. By referencing the table presented in the MOVES5 VSP Bin Definitions Worksheet, the system categorizes each data point into exactly one bin. The equation employed in the second-by-second cells first checks to make sure that a cycle was selected and that duty cycle data exists for the cell (if the duty cycle has ended, there is no need to process the cell, and a blank (“”) cell is returned). The calculation then employs a series of “if/then” statements to identify whether the second operation constitutes a deceleration or idle mode (identified based upon speed and acceleration rules), and if not, which low-speed, medium-speed, or high-speed coast/cruise mode the VSP calculation (which also includes user-defined grade, as discussed later). The equation returns the corresponding bin assignment for each second-by-second cycle cell. The MOVES energy use and emission rate is a constant for each operating mode bin for the source type and regulatory group combination (given all other variables). Hence, with the assignment of the bin in this worksheet, equations in the subsequent MOVES5 Bin Distribution Energy Processor can look up the applicable energy use and emission rates from its internal MOVES5 2025 LDV OpMode Rate Worksheet for that single second of operation. The equation below is an example taken from one cell in the worksheet. The equation first looks to make sure that the user has specified a duty cycle, uses the instantaneous speed (described in a subsequent worksheet), acceleration (described in a subsequent worksheet), grade (described in a subsequent worksheet), and VSP rules described earlier to assign the second of operation for that vehicle class into the applicable Operating Mode Bin.

```
=IF(‘Cycle Selected’!I5<>””,IF(‘Cycle
Accel'!I5+9.81/0.44704*SIN(ATAN('Cycle Grade'!I5*0.01))<=-
2,0,IF(AND('Cycle Accel'!G5+9.81/0.44704*SIN(ATAN('Cycle
Grade'!G5*0.01))<=-1, 'Cycle Accel'!H5+9.81/0.44704*SIN(ATAN('Cycle
Grade'!H5*0.01))<=-1, 'Cycle Accel'!I5+9.81/0.44704*SIN(ATAN('Cycle
Grade'!I5*0.01))<=-1),0,IF('Cycle Selected'!I5<1,1,IF(AND('Cycle
Selected'!I5>=1,'Cycle Selected'!I5<25,'Cycle VSP'!I5<0),11,IF(AND('Cycle
Selected'!I5>=1,'Cycle Selected'!I5<25,'Cycle VSP'!I5>=0,'Cycle
VSP'!I5<3),12,IF(AND('Cycle Selected'!I5>=1,'Cycle Selected'!I5<25,'Cycle
VSP'!I5>=3,'Cycle VSP'!I5<6),13,IF(AND('Cycle Selected'!I5>=1,'Cycle
Selected'!I5<25,'Cycle VSP'!I5>=6,'Cycle VSP'!I5<9),14,IF(AND('Cycle
Selected'!I5>=1,'Cycle Selected'!I5<25,'Cycle VSP'!I5>=9,'Cycle
VSP'!I5<12),15,IF(AND('Cycle Selected'!I5>=1,'Cycle Selected'!I5<25,'Cycle
VSP'!I5>=12),16,IF(AND('Cycle Selected'!I5>=25,'Cycle
Selected'!I5<50,'Cycle VSP'!I5<0),21,IF(AND('Cycle Selected'!I5>=25,'Cycle
Selected'!I5<50,'Cycle VSP'!I5>=0,'Cycle VSP'!I5<3),22,IF(AND('Cycle
Selected'!I5>=25,'Cycle Selected'!I5<50,'Cycle VSP'!I5>=3,'Cycle
VSP'!I5<6),23,IF(AND('Cycle Selected'!I5>=25,'Cycle Selected'!I5<50,'Cycle
VSP'!I5>=6,'Cycle VSP'!I5<9),24,IF(AND('Cycle Selected'!I5>=25,'Cycle
Selected'!I5<50,'Cycle VSP'!I5>=9,'Cycle VSP'!I5<12),25,IF(AND('Cycle
Selected'!I5>=25,'Cycle Selected'!I5<50,'Cycle VSP'!I5>=12,'Cycle
VSP'!I5<18),27,IF(AND('Cycle Selected'!I5>=25,'Cycle Selected'!I5<50,'Cycle
VSP'!I5>=18,'Cycle VSP'!I5<24),28,IF(AND('Cycle Selected'!I5>=25,'Cycle
Selected'!I5<50,'Cycle VSP'!I5>=24,'Cycle VSP'!I5<30),29,IF(AND('Cycle
Selected'!I5>=25,'Cycle Selected'!I5<50,'Cycle
VSP'!I5>=30),30,IF(AND('Cycle Selected'!I5>=50,'Cycle
VSP'!I5<6),33,IF(AND('Cycle Selected'!I5>=50,'Cycle VSP'!I5>=6,'Cycle
VSP'!I5<12),35,IF(AND('Cycle Selected'!I5>=50,'Cycle VSP'!I5>=12,'Cycle
VSP'!I5<18),37,IF(AND('Cycle Selected'!I5>=50,'Cycle VSP'!I5>=18,'Cycle
VSP'!I5<24),38,IF(AND('Cycle Selected'!I5>=50,'Cycle VSP'!I5>=24,'Cycle
VSP'!I5<30),39,IF(AND('Cycle Selected'!I5>=50,'Cycle
VSP'!I5>=30),40)))))))))))))))))))))))),"")
```

