ABSTRACT

Title: COMPREHENSIVE HIGHWAY CORRIDOR PLANNING WITH SUSTAINABILITY INDICATORS

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This thesis develops a Model Of Sustainability and Integrated Corridors (MOSAIC) to select the best program-level plans for corridors within Maryland by estimating the sustainability impact of multimodal highway improvement options early in the transportation planning and environmental screening processes with minimum requirements on staff time and other resources. Six categories of sustainability indicators (mobility, safety, socio-economic impact, natural resources, energy and emissions, and cost) and more than thirty sustainability performance measures have been defined as evaluation criteria for the selection of highway corridor improvement options. Currently, MOSAIC considers the no-build case and two highway improvement options, including adding a general-purpose lane and converting at-grade intersections to grade-separated interchanges. Mode choice model has also been introduced for future study on multimodal improvement types. MOSAIC has been applied to the US 15 and I 270 corridors, thus demonstrating the feasibility and usefulness of this comprehensive tool for sustainable highway corridor planning.

COMPREHENSIVE HIGHWAY CORRIDOR PLANNING WITH SUSTAINABILITY INDICATORS

by

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Dedication

This thesis is dedicated to my dear parents.

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Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

A transportation corridor planning study usually consists of several sequential steps including problem identification, study organization, determination of goals and evaluation criteria, development/evaluation of initial alternatives, development/evaluation of detailed alternatives, financial analysis, alternative selection, transportation plan updates, project development, and project implementation. The impacted communities and interested stakeholders may also be involved in each corridor planning step. The greatest benefit of and the most streamlined process for transportation corridor improvement are obtained when the relevant agencies and stakeholders are involved early in the planning process, when environmental impact mitigation is provided in a proactive and systematic fashion, when multiple corridor projects are considered at the program level (instead of on a project-by-project basis), as well as when decisions are driven by clear goals and objectives, high-quality data, and valid objective modeling tools. A negative impact in one corridor can be balanced cost-effectively by a benefit in another corridor. However, the successful application of such proactive measures would require prior knowledge of the likely sustainability impact of multiple corridor improvement projects, so that the appropriate type and amount of mitigation can be planned ahead systematically.

The aim of this research is to develop a Model Of Sustainability and Integrated Corridors (MOSAIC) to select the best program-level plans for the corridor within Maryland by estimating the sustainability impact of multimodal highway improvement options early in the transportation planning and environmental screening processes with minimum requirements on staff time and other resources.

As part of the initial effort, six categories of sustainability indicators (mobility, safety, socio-economic impact, natural resources, energy and emissions, and cost) and more than thirty sustainability performance measures have been defined as evaluation criteria for the selection of highway corridor improvement options. Currently, MOSAIC is focus on comparing the sustainability impact of both the no-build case and two highway corridor improvement options, namely adding a general-purpose lane to the existing roadway and building grade-separated interchanges at this stage. Various quantitative models have been developed to analyze the impacts of these alternative corridor improvement options on identified sustainability indicators. Different from microscopic traffic simulation (e.g Synchro, Vissim) and EPA emission models (e.g. MOVES) that provide detailed pollution and green house gas (GHG) emission estimates for a particular project with a predetermined improvement type, MOSAIC integrates sustainability objectives before the selection of an improvement type, incorporates a more comprehensive set of sustainability indicators, and provides high-level impact analysis convenient for the users to the largest extent. The impacts on these sustainability indicators are then weighted based on policy considerations and the users' priorities. MOSAIC would be able to provide both numerical and graphical outputs that identify the corridor improvement option that best balances these sustainability indicators, and avoid improvement options with major negative environmental impacts that often lead to costly and lengthy environmental screening and mitigation procedures.

After completing the modules development, MOSAIC has been applied to the US 15 corridor north of Fredrick, MD, thus demonstrating the feasibility and usefulness of this comprehensive tool for sustainable highway corridor planning. When the same weights are given to all six categories of sustainability indicators, the final evaluation results suggest that converting at-grade intersections to grade-separated interchanges along the US 15 corridor would be more effective in enhancing sustainability than constructing additional travel lanes, and both of the two improvement types would have positive impact in sustainability compared with the no-build scenario.

The current version of MOSAIC runs within a Microsoft Excel spreadsheet environment, and includes: (1) A user input module where users can select a corridor and candidate highway improvement options for that corridor; (2) Several analysis modules that quantitatively estimate the impact of user-specified improvement options on all sustainability indicators; and (3) An output module that provides both numerical and graphical outputs.

Planned future research will improve MOSAIC to consider multimodal improvements in highway projects, such as bus rapid transit, light rail, bus-only lane, HOV/HOT operations, park-and-ride, express toll lanes, truck-only lane, bike/pedestrian facilities, ITS/ATIS deployment, access management, and local land use plans. In this way, as a portion of the initial work for assessing the Travel Demand Management (TDM) strategies that belongs to part of the future research, the pivot-point mode choice model has also been introduced in the thesis. Meanwhile, Existing MOSAIC tool will be integrated into the SHA Enterprise GIS (eGIS) environment in phase two of the project, which will further streamline MOSAIC input and output procedures for state-wide planning applications in Maryland.

The remainder of the project report is organized as follows. Chapter 2 summarizes and briefly discusses sustainability indicators as well as the major distinguished tools relevant to the comprehensive highway corridor planning we referred to. Chapters 3 through 8 document the technical details of various MOSAIC input/output and analysis modules. Chapter 9 introduces the pivot-point mode choice model that could be applied to generate part of the initial input data for MOSAIC phase two study. Chapter 10 illustrated the output types of MOSAIC. Chapter 11 presents the findings from a case study that applies MOSAIC to the US 15 corridor between Frederick, MD and the Maryland-Pennsylvania border, while Chapter 12 demonstrate the mode choice case study along a section of I 270. Finally, the conclusions and future study suggestions will be provided in Chapter 13.

Chapter 2 Literature Review

To ensure MOSAIC is developed upon the best practices and prior lessons from other states, a comprehensive review of integrated sketch-planning transportation indicators, strategies and tools from various State Departments of Transportation (state DOTs) and other government agencies in and outside of the U.S. has conducted. The following sections summarize and briefly discuss the sustainability indicators adopted in previous transportation planning studies, several modeling tools developed in previous research that quantitatively evaluate these sustainability indicators, and finally the findings and recommendations for MOSAIC development.

2.1 Sustainability Indicators

Several State Departments of Transportation (state DOTs) and other government agencies in and outside of the U.S. have developed sustainability indicators for transportation planning and in some cases implemented them at the corridor level. The following three subsections summarizes and briefly discusses the sustainability indicators developed by state DOTs, other U.S. organizations, and agencies outside of the U.S. respectively. This review is not comprehensive and focuses on indicators applicable at the corridor level. Most of the sustainability indicators fall into the following six categories in Table 1. This categorization scheme will be followed in this section to allow easy comparison among multiple past studies.

Table 1. General Sustainability Indicators
1. Environmental 2. Socioeconomic 3. Transportation 4. Climate Change/Energy Use 5. Resources/Recycling 6. Financial

2.1.1 Indicators Developed by State Agencies

2.1.1.1 Chesapeake Bay Program

Within the Chesapeake Bay program, the Maryland Department of Natural Resources (MDNR) developed Maryland's Green Infrastructure Assessment as a tool to measure ecological impacts of various urbanization projects. Hubs and corridors in the Green Infrastructure System are assigned a relative risk-of-development measurement. The primary measures used by MDNR to rank the ecological importance of various corridor sections are listed in Table 2.

Table 2. Chesapeake Bay Program Ecological Parameters	
Area of Delmarva fox squirrel habitat	Length of streams within interior forest
Area of natural heritage areas	Number of vegetation types
Mean fish Index of Biotic Integrity	Number of physiographic regions in hub
Number of stream sources and junctions	Area of highly erodible soils
Marsh within 10 km of hub periphery	Remoteness from major roads
Proportion of interior natural area in hub	Nearest neighboring hub distance
Area of wetland interior forest	Patch shape
Area of other unmodified wetlands	Topographic relief (standard deviation of elevation)
Fraction in mature vegetation communities	

2.1.1.2 Efficient Transportation Decision Making

Efficient Transportation Decision Making (ETDM) process was developed by The Florida Department of Transportation (FDOT) between 1999 and 2003. ETDM involves all environmental reviewing agencies early in the planning process in order to expedite environmental review and project completion, reduce costs, and create better environmentally-sound transportation solutions. The indicators used by the various Florida state agencies to evaluate environmental impacts are summarized in Table 3.

Table 3. ETDM Indicators		
Environmental	Socioeconomic	Transportation
◆ Air quality	◆ Recreation Areas	◆ Mobility
◆ Coastal & Marine	◆ Farmland	
◆ Water quantity & quality	◆ Infrastructure	Financial
◆ Contaminated sites	◆ Navigation	◆ Economics
◆ Wetlands	◆ Special Destinations	
◆ Wildlife and Habitat	◆ Section 4(f) potential	
	◆ Relocation	
	◆ Historical and Archeological Sites	
	◆ Aesthetics	
	◆ Equity	

2.1.1.3 Texas Department of Transportation Sustainability Enhancement Tool

The Texas Department of Transportation (TxDOT) developed the Sustainability Enhancement Tool (SET) between 2006 and 2008. The SET strategic plan has five goals for improving the sustainability of transportation improvements: reduce congestion, improve safety, increase economic opportunity, enhance the value of transportation assets, and improve air quality. Table 4 shows the performance measures used as inputs in SET.

Table 4. Sustainability Objectives and Performance Measures for TxDOT's Goals		
Environmental	Transportation	Climate Change/Energy Use
◆ Daily NO_x, CO and VOC emissions per mile of roadway	◆ Travel Time Index	◆ Daily CO_2 emissions per mile of roadway
◆ Attainment of ambient air quality standards	◆ Buffer Index	
	◆ Truck throughput efficiency	Financial
Socioeconomic	◆ Proportion of non-single-occupant travel	◆ Cost recovery from alternative sources
◆ Land use balance	◆ Annual severe crashes per mile	◆ Average pavement condition score
	◆ Percentage of lane-miles under traffic monitoring/surveillance	◆ Capacity addition within available right of way

2.1.1.4 Oregon Department of Transportation Sustainability Plan

In 2000, Governor Kitzhaber enacted an Executive Order that promotes sustainability in state government operations. In 2001, the state legislature passed the

Oregon Sustainability Act, which established the Oregon Sustainability Board and set objectives for state agencies. The Oregon Department of Transportation then developed a Sustainability Plan in September 2008 in order to address the potential effects of climate change with some of its goals listed in Table 5.