For practical purposes (i.e., to keep spreadsheet size manageable), the modeling regime employs only three vehicle classes: light-duty automobiles (LDVs), medium-duty delivery trucks (MDTs), and heavy-duty long-haul combination trucks (HDVs). However, the team processed all 13 source types (and any combination of regulatory classes within source type) in this worksheet by appending 109 rows for each new vehicle class and regulatory class combination. Users can also add new duty cycles to the various worksheets as desired.

- Cycle Acceleration Worksheet - This worksheet calculates instantaneous acceleration (the rate of change in speed) required for the VSP calculation for each second-by-second. The calculation of acceleration employs the second-by-second speed values associated with the cycle, which are provided in the Cycle Selected Worksheet. The MOVES convention is to calculate backward-looking acceleration, or the change in speed from the current second compared to the previous second. Because the initial zero second (initial starting speed value) does not have a preceding speed value, per MOVES convention, the cell is assigned the same acceleration rate as the following driving cycle second (calculated as v_1-v_0). Hence, the acceleration rate for the first second of the cycle always equals the acceleration rate of the subsequent second.
- Cycle Grade Worksheet - The VSP formula allows users to account for grade as an acceleration against gravity in VPS engine load calculations (see the previous VSP calculation that includes "$a + g \times \sin(\theta)$" for grade integration). To simplify the analysis in this research project, all road segments are assumed to have a level grade (i.e., $\theta=0$) for every second of vehicle operation on a driving cycle. However, this

worksheet serves as a data-entry tool, allowing users to assign representative grade values to the cycle if they wish to account for the terrain's impact on VSP.

- Cycle Selected Worksheet - This worksheet returns the second-by-second speed data for the specific MOVES duty cycle listed in each row. To generate outputs for the next step in the modeling chain, the research team processed all 109 duty cycles for one vehicle class at a time. Due to spreadsheet performance limitations, calculating all 1,417 combinations (13 source types × 109 duty cycles) simultaneously was not feasible. Instead, a piecewise approach was employed. The research team entered the first vehicle class across all 109 duty cycles to generate a single set of vehicle class results in the Results Worksheet. These results were then transferred to the MOVES Duty Cycle VSP and OpMode Bin Outputs Spreadsheet. This sequence was repeated iteratively for all 13 source types until the dataset was complete.
- Results Worksheet - This worksheet aggregates the total duration (in seconds) that a specified vehicle class operates in each MOVES operating mode bin for a given cycle. The 23 operating mode bins are organized into columns, and the function quantifies the total number of seconds that the specified vehicle class on the specified duty cycle spends in that operating mode bin (summarized from each row from the 5,400 (second-by-second) columns in the Cycle OpModeBin worksheet). The research team transferred the results for the specified vehicle class × 109 Duty Cycles to the MOVES Duty Cycle VSP and OpMode Bin Outputs Spreadsheet, ran the next vehicle class, transferred those results, and repeated the process until all 13 source types had been processed and transferred.

MOVES Duty Cycle VSP and OpMode Bin Outputs Spreadsheet

The MOVES Duty Cycle VSP and OpMode Bin Outputs Spreadsheet is designed to receive the outputs from 13 source type runs across all 109 MOVES-related driving cycles generated by the MOVES Duty Cycle VSP and OpMode Bin Processor spreadsheet. The research team performed each run, one at a time, for the 13 source types and their single assigned regulatory class group. Results were manually copied into this worksheet for each vehicle class run (starting with motorcycles and ending with combination long-haul trucks. There are only two worksheets within this spreadsheet. The first worksheet carries the data manually copied from the Results Worksheet of the MOVES Duty Cycle VSP and OpMode Bin Outputs Spreadsheet. The second worksheet simply sorts the outputs to display 13 source types per cycle, rather than 109 cycles per source type. This restructuring facilitates the data integration into the third spreadsheet.

Duty Cycle OpMode Bins Worksheet - The user manually inputs data into this worksheet from the Results Worksheet of the MOVES Duty Cycle VSP and OpMode Bin Processor Spreadsheet. Each source type is run one at a time in the upstream process, and results for each are copied into this worksheet (appending new rows to the bottom of what has already been entered). Thus, the first 109 rows contain the motorcycle (Source Type 11) results for the 109 driving cycles, and the last 109 rows contain the combination long-haul truck (Source Type 62) results for the same 109 driving cycles. Recalling that in the upstream process, even though the driving cycle is constant (same speed-acceleration pattern), all five of the VSP parameters vary across source types; hence, each source type yields a unique VSP bin distribution even when operating on the same cycle.

In each row, the user will find the basic cycle information (cycle name, average speed, duration, and distance traveled) in Columns E through H. The number of seconds that fall into each of the 23 Operating Mode bins appears in columns (Columns K through AG). The Operating Mode bin total number of seconds always equals the number of seconds in that driving cycle (each second falls into one, and only one, of the 23 operating mode bins). The energy and emissions calculator spreadsheet uses these distributions to allocate the number of seconds of operation on a link into the relative distribution of vehicle activity by bin, for the selected vehicle class and cycle.

Duty Cycle OpMode Bins by Cycle Worksheet - This worksheet contains the same columns as the data entry worksheet, but it reorders the data around Column E (Cycle Name) rather than Column C (vehicle class). A series of XLOOKUP functions populates the driving cycle operating mode bin cells (Columns K through AG) from the Duty Cycle OpMode Bins Worksheet. The results from this worksheet are copied directly into the MOVES5 Bin Distribution Energy Processor (Duty Cycle Bin Distribution Worksheet), so that the applicable Operating Mode Bin distributions can be used in energy and emissions calculations by source type and assigned regulatory class.

MOVES5 Bin Distribution Energy Processor

This third spreadsheet calculates travel time, energy use, and emissions per hour for every link in the modeled transportation system. Each link is tracked in the spreadsheet and carries the necessary data required for calculating travel time along the link (link length divided by average speed). Each record also contains the fleet composition and operating conditions required for hourly MOVES modeling of energy and emissions per link. The spreadsheet currently handles 7,500 transportation links, with separate fleets assigned to general-purpose lanes and managed lanes, and with the capability of assigning many different driving cycles to these links (any number of links can be added as rows to the spreadsheet, but additional links come with significantly increased calculation time). Users employ basic link-based model output information from a travel demand or microsimulation model and assumptions about fleet composition. The model uses these inputs to predict fleet vehicle-hours, energy use, and emissions. Each worksheet in the spreadsheet is described below, starting from the far right of the spreadsheet structure.

- Version Info Worksheet - This worksheet contains basic summary information about the spreadsheet. The information includes the spreadsheet name, model version, and version date. The spreadsheet indicates that the model is running for Fulton County fuels for June 2025. The specific temperature and relative humidity for which the emission rates are provided are from the standard regional analysis (87.3F and 53.8% humidity). Note that different fuel programs, inspection and maintenance (I/M) programs, temperatures, and humidity settings would require a spreadsheet update for energy use and emission rates. This worksheet also contains a summary of model version updates since the last version was released.
- Menu Lookups Worksheet - The Menu Lookups Worksheet in the MOVES Bin Distribution Energy Processor spreadsheet contains the exact same lookup parameters as employed in the MOVES Duty Cycle VSP and OpMode Bin Processor Spreadsheet. Rather than repeating the descriptions here, the user can read them earlier in this Appendix.