Table 5. Oregon Transportation Plan

Environmental	Transportation	Resources/Recycling
◆ Waterway Alterations ◆ Animal Migration Obstruction ◆ Water Contamination ◆ Air Pollution ◆ Nature Tourism Socioeconomic ◆ Health and Wellness Programs ◆ Community Involvement ◆ Well-being and Development Program ◆ Open/Fair Contracting Practices ◆ Compact Community Design ◆ Mixed Development	◆ Fatalities and Injuries ◆ Driver Education & Licensing ◆ Infrastructure Maintenance ◆ Safety Management ◆ Mode Choice ◆ Accessibility ◆ Travel Time ◆ Impervious Surface Area Climate Change/Energy Use ◆ Carbon Dioxide Emissions ◆ VMT ◆ Energy Efficiency ◆ Alternative Fuels	◆ Natural Resource Extraction ◆ Environmental Management System ◆ Asset Management Initiative ◆ Development of Recycling Markets Financial ◆ Life Cycle Costs Analysis ◆ Investment in Local Business ◆ Purchase of 'Green' Products

2.1.1.5 Cleveland Innerbelt Study

In preparation for a proposed project in the Cleveland Innerbelt area, a study was conducted by Ohio DOT that provided an environmental impact analysis for several highway alignment alternatives. The sustainability indicators from that study are found in Table 6.

Table 6. Cleveland Innerbelt Analysis Measures	
Environmental ◆ Geology- Soils and Bedrock ◆ Storm Water ◆ Wetlands ◆ Threatened and Endangered Species ◆ Drinking Water Resources ◆ Floodplains ◆ Farmland ◆ Air Quality ◆ Noise ◆ Vibration Socioeconomic ◆ Parks and Other Green Spaces ◆ Visual Resources ◆ Land Use and Development ◆ Neighborhood/Community Access ◆ Community Facilities and Services ◆ Property Impacts and Relocations ◆ Demographic Conditions ◆ Environmental Justice and Title VI ◆ Cultural Resources ◆ Relationship of Local Short-Term Uses of Man's Environment and the Maintenance and Enhancement of Long-Term Productivity ◆ Secondary and Cumulative Impacts	Transportation ◆ Other Transportation Modes in Study Area ◆ Relationship to State and Local Transportation Plans Resources/Recycling ◆ Aquatic Resources ◆ Terrestrial Resources ◆ Hazardous Waste ◆ Irreversible and Irretrievable Commitments of Resources Financial ◆ Regional Economic Effects ◆ Local Economic Effects ◆ Construction Impacts

2.1.1.6 New York State Department of Transportation GreenLITES

The New York State Department of Transportation created a program, GreenLITES (Green Leadership in Transportation Environmental Sustainability), to improve the quality of transportation infrastructure while minimizing impacts to the environment. A "Project Environmental Sustainability Rating System Scorecard" is used to rate proposed federally-funded projects. Projects are rated based on the following measures in Table 7.

Table 7. GreenLITES Scorecard	
Environmental ◆ Alignment Selection ◆ Protect, Enhance or Restore Wildlife Habitat ◆ Protect, Plant or Mitigate for Removal of Trees & Plant Communities ◆ Noise Abatement ◆ Stray Light Reduction ◆ Storm water Management Socioeconomic ◆ Context Sensitive Solutions ◆ Land Use/Community Planning	Transportation ◆ Improved Traffic Flow ◆ Improve Bicycle and Pedestrian Facilities Climate Change/Energy Use ◆ Reduce Electrical Consumption ◆ Reduce Petroleum Consumption ◆ Local Materials Resources/Recycling ◆ Reuse of Materials ◆ Recycled Content ◆ Bioengineering Techniques ◆ Hazardous Material Minimization Financial ◆ Best Management Practices

2.1.2 Indicators developed by Other U.S. Organizations

2.1.2.1 Sustainable Society Foundation

The Sustainable Society Foundation is an organization whose objective is to stimulate and assist societies toward sustainability. One of its most recent projects has been to develop a Sustainable Society Index as an understandable way to integrate important aspects of sustainability and quality of life to measure a country's level of sustainability. 22 indicators were developed and grouped into 5 categories based on the definitions of the Brundtland Commission (Kerk 2009) shown in Table 8. The scoring system has a scale of 0 to 10 where a score of 0 is unsustainable and 10 indicates complete sustainability. While these sustainability indicators are developed for macroscopic national-level analysis, some of them can be applied to corridor-level transportation improvement analysis, such as air/water/land quality, greenhouse gas emissions, and ecological footprints.

Table 8. Sustainability Society Indicators		
I Personal Development ◆ Healthy Life ◆ Sufficient Food ◆ Sufficient to Drink ◆ Safe Sanitation ◆ Education Opportunities ◆ Gender Equality II Healthy Environment ◆ Air Quality ◆ Surface Water Quality ◆ Land Quality	III Well-balanced Society ◆ Good Governance ◆ Employment ◆ Population Growth ◆ Income Distribution ◆ Public Debt IV Sustainable Use of Resources ◆ Waste Recycling ◆ Use of Renewable Water Resources ◆ Consumption of Renewable Energy	V Sustainable World ◆ Forest Area ◆ Preservation of Biodiversity ◆ Emission of Greenhouse Gases ◆ Ecological Footprint ◆ International Cooperation

2.1.2.2 Center for Clean Air Policy

The Center for Clean Air Policy created a guidebook to help state and local government officials understand the impact of policy decisions on air pollution, energy use and greenhouse gas emissions (see Table 9). Its Transportation Emissions Guidebook is divided into two parts: (1). Land Use, Transit & Travel Demand Management; and (2). Vehicle Technology & Fuels. The various policies analyzed are listed in Table 10. Each part consists of three main sections: (1). A Guidebook Emissions Calculator that can quantify the emissions benefits of a particular project; (2). A series of Policy Briefs; and (3). A Background section with supplementary information. The Transportation Emissions Guidebook emphasizes the integration of land use and transportation decision-making in order to reduce vehicle miles traveled at all levels.

Table 9. CCAP Guidebook	
Part One	Part Two
◆ Transit Oriented Development	◆ Feebates
◆ Bicycle Initiatives	◆ Hybrid Vehicles
◆ Pay as You Drive Insurance	◆ Biofuels
◆ Light Rail	◆ Low Rolling Resistance Tires
◆ Comprehensive Smart Growth Policy	◆ Truck Stop & Vessel Electrification
	◆ Locomotive Technologies
	◆ Driver Training

2.1.2.3 Transportation Research Board Committee on Transportation and Sustainability

The Transportation and Sustainability Committee of the Transportation Research Board has proposed a transportation project evaluation system with indicators that encourage comprehensive and sustainable transportation planning. Table 10 below includes the most important indicators recommended by the Committee.

Table 10. TRB Recommended Indicator Sets	
<u>Environmental</u> ◆ Per capita air pollution emissions, disaggregated by mode ◆ Air and noise pollution exposure and health damages ◆ Impervious surface coverage and storm water management practices <u>Socioeconomic</u> ◆ Quality of transport for disadvantaged people ◆ Affordability ◆ Overall satisfaction rating of transport system ◆ Universal Design	<u>Transportation</u> ◆ Per capita mobility ◆ Mode split ◆ Average commute travel time and reliability ◆ Average freight transport speed and reliability ◆ Per capita congestion costs ◆ Total per capita transport expenditures ◆ Per capita traffic crashes and fatalities <u>Climate Change/Energy Use</u> ◆ Per capita energy consumption disaggregated by mode ◆ Energy consumption per freight ton mile

2.1.2.4 Strategic Highway Research Program II Performance Measurement Framework

The Performance Measurement Framework for Highway Capacity Decision Making is a web resource developed for the second Strategic Highway Research Program (SHRP2) to help state and local transportation agencies evaluate major highway capacity improvement projects. This web resource was developed by Cambridge Systematics, Inc., in association with High Street Consulting Group, TransTech Management, Inc., Spy Pond Partners and Ross & Associates. The five areas of concern in the Performance Measure Checklist are transportation, environment, economic, community, and cost, as listed in Table 11 (Transportation Research Board 2009).

Table 11. SHRP 2 Capacity Performance Measures

Environmental	Socioeconomic	Transportation
◆ Loss of Habitats	◆ Job accessibility	◆ Trip Travel Time
◆ Natural Resource Plan Consistency	◆ Destination Accessibility	◆ Travel Time Index
◆ Animal-Vehicle Collisions	◆ Labor Force Accessibility	◆ Volume to Capacity Ration
◆ Losses of Native Plants	◆ Market Accessibility	◆ Level of Service
◆ Water Quality Protection Areas	◆ Environmental Justice	◆ VMT
◆ Hydromodification	◆ Economic Impact	◆ Mode Share
◆ Losses of Riparian and Floodplain Areas	◆ Economic Development	◆ Travel Time Reliability Index
◆ Water Resource Plan Consistency	◆ Transportation and Land Consumption	◆ On-Time Trip Reliability
◆ Construction Related Water Quality Impacts	◆ Induced Development Land Consumption	◆ Throughput Efficiency
◆ Water Quality Standards Compliance	◆ Support of Project for Growth Centers	◆ Incident Duration
◆ Highway Runoff	◆ Local-Regional Plan Consistency	◆ Crash Analysis
◆ Ratio of Wetland Acres Taken and Replaced	◆ Consistency of Induced Land Consumption with Land Use Plans	◆ Crash Rate
◆ Losses of High Quality Wetlands	◆ Site Location	◆ Crashes
◆ Wetlands Plan Consistency	◆ Artifact Location	◆ Transportation Conformity
◆ Carbon Monoxide and Particulate Matter Concentrations	◆ Community Cohesion	
◆ Air Toxics Concentrations	◆ Noise	Climate Change/Energy Use
◆ Air Toxics Exposure	◆ Visual Quality	◆ Greenhouse Gas Emissions
	◆ Emergency Response Time	◆ Infrastructure Vulnerability
	◆ Citizens' Concerns	◆ Carbon Sequestration
		Financial
		◆ Cost stability
		◆ Construction Cost Escalation Factor
		◆ Benefit Cost (B/C) Analysis
		◆ Project Unit Cost
		◆ Qualitative Cost Effectiveness
		◆ Construction Productivity Index
		◆ Local/Regional Match
		◆ Private Investment

2. 1.3 Indicators Developed Outside of the U.S.

2.1.3.1 England Sustainability Checklist

In England, Communities and Local Government, Northwest Regional Assembly, Northwest Regional Development Agency, World Wildlife Federation and BRE Group have teamed together to develop a sustainability Checklist to guide the design of new or regeneration developments. The Checklist in Table 12 covers regionally-specific sustainability and planning issues, and is intended to be a tool for decision makers (developers, local authority planners, local authority planning committee members, and funding bodies) in both the public and private sectors.

Table 12. England Sustainability Checklist

Environmental	Socioeconomic	Climate Change/Energy Use
◆ Air quality ◆ Water conservation ◆ Water resources planning ◆ Conservation ◆ Enhancement of Ecology ◆ Planting	◆ Noise Pollution ◆ Land Use Efficiency ◆ Landscaping ◆ Form of Development (Permeability) ◆ Mix of Use ◆ Involvement in Decision Making ◆ Supporting Public Services, Social Economy and Community Structure ◆ Community Management of the Development	◆ Flash flooding ◆ Heat Island ◆ On Site Renewable Energy Production ◆ Site Infrastructure Resources/Recycling ◆ Appropriate use of land resources ◆ Environmental Infrastructure ◆ Waste minimization
	Transportation ◆ General Policy ◆ Pedestrians/cyclists ◆ Proximity of local amenities ◆ Parking	Financial ◆ Competitive business ◆ Effective infrastructure ◆ Employment ◆ Business Types

2.1.3.2 EFECT for Athens, Greece

The Department of Transportation Planning and Engineering at the National Technical University of Athens developed a model called EFECT (Tsamboulas 2000). It is a methodological framework for evaluating the impact of transportation projects with a specific focus on environmental impacts. It combines Multi-Criteria Analysis (MCA) and Cost-Benefit Analysis (CBA) methods to estimate proposed transportation initiatives in different regions and time periods. The environmental indicators for the EFECT program are listed in Table 13.