- Duty Cycle Library Worksheet - This worksheet serves as a reference library containing the same 109 MOVES driving cycles as the library employed within the MOVES Duty Cycle VSP and OpMode Bin Processor Spreadsheet. If users add their own driving cycles, they will need to ensure that the cycles appear in both spreadsheets. Rather than repeating the variable descriptions here, the user can read these descriptions earlier in this Appendix. The MOVES5 Bin Distribution Energy Processor Spreadsheet does not use any of the second-by-second data in this worksheet for any calculations (these calculations were already handled in the MOVES Duty Cycle VSP and OpMode Bin Processor Spreadsheet to prepare the cycle bin distributions employed in this spreadsheet). This worksheet provides cycle data solely for user convenience, enabling cycle inspection without opening the precursor cycle processing spreadsheet. Various worksheets in the MOVES5 Bin Distribution Energy Processor refer to these driving cycle names, average speeds, durations, and distances. To reduce spreadsheet size, Version 1.04 may eliminate this spreadsheet and move relevant data to the Menu Lookups Worksheet.
- Duty Cycle Bin Distribution Worksheet - This worksheet contains the final processed results from the MOVES Duty Cycle VSP and OpMode Bin Processor Spreadsheet, which are also stored in the MOVES Duty Cycle VSP and OpMode Bin Outputs Spreadsheet. As described earlier, including these bin distributions in the same spreadsheet as the emissions calculations would make the spreadsheet unwieldy and too slow to process. Hence, the research team copied the data directly from the MOVES Duty Cycle VSP and OpMode Bin Outputs Spreadsheet into this worksheet. As described in the previous spreadsheet, users will find the number of seconds that

fall into each of the 23 Operating Mode bins in Columns K through AG. These values will be used to calculate energy use and emissions for a vehicle class operating on that cycle on a given roadway link.

- MOVES5 VSP Bin Definitions Worksheet - This worksheet is repeated in the spreadsheet as a reference for users who want to review the criteria for operating mode bins, which are defined as a function of VSP, speed, and acceleration. The VSP calculations were already handled in the MOVES Duty Cycle VSP and OpMode Bin Processor Spreadsheet and used to generate the Operating Mode Bin distributions. Users can refer to these descriptions provided earlier in this appendix.
- MOVES5 2025 LDV OpMode Rates Worksheet - This worksheet contains the energy and emissions rates pulled from MOVES-Matrix 5. The source matrix was generated by executing 30,429 iterative MOVES5 runs and saving all component outputs into a 5.8-trillion cell 121.2 GB matrix. As described in the report for this project, MOVES-Matrix 5 allows users to query the huge matrix to obtain the same energy use and emission rates delivered by MOVES for any modeled scenario (because every potential modeled scenario was already run in MOVES5 and stored in the huge lookup matrix). With MOVES-Matrix, users need to specify the fleet composition, on-road operating conditions, and environmental conditions. Queries can then be used to obtain fleet-average energy use and emission rates (in kJ/second/vehicle and grams/second/vehicle) for a given scenario or for the link in the transportation system. To ensure that the spreadsheet for this project remained functional, a set of limiting assumptions was made to pull a small set of energy use and emission rates from MOVES-Matrix 5 into the spreadsheet. The modeling regime assumes that

users are looking at 2025 model year vehicles operating in calendar year 2025, and that the most common regulatory class group is operating for each source type. The modeling regime also assumes that only modeling light-duty passenger vehicles (MOVES Source Type 21), medium-duty delivery trucks (MOVES Source Type 32), and heavy-duty long-distance trucks (MOVES Source Type 62) are modeled. Columns A through D specify these modeling parameters, identifying calendar year, vehicle source type, regulatory class, and model year, Columns G through M of the spreadsheet contain the MOVES rate outputs for each of these three vehicle classes, operating in each of the 23 Operating Mode Bins, including energy (kJ/hour), and CO_2, CO, NO_x, VOC, PM_{10}, and $PM_{2.5}$ (all in grams/hour). Because this spreadsheet tracks vehicle activity in vehicle-seconds per analytical period (one hour of vehicle activity), columns P through V convert the rate values to fuel use and emissions per second, so spreadsheet calculations can multiply vehicle activity by these per-second rates. MOVES5 assigns these specific source-type energy-use and emission rates to every second of operation that falls within the corresponding Operating Mode Bin.