Table 13. EFECT Environmental Impacts (MCA)	
Environmental	Resources/Recycling
◆ Soil	◆ Natural Resources
◆ Ecosystems	
◆ Waters	Socioeconomic
◆ Air	◆ Land Use
◆ Landscape	◆ Residential Areas
	◆ City Planning
Transportation	◆ Public Acceptance
◆ Noise	◆ Cultural Heritage
◆ Traffic	
◆ Accidents/hazards	

2.1.4 Summary and Recommendations

Based on the comprehensive review of current practices, the following sustainability indicators are considered being incorporated in MOSAIC analysis (see Table 14). These sustainability indicators are selected for several reasons: (1). They are widely adopted in previous studies as practical measures of sustainability; (2). The data sources required for the computation of these indicators at the corridor level are available; (3). They adequately reflect unique sustainability initiatives in Maryland (e.g. PFA); (4). They are consistent with Maryland State Highway Administration (SHA)'s mobility, safety, socio-economic, and environmental stewardship objectives.

Table 14. Recommended Sustainability Indicators

Energy, Environment and Natural Resources	Socio-Economic Impact and Cost	Mobility and Safety
Green House Gas	Within Smart Growth –PFA Boundaries	Travel Time Savings, Delay, Speed, LOS
Pollution emissions	Compatibility with Existing Land Use	Travel Reliability
Fuel Consumption	Economic Impact	Accident Counts, Rate and Severity
Quantity of and degree of disturbance on Impacted Cultural/Historical Sites, Steep Slopes, Highly Erodible Soils, Wetlands, Waterways, Floodplains Forests, Critical Areas, Springs/Seeps, Bedrock/Geology Areas, Natural Species, Storm Water Facilities, etc	Livability	
	Noise	
	Aesthetics	
	Compatibility with Sustainable Transportation Modes (Transit/Bike/Walk)	
	Costs	

The research team has also worked with SHA in the compilation of all required input data for the case study site (US 15). The following chapter will introduce the methodology adopted in MOSAIC after the comprehensive literature review.

2.2 Models and Tools for Corridor-level Sustainability Analysis

This section focuses on the modeling methods and implementation approaches for evaluating the various sustainability indicators identified in the previous section. The following subsections summarize and briefly discuss the six major tools relevant to comprehensive highway corridor planning: Sketch Planning Analysis Spreadsheet Model (SPASM) and Surface Transportation Efficiency Analysis Model (STEAM) introduced by Federal Highway Administration, Sustainability Enhancement Tool (SET) developed by Texas Department of Transportation (TTI), Efficient Transportation Decision Making (ETDM) developed for the Florida Department of Transportation(FDOT), and MOBILE and MOVES introduced by EPA. Data sources and inputs for model development are also discussed for selected previous studies.

2.2.1 Sketch Planning Analysis Spreadsheet Model (SPASM)

Sketch Planning Analysis Spreadsheet Model (SPASM) is the early corridor-level planning tools that assist decision-makers in assessing multimodal alternatives and demand management strategies from various aspects.

As aforementioned, SPASM is an EXCEL or LOTUS based spreadsheet produced by FHWA, which helps assess multimodal transportation improvement alternatives and demand management strategies. It provides information on the economic efficiency of each improvement option by estimating transportation costs and benefits, and social-environmental impacts at the system or corridor level. SPASM defines three impacted groups for analysis: (1). Transportation system users; (2). Non-users such as employers/businesses; and (3). Society at large (primarily environmental impacts). Five alternative transportation improvement categories modeled in SPASM are: transit system improvements, highway capacity improvements, HOV improvements, auto use disincentives, and a combination of the above actions.

Users define the features of one or more of the above transportation improvement alternatives through three worksheets in SPASM: A public agency cost worksheet, which requires the user to provide capital and operating cost estimates; A facilities worksheet, used to provide a description of modal characteristics; and A travel demand worksheet, used to provide estimates of modal use, vehicle occupancies, access times and distances for each alternative. SPASM then estimates the effects of each improvement alternative on highway speeds and subsequent changes in highway usage, emissions, and fuel consumption. The final SPASM output shows the following aggregated estimates by modes for each proposed alternative: user benefits, including travel time, out-of-pocket cost savings, and fuel cost savings; costs to public agencies, including capital costs, vehicle operating costs and other operating costs; revenue transfers, which are "benefits" shifted from users to public agencies; external costs, including pollution costs and other external costs; net benefits (or costs); and benefit/cost ratio.

SPASM meets users’ needs for decision-making through benefit and cost analysis. However, it can only be used in limited sketch-planning situations owing to several simplifying assumptions, especially with respect to demand modal shift estimation. Instead, SPASM provides the basic idea and methods for the development of a more advanced model in benefit and cost analysis on various corridor-level projects, such as STEAM.

2.2.2 Surface Transportation Efficiency Analysis Model (STEAM)

The first version of the Surface Transportation Efficiency Analysis Model (STEAM) was introduced by the Federal Highway Administration (FHWA) in 1997. STEAM was the first FHWA computer-based impact analysis product to use input directly from the four-step travel demand modeling process for detailed, system-wide analysis of alternative transportation investments at regional and corridor levels. FHWA released STEAM 2.0 in 2000 to expand the scope of the model to address environmental justice measures.

Compared to SPASM (discussed in Section 2.2.4), STEAM is an enhanced modeling tool that can be applied more widely. Most of the advantages of the STEAM model result from its coupling with travel demand models, and are described in detail herein. These advantages, of course, come with higher model implementation costs. The outputs STEAM provided include: scenario annual results showing the scenario results of base case, improvement case, changes separately for each mode, and summary of a benefit-costs analysis; market sectors that describe the characters of each improvement alternatives; and risk outputs which demonstrate the probability distributions for each result metric.

However, the amount of indicators analyzed by SPASM and STEAM are far from enough in comparison to our Comprehensive Highway Corridor Planning with Sustainability Indicators project. Meanwhile, the methodologies behind many existing indicators of SPASM and STEAM have been replaced by new methods and tools. However, the framework of these two tools helped us in developing and scoping initial models for MOSAIC.

2.2.3 Sustainability Enhancement Tool (SET)

Sustainability Enhancement Tool (SET), previously discussed in Section 2.1.1.3, is a spreadsheet-based tool that produces a score for each of the TxDOT's five Strategic Plan goals: reduce congestion, improve safety, increase economic opportunity, enhance the value of transportation assets, and improve air quality.

SET is valuable for project screening in the very early stages of project evaluation by using a multi-criteria decision-making (MCDM) approach as the basis for the sustainability evaluation and is able to evaluate a base case scenario and up to three future cases. (Ramani 2009) SET is able to identify the extent of sustainability in the highway mode at the "sketch-planning" level, and to rank the projects by comparing certain projects at different locations, or among various alternative planning scenarios at a given location. The scores are calculated based on the Multi-Attribute Utility Theory (MAUT). Some examples of how SET's indicators are computed are provided in Table 15a. MAUT requires that a utility value from 0 (worst) to 1 (best) is determined for each indicator. This allows for direct comparison and aggregation of multiple indicators for decision analysis. Tables 15b and 15c list the data sources and the data inputs for the calculation of the sustainability indicators in SET. These data inputs are available from various Federal and Texas State agencies.

The outputs from SET are categorized either by the goal-wise sustainability indicators for the entire study section or by the link-wise sustainability indicator values. The result in the goal-wise performance is helpful for the users to identify which goals were not being met, the graph of the aggregate index values by link can tell the users which links performed worse than the average, and thus, provide users the key point that should be achieved in a sustainable manner.

SET requires the user to insert data inputs for each indicator into a number of Excel worksheets for each current and future corridor improvement scenario under consideration. The application would be made more user-friendly if a GIS tool was incorporated to load for current roadway alignments while also allowing users to specify future alignments. In this way, available GIS data for each indicator along with data from travel demand models could be automatically loaded into the spreadsheet application.

Table 15a SET Indicator Example Calculations

Performance Indicator	Calculation	Best	Worst
Travel Time Index (TTI)	TTI = Peak Hour Travel Rate (Minutes per Mile) / Travel Rate at Posted Speed Limit (Minutes per Mile)	1 (no delay due to congestion)	1.5 (Los Angeles)
Buffer Index (BI)	BI = (95th Percentile Travel Time (Minutes) – Average Travel Time (Minutes)) / Average Travel Time (Minutes)	0 (no variability)	0.65
Land Use Balance (LUB)	LUB = ∑Pi * ln(Pi) / ln(N), Pi = proportion of total land occupied by each classification, N = total number of categories	1	0
Truck Throughput Efficiency (TTE)	TTE = Daily Truck Volumes per Lane * Truck Operational Speed	170,700 daily truck miles/ per hour / per lane	5,600 daily truck miles/ per hour / per lane
Pavement Condition Score	Obtained from PMIS (Texas) database	100	0
Possible Lane Addition within ROW	= length weighted average of link scores, where Score Assigned = #Lane Addition in ROW * .25	1	0
Proportion of Total Person-Miles in non-SOVs	= (PMT(hov) + PMT(bus) + PMT(rail)) / PMT (total)	1.63 (Source: National Household travel survey)	1.14
Daily NOx, CO, and VOC Emissions (grams/mile of roadway)	= NOx*W(NOx) + CO*WCO + VOC*WVOC	1.3 kg/mile	181 kg/mile
Current Attainment of Ambient Air Quality Standards	Score = 0:0.2:1 based on level of attainment	1 (in attainment)	0 (extreme nonattainment)
Future Attainment	Score = current score + delta(NOX, VOC)/delta(Max NOX, VOC)	1 (in attainment)	0 (extreme nonattainment)

Table 15b SET Data Sources

Environmental	MOBILE6, Damage Costs from the Highway Economic Requirements System, US EPA Attainment Level
Socioeconomic	MPO land use data, land use plans
Transportation	Transportation Planning and Programming (TPP) Data Management Section, Public transportation data within the study area, State Highway Administration crash data
Climate Change/Energy Use	MOBILE6,
Financial	PMIS database

Table 15c SET Data Inputs

Environmental	Peak and off peak speeds and average daily travel occurring at peak and non-peak times; US EPA Attainment Level
Socioeconomic	GIS data or future land-use plan for residential, commercial/industrial, and institutional/public land use within 1/2 mile of corridor
Transportation	VMT per link, roadway length, intersection types, truck percentages, daily traffic volumes per lane, operational speed for trucks; length, frequency of service, and average ridership of public transportation routes.; number of HOV lane miles.
Climate Change/Energy Use	Peak and off-peak speeds and average daily travel occurring at peak and non-peak times.
Financial	PMIS database, future estimation based on DOT funding sources and existing maintenance routes; GIS or physical inspection of the area

2.2.4 Efficient Transportation Decision Making (ETDM) Tool

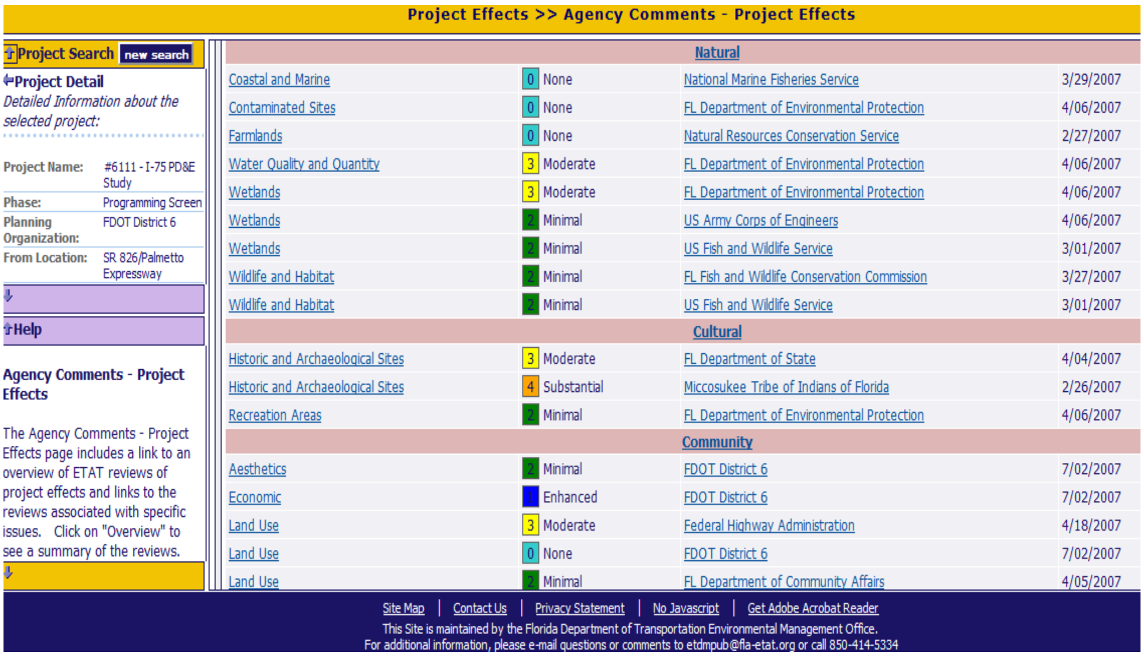
The Efficient Transportation Decision Making (ETDM) Tool, supported by Florida Department of Transportation (FDOT), is a web-based systematic tool that integrates land use, social, economic, environmental, and transportation considerations by the active participation of federal, state, and local agencies early in the planning process in order to expedite environmental review and project completion, reduce costs, and create better environmentally-sound transportation solutions.

ETDM system allows transportation planners to efficiently screen the affected natural resource areas of a proposed highway corridor alignment/improvement in a web-based environment. Users enter the project alignment by loading GIS data or by drawing the alignment with Internet mapping software. GIS analysis is then automatically performed on the proposed alignment for potential environmental effects. The GIS analysis identifies and quantifies natural, cultural, and community resources within 100’, 200’, 500’, and one mile buffer distances. Transportation planners can use this information to quickly identify potential problems or mitigation needs early in the project-development cycle (e.g. at the long-range planning or short-term programming stage). They can then make adjustments to the alignment as necessary before the project proposal is reviewed by other State environmental and natural resource agencies. Once the final planning-stage alignment has been chosen, the GIS analysis is saved in the ETDM database, and is available for subsequent review by Federal and State agencies and for the NEPA process (Bejleri *et al.* 2006).

The data behind the GIS analysis is gathered from participating State and Federal agencies which together form an Environmental Technical Advisory Team (ETAT) in Florida. The data is stored at the University of Florida’s Florida Geographic Data Library (FGDL), which also houses the servers for the ETDM/EST application. Communications between different servers and software are achieved with a web-based custom application in HTML, Java script, Java server pages, XML, and SQL programming languages.

Unlike the TxDOT SET tool, the Florida ETDM/EST system does not make assumptions about the relative weights of different sustainability indicators, or provide a composite score measuring the overall sustainability of highway corridor improvement projects. Instead, it provides planning and reviewing agencies a graphical view and a quantitative list of all potentially-affected natural/cultural resources. Each ETAT agency then reviews this information on a case-by-case basis independently, and provides a color-coded rating (0~5) for each sustainability indicator after the review process. A comprehensive dispute-resolution process has also been developed, as part of the EDTM/EST system, which creates a framework for resolving disagreements on environmental impacts by different ETAT agencies. Figure 1 illustrates the ETAT agency ratings for the State Route 826/Palmetto Expressway (Florida Department of Transportation 2010). In this example, while the various agencies agree on most sustainability indicators, Federal Highway Administration, FDOT District 6, and Florida Department of Community Affairs have some different views on the impact of this project on "Land Use" (see the last three rows).

Figure 1. Sample ETDM ETAT agency ratings for SR-826



Project Effects >> Agency Comments - Project Effects

Project Search | new search

Project Detail
Detailed Information about the selected project:

Project Name:	#6111 - I-75 PD&E Study
Phase:	Programming Screen
Planning Organization:	FDOT District 6
From Location:	SR 826/Palmetto Expressway

Help

Agency Comments - Project Effects

The Agency Comments - Project Effects page includes a link to an overview of ETAT reviews of project effects and links to the reviews associated with specific issues. Click on "Overview" to see a summary of the reviews.

Natural			
Coastal and Marine	0 None	National Marine Fisheries Service	3/29/2007
Contaminated Sites	0 None	FL Department of Environmental Protection	4/06/2007
Farmlands	0 None	Natural Resources Conservation Service	2/27/2007
Water Quality and Quantity	3 Moderate	FL Department of Environmental Protection	4/06/2007
Wetlands	3 Moderate	FL Department of Environmental Protection	4/06/2007
Wetlands	2 Minimal	US Army Corps of Engineers	4/06/2007
Wetlands	2 Minimal	US Fish and Wildlife Service	3/01/2007
Wildlife and Habitat	2 Minimal	FL Fish and Wildlife Conservation Commission	3/27/2007
Wildlife and Habitat	2 Minimal	US Fish and Wildlife Service	3/01/2007
Cultural			
Historic and Archaeological Sites	3 Moderate	FL Department of State	4/04/2007
Historic and Archaeological Sites	4 Substantial	Miccosukee Tribe of Indians of Florida	2/26/2007
Recreation Areas	2 Minimal	FL Department of Environmental Protection	4/06/2007
Community			
Aesthetics	2 Minimal	FDOT District 6	7/02/2007
Economic	Enhanced	FDOT District 6	7/02/2007
Land Use	3 Moderate	Federal Highway Administration	4/18/2007
Land Use	0 None	FDOT District 6	7/02/2007
Land Use	2 Minimal	FL Department of Community Affairs	4/05/2007

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The information generated by the planning screen analysis is stored in the ETDM database. The results of the ETAT review and agency comments are available to the general public if the information is not considered confidential. Project information is stored in the ETDM database before construction and for 5 years after the completion of construction. It has been reported that the implementation of the ETDM/EST system in Florida has reduced the average duration of environmental screening processes for highway improvement projects from 18-24 months to just 15 weeks.

However, although ETDM provides substantial information on projects for early and continuous involvement of agencies and the public, and establishes coordinated time schedules for agency action, it cannot generate its own results by applying certain models or methods. In addition, ETDM is not able to tackle the project improvements types relevant to managed lanes. Therefore, ETDM acts better in providing qualitative results rather than quantitative ones for the new construction of roadways.

2.2.5 EPA's MOBILE and MOVES Emission Analysis Tools

While MOBILE and MOVES are only developed for emission analysis, they are briefly discussed here because their underlying emission estimation methods may be applied for comprehensive corridor sustainability planning analysis.

The EPA MOBILE Vehicle Emission Modeling Software estimates three criteria pollutants: volatile organic compounds (VOC), carbon monoxide (CO), and nitrogen oxides (NOx), for vehicles from 1970 to 2050, under various conditions affecting emission levels such as ambient temperatures and average speed. The EPA developed its MOBILE6 version in 1999. In MOBILE6, the EPA revised some of the inputs to make MOBILE more relevant to the current vehicle fleet. It also revised the way some output is presented in order to better integrate air quality modeling with transportation planning and analysis needs (EPA 2003).

The pollution emissions estimates from MOBILE6 are based on extensive EPA testing of the nation's vehicle fleet in different operating conditions. The output from the model is in the form of emission factors expressed as grams of pollutant per vehicle per hour (g/hr), or per vehicle mile traveled (g/mi). Emission factors from MOBILE6 can be combined with estimates of total vehicle miles traveled (VMT) to develop highway vehicle emission inventories for varying time scales. Users must specify at a minimum the calendar year, minimum and maximum daily temperature, and fuel volatility. A default value is provided for all other optional inputs.

The new EPA's Motor Vehicle Emissions Simulator (MOVES) application is an improvement on MOBILE. MOVES is developed in order to increase user friendliness, ease of analysis, and to update the algorithms which estimate emissions factors. It allows users to analyze different policy scenarios related to mobile source emissions. (EPA

2009). Two recent studies in Arizona and Kansas City improve the estimation of HC, CO, NOx, and PM (Beardsley 2009).

MOVES also allows users to scale the geographic bounds of analysis to the national, county, project, and custom levels. Analysis at the national level scale uses the default values contained within MOVES and cannot be used to develop a State Implementation Plan (SIP) for emissions conformity. The county level scale is designed for users to input a larger amount of local data. Emissions inventories must be collected based on hourly or daily meteorology and activity inputs for a specific non-attainment episode. At the county level, data is inputted into MOVES via the County Data Manager (CDM), which requires that specific data for the county of analysis be imported or be reviewed. If the project level scale is selected, users then input micro-scale analysis of emissions along roadways or at locations where many starts or idles occur such as parking lots. For each geographic scale, users select a time scale for analysis (e.g. years, months, days, or hours).

While the methods for vehicle emission estimation in MOVES and MOBILE may be more complex than necessary for the type of corridor planning analysis in this SHA research project, they may be simplified and incorporated into MOSAIC.

2.2.6 Other Corridor Planning Tools with Sustainability Indicators

Other corridor planning applications with sustainability indicators we reviewed include: Colorado Department of Transportation (CDOT) 's Strategic Transportation, Environmental and Planning Process for Urbanizing Places (STEP UP), Maine Department of Transportation (MDOT) 's Integrated Transportation Decision-Making (ITD) Process, Virginia Department of Transportation (VDOT)'s Dashboard web-based performance measurement tool, the Measurement Framework for Highway Capacity Decision Making developed for the second Strategic Highway Research Program (SHRP2).

Chapter 3   Mobility

3.1 Travel Time Savings

Travel time savings are computed for each improvement scenario compared with the base-case scenario for both peak and off-peak periods, respectively. The general steps for the estimation of travel time savings are shown in Figure 2.

The corridor under consideration is first divided into several sections based on Average Annual Daily Traffic (AADT). Ideally, each section should have uniform traffic flow characteristics such as traffic volume, number of lanes, etc. Each section may include more than one intersections or interchanges. Based on intersection/interchange locations, a section is further divided into multiple links (see Figure 3). With sections and links defined, the methodology for estimating travel time savings can be applied to individual sections for peak and off-peak trips (see the flow chart in Figure 4). Intersection-level travel time savings are then aggregated to corridor-level estimates.