- Vehicle-Seconds by OpModeBin Worksheet - For any modeled link in the transportation network, calculation of energy use and emissions over any operating period requires knowledge of the number of vehicle-seconds of operation, by vehicle class, that occur within each of the 23 Operating Mode Bins (recall that MOVES assumes that energy use and emission rates are constant for every second of operation that falls into each operating mode bin). As discussed later (with respect to user inputs), each row in this worksheet represents a roadway link in the modeled system and records the user-provided vehicle activity by source type for that link. The vehicle activity on each link is also assigned to a representative driving cycle (discussed later). Because the operating mode bin distribution is already known for each source type and driving cycle, this worksheet performs a ratio-based calculation to assign the total seconds of vehicle operation on that link (for each source type) to the 23 operating mode bins, using the relative bin ratios associated with that driving cycle. For example, if the duty cycle spends 12% of its operation in idle mode, and the light-duty vehicles operate for 10,000 vehicle-seconds on the link, then 1,200 seconds of light-duty link vehicle activity in the link are assigned to the idle bin. Columns A through G carry the driving cycles by source type, and columns I through K carry the traffic volumes by source type provided by user inputs. Total vehicle activity for each source type (Column M) is defined by vehicle activity (vehicles/hour, columns I, J, K) multiplied by link travel time (Column H) in seconds. Columns P through CQ provide the ratio calculations, assigning the total travel time for each source type to the applicable operating mode. Column N provides a checksum to make sure that total vehicle activity in vehicle-seconds is accounted for. Now that the total number of seconds per vehicle class on each link has been quantified, the next set of seven spreadsheets will calculate energy use and emissions for each link.

- Link Worksheets (Link PM25, Link PM10, Link VOC, Link NOx, Link CO, Link CO2e, Link Energy) - Each of these worksheets has the same structure and employs the same algorithms and procedures, except that various applicable energy use or emission rates are employed in each sheet. For example, the algorithms in the Link VOC Worksheet look up applicable VOC rates (g/second), and those in the Link

Energy Worksheet look up applicable energy use rates (kJ/second). In opening any spreadsheet, users will see that Columns A through D carry the same duty cycle information for each link as described in the previous worksheets. Columns L through CK perform the calculations for each vehicle class (LDVs are in Columns L through AI, MDTs are in Columns AM through BJ, and HDVs are in Columns BN through CK). For each bin calculation, the spreadsheet cell equation uses an XLOOKUP function to obtain the rate from the MOVES5 2025 LDV OpMode Rates Worksheet for the vehicle source type, regulatory class, and operating mode bin ID. The equations in each worksheet refer to the specific energy use or pollutant column in the MOVES5 2025 LDV OpMode Rates Worksheet; for example, the Link Energy Worksheet looks up rates from Column G, and the Link VOC Worksheet looks up rates from Column K. The number of bin-seconds in each operating mode bin, as carried in the Vehicle-Seconds by OpModeBin Worksheet, is multiplied by the applicable rates, and total energy use and emissions are calculated for each bin. Columns L, AM, and BN summarize the total energy use or mass emissions on the link (summed across all 23 bins); repeated in Columns E, F, and G for convenience. Column H contains the total amounts for each link across the three vehicle classes.

- Vehicle Activity Worksheet - The Vehicle Activity Worksheet contains only calculated values (users do not enter data into this worksheet). The worksheet first reads traffic volume data (by vehicle class) from the VISSIM™ Input Data Worksheet. Then it assigns traffic volumes to the vehicle class columns by multiplying the total volume by the fleet penetration percentage for each Source Type (LDVs, MDTs, and HDTs). The worksheet also reads link length and average speed from the VISSIM™ Input Data worksheet and calculates travel time on the link (Column H). In Column I, the XLOOKUP function uses the VISSIM™ Input Data Worksheet code for managed lanes (True/False). It classifies each link as either a “Managed Lane” or a “General-Purpose Lane,” allowing the spreadsheet to assign different fleet mixes in the Fleet Input Worksheet to each facility type. Similarly, Column J decodes the numeric facility type value in the VISSIM™ Input Data Worksheet, representing the five VISSIM™ facility types as Freeway, Arterial, or Ramp, enabling the worksheet to assign an appropriate driving cycle to the activity on the link. Columns K through M assign driving cycles from the MOVES driving cycle library to each vehicle class, given the VISSIM™-predicted average operating speed on the link. As discussed earlier, the library contains different duty cycles for these vehicle classes operating under specific levels of service. The XLOOKUP function uses the facility type (Column J), the assigned vehicle class to each column (LDV, MDT, HDT), and the average speed (Column G), to find the applicable cycle row in the Menu Lookups Worksheet (Columns AT, AU, AV), returning the most appropriate cycle for that vehicle class operating on that link (Column AX). The Menu Lookup Worksheet includes a minimum and maximum average speed assigned to each cycle (Columns AV and AW). By design, the XLOOKUP function automatically selects the cycle for which the minimum speed is exceeded when no subsequent cycle satisfies that condition; hence, the selected cycle corresponds to the range in which the average speed exceeds the minimum speed and does not exceed the maximum speed. (see XLOOKUP function below).

```
=XLOOKUP($J4&"LDV"&$G4,'Menu Lookups'!$AT$4:$AT$64&'Menu
Lookups'!$AU$4:$AU$64&'Menu Lookups'!$AV$4:$AV$64,'Menu
Lookups'!$AX$4:$AX$64,"Error",-1)
```