Figure 2. Estimation of Travel Time Savings

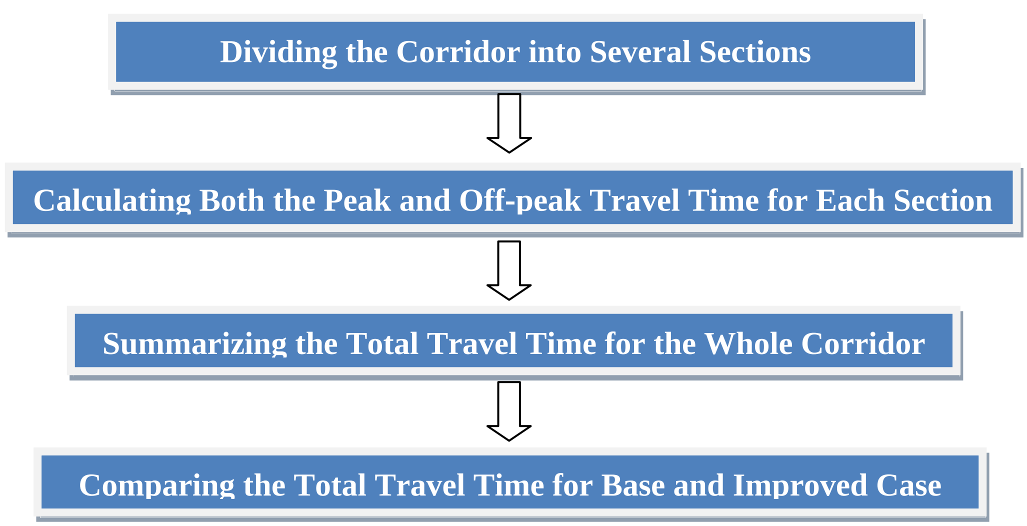


Figure 3. Section and Link Definitions in MOSAIC

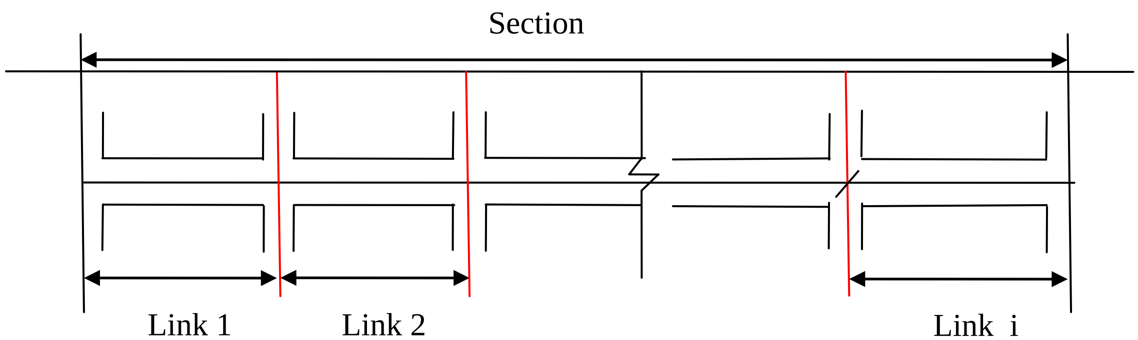
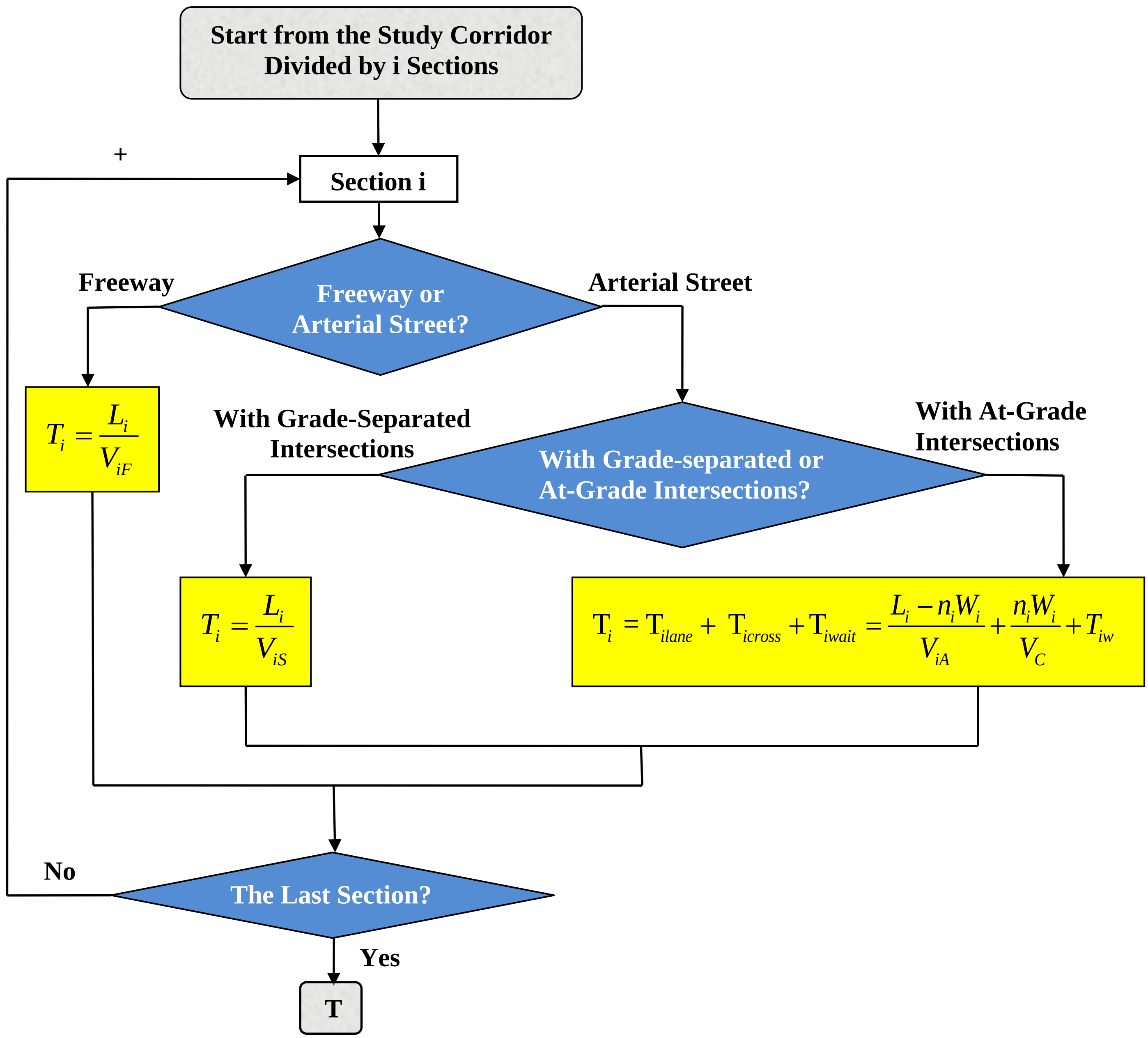


Figure 4. Travel Time Estimation



Notation

T_{ilane}: Average travel time along the roadway (besides the time for crossing the intersection) in section i;

T_{icross}: Average travel time for crossing the intersection in section i;

T_{iwait} / T_{iw} : Average time spent on stop control at intersections in section i;

V_{iF} : The travel speed for freeway in section i;

V_{iS} : The travel speed for arterial street with grade-separated intersections in section i;

V_{iA} : The travel speed for arterial street with at-grade intersections in section i;

V_C : The average cross-intersection speed along the corridor;

L_i : The length of the section i;

W_i : The average length of the intersections in section i (assume W_i = the average width of the roadway in section i);

n_i : Number of links along section i.

To estimate the peak and off-peak period speeds for both freeways and arterial streets, the procedure outlined in Texas Transportation Institute's Urban Mobility Report (David, 2007) was employed, (See Table 16).

As for the cross-intersection speed V_C, it was regarded as the process of slowing down, turning and accelerating to running speed, which is assumed to be on average 10 mph (James M., 1988) in the analysis, while the intersection delay for vehicles traveling on grade-separated intersections should be zero.

The travel delay due to traffic signal or stop-sign control is based on the Level of Service (LOS) at unsignalized and signalized intersections, and the traffic control delay at the intersections was determined (in Table 18) by employing the LOS method from the Highway Capacity Manual (see Table 17).

The final outputs of travel time savings module are the travel time differences between each improvement case and its base case for peak and off-peak trips respectively:

$$T_{peak} = T_{pimproved} - T_{pbase}$$
$$T_{offpeak} = T_{oimproved} - T_{obase}$$

Table 16. Speed Estimating Based on Daily Traffic Volume per Lane

Facility and Congestion Level	Daily Traffic Volume per Lane	Speed Estimate Equation	
		Peak Speed (mph)	Off-Peak Speed (mph)
Freeway			
Uncongested	< 15,000	60	60
Medium	15,001 – 17,500	70-(0.9*ADT/LANE)	67-(0.6*ADT/LANE)
Heavy	17,501-20,000	78-(1.4*ADT/LANE)	71-(0.85*ADT/LANE)
Severe	20,001-25,000	96-(2.3*ADT/LANE)	88-(1.7*ADT/LANE)
Extreme	>25,000	76-(1.46*ADT/LANE)	85.7-(1.6*ADT/LANE)
		Lowest speed is 35 mph	Lowest speed is 40 mph
At-grade Arterial Street			
Uncongested	< 5,500	35	35
Medium	5,501 – 7,000	33.58-(0.74*ADT/LANE)	33.82-(0.59*ADT/LANE)
Heavy	7,001-8,500	33.80-(0.77*ADT/LANE)	33.90-(0.59*ADT/LANE)
Severe	8,501-10,000	31.65-(0.51*ADT/LANE)	30.10-(0.15*ADT/LANE)
Extreme	>10,000	32.57-(0.62*ADT/LANE)	31.23-(0.27*ADT/LANE)
		Lowest speed is 20 mph	Lowest speed is 27 mph
Source: David Schrank, Tim Lomax, The 2007 Urban Mobility Report, Texas Transportation Institute, The Texas A&M University System, September 2007, http://mobility.tamu.edu)			
Grade-separated Arterial Street			
Uncongested	< 5,500	35	35
Medium	5,501 – 7,000	35.57-(0.74*ADT/LANE)	36.25-(0.59*ADT/LANE)
Heavy	7,001-8,500	35.03-(0.77*ADT/LANE)	35.87-(0.59*ADT/LANE)
Severe	8,501-10,000	32.82-(0.51*ADT/LANE)	32.13-(0.15*ADT/LANE)
Extreme	>10,000	34.92-(0.62*ADT/LANE)	33.53-(0.27*ADT/LANE)
		Lowest speed is 20 mph	Lowest speed is 27 mph

(**Here ADT/Lane is in thousands; example: 15,000 ADT per lane has a value of 15 in the equation.*)

Table 17. Level of Services at Intersections

Signalized Intersections		Unsignalized Intersections	
Level of Service	**Average Delay Time (seconds)**	**Level of Service**	**Average Delay Time (seconds)**
A	≦10	A	≦10
B	>10 - ≦20	B	>10 - ≦15
C	>20 - ≦35	C	>15 - ≦25
D	>35 - ≦55	D	>25 - ≦35
E	>55 - ≦80	E	>35 - ≦50
F	>80	F	>50

(Highway Capacity Manual (HCM), 2000)

Table 18. Traffic Control Delay at Intersections

Facility and Congestion Level	Daily Traffic Volume per Lane		Average Delay at Intersections (Seconds per vehicle)	
	Freeway	Arterial	Signalized Intersections	Unsignalized Intersections
Uncongested	< 15,000	< 5,500	10	10
Heavy	17,501-20,000	7,001-8,500	35	25
Severe	20,001-25,000	8,501-10,000	55	35
Extreme	>25,000	>10,000	80	50

(Highway Capacity Manual (HCM), 2000)

3.2 Travel Reliability

Reliability is measured as the additional travel time (in minutes, percent extra time, etc.) that travelers endure under worse-than-normal traffic conditions (PMF, 2009).

MOSAIC evaluates travel reliability by incorporating the concepts of Reliability Index and Travel Time Index, which indicate the extent to which the longest travel times (including peak and off-peak ones) exceed the average travel time based on the distribution of travel times for a given section of roadway over a period of time (day-to-day or month-to-month).

$$\text{Reliability Index} = \frac{\text{95th Percentile Travel Time - Average Travel Time}}{\text{Average Travel Time}}$$

The Texas Transportation Institute has developed an empirical relationship between the Reliability Index and the Travel Time Index using available real-time data (Tara et al, 2008):

$$\text{Reliability Index} = 2.189 \times (\text{Travel Time Index-1}) - 1.799 \times (\text{Travel Time Index-1})^2$$

Where：

$$\text{Travel Time Index} = \frac{\text{Peak Hour Travel Time}}{\text{Travel Time at Posted Speed Limit}}$$ for the peak-hour direction and,

$$\text{Travel Time Index} = \frac{\text{Off-peak Hour Travel Time}}{\text{Travel Time at Posted Speed Limit}}$$ for the off-peak one.

Peak or Off-peak Hour Travel Time can be obtained from Table 1 for travel time estimation, and the speeds corresponding to the ADT per lane less than 15,000 for the freeways, and 5,500 for the arterial streets, are estimated as the posted speed limit.

As with the Travel Time Index, the Reliability Index is estimated for each individual section and the Reliability Index for the entire corridor (RI) is calculated as the average across all sections, weighted by vehicle miles traveled (VMT) on each section:

$$\text{RI} = \frac{\sum_i (RI_i \times VMT_i)}{\sum_i VMT_i} = \frac{\sum_i (RI_i \times ADT_i \times L_i)}{\sum_i (ADT_i \times L_i)}$$

Where:

RI_i: Reliability Index along section i;

VMT_i : The average vehicle miles traveled along section i;

ADT_i : Average daily traffic volume along section i, (vehicles/day);

L_i : The length of section i (miles);

A higher Reliability Index indicates less reliable travel conditions. For example, an RI value of 40% means a traveler should budget an additional 8 minutes for a 20-minute trip under average traffic conditions to ensure on-time arrival 95% of the time. The Reliability Index is also positively correlated with level of congestion and the Travel Time Index.

Chapter 4 Safety

4.1 Crash Rates

Crash Rate is measured as the expected number of crashes per year for a certain corridor. MOSAIC applied the Safety Performance Function (SPF) method in the most recent Highway Safety Manual (2010) to estimate total crash rates for both roadways and intersections. The expected number of crashes at the corridor level can be computed using the below formula:

$$N = \sum^{i} (N_{Ri} \times \Pi CMF_{Ri} + N_{Ii} \times \Pi CMF_{Ii})$$

where:

N : Expected number of crashes along corridor (crashes/yr);

N_{Ri} : Expected number of crashes under roadway base conditions on section i (crashed/yr);

N_{Ii} : Expected number of crashes under intersection base conditions on section i (crashed/yr);

CMF_{Ri} : Combination of Crash Modification Factors (CMF) that adjust crash rate estimates based on real-world conditions on section i roadways;

CMF_{Ii} : Combination of CMFs that adjust crash rate estimates based on real-world conditions on section i intersections.

4.1.1 Expected Number of Crashes under Base Conditions

If a section within the corridor has a lane width of 12-feet and a shoulder width of 6-feet, as well as a paved shoulder, no left or right turn lanes, and a 30-feet median width in its multi-lane segments, the expected crash rates at this base section can be denoted as N_R for its roadways, and N_I for its intersections.

4.1.1.1 Roadways

The expected crash rates can be computed using the following formula:

$$N_{bri} = \exp[a + b \times \ln(AADT_i) + \ln(L_i)]$$

N_{bri}: Expected number of crashes for base conditions (crashes/yr);

$AADT_i$: Annual Average Daily Traffic Volume (veh/d) along section i;

L_i: Length of the section i (mile);

a, b: Regression coefficients. (Refer to Table 19)

Table 19. Coefficients for Total Crash Rates on Various Types of Roadways

Roadway Types		a	b
Two-lane, two-way roadway		-7.604	1.000
Four-lane, two-way roadway	Undivided	-9.653	1.176
	Divided	-9.025	1.049

(Source: Highway Safety Manual, AASHTO, 2010)

4.1.1.2 Intersections

The expected crashes rates at the intersections are:

$$N_{bii} = \exp(a + b \times \ln AADT_{major} + c \times \ln AADT_{minor})$$

where:

N_{bii}: Expected number of crashes for base conditions at intersections (crashes/yr);

ADT_{major}: Average daily traffic volume (veh/day) on the major road along section i;

ADT_{minor}: Average daily traffic volume (veh/day) on the minor road along section i;

a, b, c: Regression coefficients. (Refer to Table 20)

Table 20. Coefficients for Total Crashes at Various Types of Intersections

Intersection Type		a	B	c
Two-lane, two-way roadway	Three-Leg STOP-Controlled	-9.86	0.79	0.49
	Four-Leg STOP-Controlled	-8.56	0.60	0.61
	Four-Leg Signalized	-5.13	0.60	0.20
Four-lane, two-way roadway	Three-Leg Minor Road STOP-Controlled	-12.526	1.204	0.236
	Four-Leg Minor Road STOP-Controlled	-10.008	0.848	0.448
	Four-Leg Signalized	-7.182	0.722	0.337

(Source: Highway Safety Manual, AASHTO, 2010)

Since the Highway Safety Manual (2010) only provides crash rate estimation procedures for two- and four-lane highways, the crash rates for three-lane roadways and intersections are set as the average rates of two-lane and four-lane crash rates. For corridors with more than four lanes, the total crash rates are estimated by extrapolation based on two- and four-lane corridor total crash rates.

4.1.1.3 Corridor

The expected crash rates (crash rates per mile) for the entire corridor under base conditions can be estimated based on roadway and intersection crash rates:

$$N_{ub} = \sum_i N_{bi} / \sum_i L_i = \sum_i (N_{bri} + N_{bii}) / \sum_i L_i$$

where:

N_{ub}: Unit expected crash rate for base conditions (annual crash rates per mile) for the corridor;

N_{bi} : Total expected number of crashes for base conditions along section i (crashes/yr);

N_{bii}: Expected number of crashes for base conditions on the roadways along section i (crashes/yr);

N_{bii}: Expected number of crashes for base conditions at intersections along section i (crashes/yr);

L_i: Length of section i (mile);

4.1.2 Crash Modification Factors

If roadway and intersection configurations on a highway section are not the same as those of the base condition, the actual crash rates should be adjusted with Crash Modification Factors (CMF). A CMF is an estimate of the change in crashes expected after implementation of a countermeasure, the HSM provided multiple CMFs to match the various highway conditions.

4.1.2.1 Roadways

4.1.2.1.1 Adjustment for Lane Width (CMF_{rl})

The crash modification factors for lane width are distinct between two-lane and four-lane sections. The corresponding CMFs are listed in Tables 21 and 22 respectively.

Table 21. Crash Modification Factor for Lane Width (Two-Lane, Two-Way) CMF_{ra}

Lane Width (ft)	AADT < 400	401≤ AADT ≤ 2000	AADT > 2000
9 or less	1.05	1.05 + 0.000281 × (AADT - 400)	1.50
10	1.02	1.02 + 0.000175 × (AADT - 400)	1.30
11	1.01	1.01 + 0.000250 × (AADT - 400)	1.05
12 or more	1.00	1.00	1.00

Table 22. Crash Modification Factor for Lane Width (Four-Lane, Two-Way) CMF_{ra}

Lane Width (ft)	**AADT ≤ 400**	**401≤ AADT ≤ 2000**	**AADT > 2000**
9 or less	1.04	1.04 + 0.000213 × (AADT - 400)	1.38
10	1.02	1.02 + 0.000131 × (AADT - 400)	1.23
11	1.01	1.01 + 0.000188 × (AADT - 400)	1.04
12 or more	1.00	1.00	1.00

(Source: Highway Safety Manual, AASHTO, 2010)

Using this information, the crash modification factors for the lane's related crash rates will be CMF_{rl} calculated by using the following formula:

$$CMF_{rl} = (CMF_{ra} - 1.0) \times p_{ra} + 1.0$$

p_{ra} : Proportion of total crashes constituted by related crashes (default values are 0.574 for two- lane's, while 0.27 for four-lane's) based on the related crash type distributions.

4.1.2.1.2 Adjustment for Shoulder Characteristics (CMFrs)

The CMFs for shoulders both consider the width and the type of shoulder. The changes of CMFs with the Shoulder Effective Width (SEW) and ADT are presented both for two-lane and four-lane sections in Table 23. The CMFs for shoulder type are listed in Table 24.

Table 23. Crash Modification Factor for Shoulder Width (Two-Lane, Two-Way)

Shoulder Effective Width (SEW) (ft)	**AADT ≤ 400**	**401≤ AADT ≤ 2000**	**AADT >2000**
0	1.10	1.10 + 0.000250 × (AADT - 400)	1.50
2	1.07	1.07 + 0.000143 × (AADT - 400)	1.30
4	1.02	1.02 + 0.0008125 × (AADT - 400)	1.15
6	1.00	1.00	1.00
≥ 8	0.98	0.98 + 0.0000688 × (AADT - 400)	0.87

(Source: Highway Safety Manual, AASHTO, 2010)

Table 24. Crash Modification Factor for Shoulder Type

Shoulder Type	**0 (ft)**	**1 (ft)**	**2 (ft)**	**3 (ft)**	**4 (ft)**	**6 (ft)**	**8 (ft)**
Paved	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Gravel	1.00	1.00	1.01	1.01	1.01	1.02	1.02
Composite	1.00	1.01	1.02	1.02	1.03	1.04	1.06
Turf	1.00	1.01	1.03	1.04	1.05	1.08	1.11

(Source: Highway Safety Manual, AASHTO, 2010)

The final CMF for a shoulder is calculated using the following formula:

$$CMF_{rs} = CMF_{rsw} \times CMF_{rst}$$

CMF_{rs} : Crash Modification Factor for Shoulder;

CMF_{rsw} : Crash Modification Factor for Shoulder width;

CMF_{rst} : Crash Modification Factor for Shoulder type.