Given the average speed and traffic volume per hour for each vehicle class, the worksheet calculates the total travel time per hour for all vehicles in that class traversing the link (Columns N through P). These vehicle-hours per vehicle class for the one-hour analytical period are multiplied by the hourly value of time for each vehicle class contained in the Fleet Inputs Worksheet to generate the total value of travel time experienced by each vehicle class per hour operating on that link (Columns Q through S). These calculated values also appear in the Results Worksheet.

- Fleet Inputs [User Input] - Users enter the percentage distribution of vehicle class Source Type (LDVs, MDTs, and HDTs) for general-purpose lanes. Default values are 55% for passenger cars, 35% for medium-duty trucks (light commercial trucks), and 10% for heavy-duty trucks. Because heavy-duty trucks are not allowed to operate on managed lanes, the percentage allocation on the managed lanes is re-allocated, with passenger cars at 61.1% and medium-duty trucks (light commercial trucks) at 38.9%. However, users can enter any percentage they desire into these six cells. Users also enter the value of time for each vehicle-hour of activity by vehicle class ($/vehicle-hour). The default values in the worksheet were inflation-adjusted from a 2016 FHWA report, setting the time values at $33.00/vehicle-hour for LDVs, $36.00/hour for MDTs, and $36.00/hour for HDTs. Users can enter any values of time into these three cells if better values are available and for use in sensitivity analyses.

- VISSIM™ Input Data [User Input] - The outputs from any VISSIM™ modeling run can be deposited directly into the VISSIM™ Input Data Worksheet. For each row (representing a link in the VISSIM™ model and in the real-world network), the VISSIM™ model outputs contain the following variables in each column (where the VISSIM™ variable name is presented within parentheses): VISSIM™ link number ($LINK:NO), link name (NAME), link facility type (LINKBEHAVTYPE), link display type (DISPLAYTYPE), link level (LEVEL), number of lanes (NUMLANES), link length in feet (LENGTH2D), if the link is a connector (ISCONN), where the connector runs between a source link (FROMLINK) to a destination link (TOLINK), the VISSIM™ lane change distance assumption (LNCHGDISTDISTRDEF), whether an overtaking lane is present on the link (HASOVTLN), whether the link is a managed lane and coded as true or a general-purpose lane and coded as false (MANAGEDLANE), the predicted traffic volume in vehicles/hour (VOLUME), and the average speed on the link in mph (SPEED). These values are used in the various worksheets as described in earlier sections.
- Results Worksheet - The Results Worksheet first repeats a summary of the input data for each transportation link (one link per row) in Columns A through K. The columns show Link ID, traffic volumes by Source Type (LDV, MDV, and HDV), link length, average speed, and travel time on that link, whether the link is a managed lane or general-purpose lane (as discussed earlier, because users can assign different fleets to each facility type), the vehicle-hours of total activity on the link (summed across all three vehicle Source Types) on that link, and the total value of total travel time on that link, as calculated in the Vehicle Activity Worksheet for each Source Type.

Column L additionally reports the Total Gasoline Equivalent (Gallons), which converts total link-level energy use into an equivalent gasoline consumption factor. The worksheet then summarizes the outputs of the seven primary calculation worksheets for energy use and mass emissions on that link for the modeled time-period (Link PM25, Link PM10, Link VOC, Link NOx, Link CO, Link CO2e, Link Energy in Columns M through S). Each row represents the vehicle-hours, value of travel time, energy used, and emissions generated for the one-hour analytical period for each link. Totals for the entire system (summed across all rows) are presented as "System Totals" in Row 1 for convenience. If users create separate spreadsheet analyses for different case studies or scenarios, the data in the Results Worksheet of each scenario spreadsheet can be copied into a new spreadsheet to calculate differences in system performance metrics across the scenarios.