The crash modification factors for the shoulders' related crash rates will be CMF_{rl} and is calculated as the following equation shows:

$$CMF_{sr} = (CMF_{rsw} \times CMF_{rst} - 1) \times p_{ra} + 1.0$$

p_{ra} : Proportion of total crashes constituted by related crashes (default values are 0.574 for two- lane's, while 0.27 for four-lane's) based on the related crash type distributions.

4.1.2.1.3 Adjustment for Median Width

The most important objective benefit of medians is the separation of traffic. Additional benefits include providing a recovery area for errant drivers, accommodating left-turn movements, and allowing for emergency stopping, (TRB, 2009) which can have a positive effect in reducing crash rates.

The CMFs for various median widths, given in 10 feet increments, are shown below in Table 25.

Table 25. Median Width for Four-Lane, Two-Way Sections (without Traffic Barriers)

Median Width (ft)	**10**	**20**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
CMF	1.04	1.02	0.99	0.97	0.96	0.96	0.95	0.94	0.94

(Source: Highway Safety Manual, AASHTO, 2010)

4.1.2.2 Intersections

4.1.2.2.1 Adjustment for Left-turn Lanes

CMFs for total intersection-related left-turn lanes, organized by types of roadway and intersection configurations, are found in Table 26.

Table 26.Crash Modification Factors for Installation of Left-turn Lanes on the Major Road Approaches to Intersection

Roadway Type	Intersection Type	Intersection Traffic Control	Number of Approaches with Left-Turn Lane			
			One Approach	Two Approaches	Three Approaches	Four Approaches
Two-Lane, Two-Way Section	Tree-leg Intersection	Minor road stop control	0.56	0.31	--	--
	Four-leg Intersection	Minor road stop control	0.72	0.52	--	--
		Traffic Signal	0.82	0.67	0.55	0.45
Four-Lane, Two-Way Section	Tree-leg Intersection	Minor road stop control	0.56	--	--	--
	Four-leg Intersection	Minor road stop control	0.72	0.52	--	--

(Source: Highway Safety Manual, AASHTO, 2010)

4.1.2.2.2 Adjustment for Right-Turn Lanes

CMFs for total intersection-related right-turn lanes are presented in Table 27.

Table 27. Crash Modification Factors for Installation of Right-turn Lanes on the Major Road Approaches to Intersection

Roadway Type	Intersection Type	Intersection Traffic Control	Number of Approaches with Right-Turn Lane			
			One Approach	Two Approaches	Three Approaches	Four Approaches
Two-Lane, Two-Way Section	Tree-leg Intersection	Minor road stop control	0.86	0.74	--	--
	Four-leg Intersection	Minor road stop control	0.86	0.74	--	--
		Traffic Signal	0.96	0.92	0.88	0.85
Four-Lane, Two-Way Section	Tree-leg Intersection	Minor road stop control	0.86	--	--	--
	Four-leg Intersection	Minor road stop control	0.86	0.74	--	--

(Source: Highway Safety Manual, AASHTO, 2010)

4.1.2.3 Corridor

The final corridor-level crash rate is based on real-world corridor conditions are computed as the sum of crash rates by sections.

$$N_{ub} = \sum_i N_i / \sum_i L_i = \sum_i (N_{ri} + N_{ii}) / \sum_i L_i$$

Where:

N_{ub} : Unit crash rate (annual crash rate per mile) for the corridor;

N_i : Total crash rate along section i (crashes/yr);

N_{ri} : Total roadway crash rate along section i (crashes/yr);

N_{ii} : Total intersections' crash rats along section i (crashes/yr);

L_i : Length of section i (mile);

4.2 Crash Severity

The severe crashes are considered as crashes that involve fatalities and/or injuries. The ratio of severe crashes can be measured in two ways. The first method employs estimates on the percentage of severe crashes along the corridor:

$$N_{sb} = \sum_i (\lambda_1 \times N_{ri} + \lambda_2 \times N_{ii}) / \sum_i L_i$$

N_{sb} : Severe crash rate per mile within the corridor;

N_{ri} : Total roadway crash rate;

N_{ii} : Total intersections' crash rate;

λ_1 : Percentage of severe crashes on roadways;

λ_2 : Percentage of severe crashes at intersections.

For instance, the Highway Safety Manual (2010) sets the severe crash rate as 32.1% of the total crash rate along roadways, and 41.5% of the total crash rate at intersections for two-lane two-way corridors. Thus, the total severe crash rate for two-lane two-way sections is:

$$N_{sb} = \sum_i (32.1\% \times N_{bri} + 41.5\% \times N_{bii}) / \sum_i L_i$$

The second method, uses empirically estimated coefficients to estimate the severe crash rate and is the preferred method used to obtain severe crash rates. For instance, severe crash rates on four-lane two-way roads can be computed based on severe crash coefficients listed in Tables 28 and 29. To estimate severe crash rates, the total crash rate coefficients in equations presented in Section 4.1.1 were replaced with these severe crash coefficients. Crash Modification Factors for severe crash rates estimation are also different from those for total crash estimation. Table 30 summarizes the CMFs resulting from adding left-turn and right-turn lanes at intersections on four-lane, two-way corridors.

Table 28. Coefficients for Severe Crash Rates on Four-lane Two-way Roadways

Roadway Types	a	b
Undivided	-8.577	0.938
Divided	-8.505	0.874

(Source: Highway Safety Manual, AASHTO, 2010)

Table 29. Coefficients for Severe Crashes at Intersections

Intersection Type	a	B	c
Three-Leg Minor Road STOP-Controlled	-11.989	1.013	0.228
Four-Leg Minor Road STOP-Controlled	-10.734	0.828	0.412
Four-Leg Signalized	-12.011	-	-

(Source: Highway Safety Manual, AASHTO, 2010)

Table 30. Crash Modification Factors for Adding Turn Lanes at Intersections

Intersection Type	Lane Type	Number of Approaches with Turning Lane	
		One Approach	Two Approaches
Tree-leg Intersection Minor road stop control	Left-turn	0.45	--
	Right-turn	0.77	--
Four-leg Intersection Minor road stop control	Left-turn	0.65	0.42
	Right-turn	0.77	0.59

(Source: Highway Safety Manual, AASHTO, 2010)

Additionaly, the research team assumes that roadway and intersection severe crash rates on three-lane corridors are the average rate of two-lane and four-lane corridors. For corridors with more than four lanes, severe crash rates are estimated by extrapolating based on two and four-lane corridor severe crash rates.

Chapter 5 Socio-economic Impact

5.1. Economic Impact

Labor productivity increases as firms in the same industry cluster near each other. A number of factors are attributed to this increase, including a specialized labor force, technological spillover, as well as a greater number of suppliers. If a transportation improvement project reduces travel time, it effectively brings firms closer to each other and increases the effective density of firms. The methodology developed by the U.K. Department of Transport in its 2005 “Wider Economic Benefits and Impacts on GDP” study (U.K. DOT 2005) was applied in this study to calculate the economic benefits due to agglomeration or clustering of economies induced by transportation investment. This is a more sophisticated method for economic impact analysis than the multiplier method employed in many U.S. practices (i.e. multiply the direct transportation benefits by a >1 factor to obtain total benefits including transportation and broader economic benefits).

The first step in estimating agglomeration effects is to measure the effective density (ED) of the employment in a corridor in the base case and then in the improved case. In order to do this, the corridor must be divided into different sections. Ideally, these sections would be divided based on areas where specific productivity elasticity for each industry is provided and areas where the transportation improvement would have a sizable impact. The study area should include the areas from which employees commute to the effected employment area.

In order to streamline the analysis and simplify input requirements for MOSAIC, the approach was to divide the corridor into different sections based on the previous methodologies (i.e. based on different AADT levels) as shown below by the formula:

$$\mathrm{ED_j} = \sum_{\mathrm{K}} \mathrm{E_K T_{jk}^{-1}}$$

$\mathrm{ED_j}$: Effective density in section j

E_k: Employment in section k

T_{jk}: Generalized cost of travel between sections j and k

The base-case effective density (ED) was calculated the from the number of employees within the buffer zone and the existing travel times between zone pairs and then calculated the improvement-case ED from the travel time savings and the current employment within each zone. For Tjk, the team assumed a cost equivalent to $4 (i.e. 8 miles) to travel within a zone, a $15/hour value of time, and $0.50/mile cost of travel. Next, the agglomeration benefits were estimated from the change in effective density.

$$\mathrm{WB} = \sum_j [(\frac{\Delta \mathrm{ED}_j}{\mathrm{ED}_j} \times \mathrm{ElP}) \times \mathrm{GDP}_j \times \mathrm{E}_j]$$

WB: Economic benefits from agglomeration effects

ElP: Productivity elasticity

GDP_j: Output per worker in zone j

E_j: Employment in zone j

In the absence of firm level employment data broken down by industry, the team had to use a productivity elasticity (ElP) estimate for all firms in the economy. Ciccone and Hall's (1996) density elasticity of 0.06 was used, which signifies that if density is doubled in an area then output will increase by six percent due to agglomeration effects.

Economic benefits from agglomeration effects were calculated according to the previous equation. WB is the sum for all zones of the change in effective density in each zone multiplied by the productivity elasticity, output per worker, and employment in that zone.

5.2 Livability

Livability as a socioeconomic indicator which includes a variety of factors that should be considered into the analysis of the effectiveness of highway corridor improvements. The qualitative and quantitative methods have been combined to measure livability from two aspects: land use compatibility and transportation accessibility. Land-use types considered include: industrial, commercial, recreational, agricultural, low and high density residential, high and medium density mixed-use, and transit oriented development. Transportation accessibility along the corridor includes accessibility for through traffic and local-area accessibility. Based on the team's definition, livability is enhanced if highway corridor improvements are compatible with existing or planned future land use and improves accessibility to activity locations.

5.2.1 Land-use Scores

The land-use scores measure the extent highway corridor improvements are compatible with different land-use types within a 1/4-mile buffer on either side of the highway corridors. This buffer distance is selected based on an extensive literature review on the social and environmental impact of highways.

An online survey was developed to obtain land-use scores representing individuals' opinions on how different highway improvement options impact various land-use types along a particular corridor (e.g. US 15). The 7-level scores range between -3 (significant negative impact) and 3 (significant positive impact). The average scores from the survey are used as default impact scores in the current version of MOSAIC and presented in Table 31.

Table 31. Impact of Highway Improvements on Land Use

Land Use Type	Improvement Type	
	Add a Lane	Grade Separated Interchange
Recreational	0.367	0.583
Agricultural	0.65	0.5
Low Density Residential	0.683	0.5
High Density Residential	0.4	0.4
Commercial	0.667	0.6
Industrial	0.733	0.567
Hight Density Mixed Use	0.483	0.517
Medium Density Mixed Use	0.6	0.5
Transit Oriented Development	0.617	0.367

5.2.2 Transportation Accessibility

The accessibility analysis consists of two parts: 1) through-traffic sections that primarily serve through traffic, and 2) local-traffic sections that primarily serve local residents and business. The accessibility measure is a weighted sum of volume scores and travel time scores. The volume score measures through-traffic accessibility. The higher the volume served, the higher the through-traffic accessibility. The travel time score measures local traffic accessibility. The lower the travel time, the higher the local traffic accessibility will be.

$$\text{Accessibility} = \frac{\sum_t (L_t \times \text{Volume Score}_t) + \sum_l (L_l \times \text{Travel Time Score}_l)}{\sum_i L_i}$$

Where:

L_i: Length of the section i;

L_t: Length of through-traffic section t;

L_l: Length of the local-traffic section l.

The volume score, based on AADT, and the travel time score, based on speeds ranging from 1 to 5, are shown in Table 32.

Table 32. Volume Scores and Travel Time Scores for Accessibility Measurement

Daily Traffic Volume per Lane of Pass-through Trips within the Whole Corridor (Vehicles/day) (AADT)	Traffic Volume Score	Travel Time of Local Trips Sections within the Whole Corridor (mph) ($\frac{L_i}{V_l}$)	Travel Time Score
Under 15,000	1	Over $\frac{L_i}{25}$	1
15,001 ~ 17,500	2	$\frac{L_l}{25} \sim \frac{L_l}{30}$	2
17,501 ~ 20,000	3	$\frac{L_l}{30} \sim \frac{L_l}{35}$	3
20,001 ~ 25,000	4	$\frac{L_l}{40} \sim \frac{L_l}{35}$	4
Over 25,000	5	Under $\frac{L_l}{40}$	5

5.3 Noise

The impact due to traffic noise depends on both local land-use patterns and corridor traffic conditions. The buffer distance is set as 1/4-mile between noise receptors (i.e. residential and business developments) and the highway corridor centerline. Figure 5 illustrates the steps for evaluating noise impact.

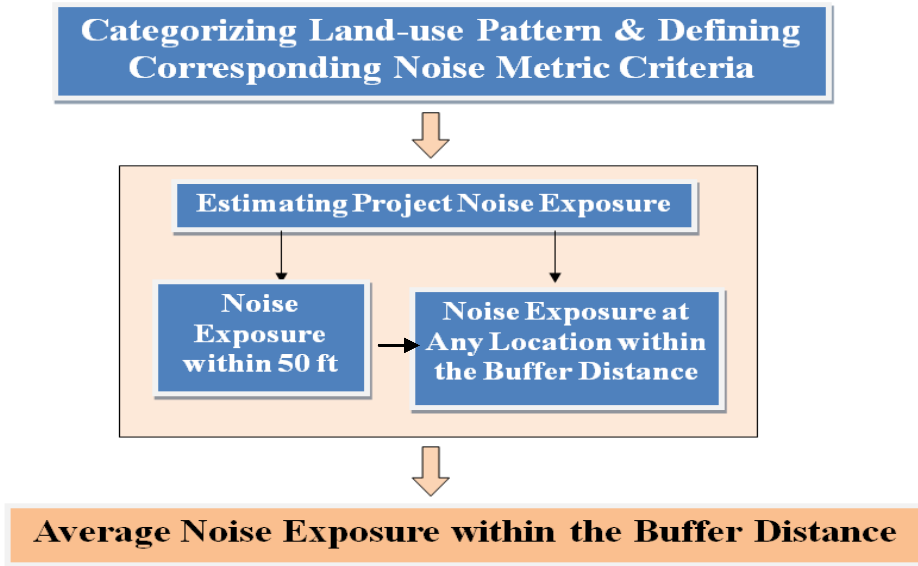


Figure 5. Measuring Noise Impact

5.3.1 Land Use Types and Metrics for Traffic Noise Impact Analysis

The noise metrics used vary by different types of land-use. The land-use types were categorized into three major types, which are described in Table 33 along with the corresponding metrics used for noise impact analysis.

Table 33. Land Use Categories and Noise Metrics

Land Use Category	Noise Metric (dBA)	Description of Land Use Category
1	Outdoor L_{eq}(h)*	Tracts of land where quiet is an essential element in their intended purpose. This category includes lands set aside for serenity and quiet, and such land uses as outdoor amphitheaters and concert pavilions, as well as National Historic Landmarks with significant outdoor use. Also included are recording studios and concert halls.
2	Outdoor L_{dn}	Residences and buildings where people normally sleep. This category includes homes, hospitals and hotels where a nighttime sensitivity to noise is assumed to be of utmost importance.
3	Outdoor L_{eq}(h)*	Institutional land uses with primarily daytime and evening use. This category includes schools, libraries, theaters, and churches where it is important to avoid interference with such activities as speech, meditation and concentration on reading material. Places for meditation or study associated with cemeteries, monuments, museums, campgrounds and recreational facilities can also be considered to be in this category. Certain historical sites and parks are also included.

(Source: Transit Noise and Vibration Impact Assessment, Office of Planning and Environment Federal Transit Administration, Fta-Va-90-1003-06, May 2006)

where：

L_{eq}(h) (Hourly Equivalent Sound Level): Describes a receiver's cumulative noise exposure from all events over a one-hour period. It is adopted to assess traffic noise for non-residential land uses. For assessment, L_{eq} is computed for the loudest traffic facility hour during the hours of noise-sensitive activity;

L_{dn} (Day-Night Sound Level): Describes a receiver's cumulative noise exposure from all events over a full 24 hours. L_{dn} is adopted to assess traffic noise for residential land uses.

5.3.2 Project Noise Estimation

5.3.2.1 Project Noise Impact at 50 ft

Noise impact on different land-use types at the distance of 50 feet were measured from the highway centerline as (FTA, 2006):

Hourly L_{eq} at 50ft:

$$L_{eq} = SEL_{ref} + 10\log(V) + C_{emission} - 10\log(\frac{S}{50}) - 35.6$$

Daytime L_{eq} at 50ft: $L_{eq}(day) = L_{eq}(h)|_{V=V_d}$

Nighttime L_{eq} at 50 ft: $L_{eq}(night) = L_{eq}(h)|_{V=V_n}$

L_{dn} at 50 ft: $$L_{dn} = 10\log\left[(15)\times 10^{(\frac{L_{eq(day)}}{10})} + (9)\times 10^{(\frac{L_{eq(night)}+10}{10})}\right] - 13.8$$

Other adjustment: -3 -> automobiles, open-graded asphalt

+3 -> automobiles, grooved pavement

SEL: Represents the Sound Exposure Level to predict the nose exposure at 50 feet with the definition as: $SEL = 10\log_{10}[\text{Total sound energy during the event}]$. The Federal Highway Administration (FHWA) categorized the default value for SEL as Table 34 shows.

Table 34. Source Reference Levels at 50 feet from Roadway, 50mph

Source†	**Reference SEL (dBA)**
Automobiles and Vans	74
Buses (diesel-powered)	82
Buses (electric)	80
Buses (hybrid)	83**

† Assumes normal roadway surface conditions

** For hybrid buses, Reference SEL should be determined on a case-by-case basis.

V : Hourly volume of vehicles of certain type, (vehicle per hour);

V_d : Average hourly daytime volume of vehicles of a certain type, (vehicle per hour)

$$= \frac{\text{Total vehicle volume (7am to 10pm)}}{15};$$

V_n: Average hourly nighttime volume of vehicles of a certain type, (vehicle per hour)

$$= \frac{\text{Total vehicle volume (10pm to 7am)}}{9};$$

$C_{emission}$: Noise emission.

For buses: $C_{emission} = 25 \times \log(\frac{S}{50})$

For accelerating 3-exle commuter buses: $C_{emission} = 1.6$

For automobiles: $C_{emission} = 40 \times \log(\frac{S}{50})$;

S: Average vehicle speed, (mph) (using the method in travel time part).

5.3.2.2 Project Noise Impact at Certain Arbitrary Receiver

For the distance between the arbitrary receiver and the noise location within the buffer distance the research team considered, each Ldn and Leq can be obtained from Ldn and Leq at 50 feet developed above, by using the following equation:

$$\text{L}_{dn} \text{ or } \text{L}_{eq} = (\text{L}_{dn} \text{ or } \text{L}_{eq})|_{at\,50\text{ ft}} - 10\log(\frac{D}{50}) - 10\text{G}\log(\frac{D}{29})$$

Where:

D: Represents the shortest distance between the geometric center of receiver's area to the major noise location;

G: Large Ground Factors: large amounts of ground attenuation with increasing distance from the source. Since it was assumed that along the general corridor there is no curve or barrier, this Ground Factor, G, is set as zero.

5.3.3 Evaluation of the Noise Impact

Finally, since the receivers in the analysis are defined in GIS in terms of different land-use types and their areas, the Noise Impact Level and Average Noise Exposure within the Buffer Distance are obtained by considering the average existing noise exposures which are:

$$L'_{eq} = 10 \times \log(\sum 10^{L_{eqi}/10})$$
$$L'_{dn} = 10 \times \log(\sum 10^{L_{dni}/10})$$

5.4 Aesthetics

Aesthetics is a branch of philosophy dealing with the nature of beauty, art, taste, and the creation and appreciation of beauty. More broadly, scholars often define aesthetics as the "critical reflection on art, culture and nature." For highway aesthetics, four primary elements are considered: facility compatibility with the surrounding natural environment, land use attractiveness in the vicinity of the highway corridor, visual appeal, historical roads and historical site protection.

As a part of this project, an online survey was developed and distributed. The survey results assisted the research team in understanding the perceived impact of highway improvement on various aesthetics indicators. The following table shows the survey results for the US 15 corridor, which can be generalized to other corridors in Maryland. In general, the survey shows that respondents believe the impact of the two highway improvement types have minimum impact on aesthetics (scores close to 0). But there are clear concerns that adding a general-purpose lane may have a negative impact on historical roads and historical sites.

Table 35. Impact of Highway Improvements on Aesthetics along the US 15 Corridor

Elements	Average Rating Scores for the Aesthetics of Base and Improved Cases along US 15 (-3 ~ +3)			Average Weighting Scores (1 ~ 7)
	Base Case	Improvement Type 1: Adding One Lane	Improvement Type 2: Grade-separation Interchanges	
Facilities' Compatibility	0.57	1.00	1.29	5.00
Land Use Attractiveness	0.43	0.71	0.43	4.43
Visual Appeal	0.43	0.29	0.43	4.29
Historical Road and Sites Protection	0.50	-0.33	0.00	3.29

Notes:

1) Facilities' Compatibility: Including the traffic control devices, lighting, the splitter island and roundabouts' design, marking, etc;

2) Land Use Attractiveness: Including the transportation network's land use issue, and landscaping, median, shoulder and other roadside design features, etc;

3) Visual Appeal: Including the visual friction (various interesting views as opposed to uninteresting ones), views conservation (without visual intrusions), sight distance and clear areas (decided by whether objects are blocking the drivers' view).

4) Historical Road and Site Protection: Indicating whether the base or improved cases did well in protecting the historical roads and site;

The final column shows how surveyed individuals rank the relative importance of the four aesthetics elements. The final score for aesthetics is computed as the weighted sum across all four aesthetics elements:

$$\text{Final Scores}_i = \frac{\sum(\text{Rank Score}_{ij} \times \text{Weight Score}_j)}{\sum \text{Weight Score}_j}$$

where:

Final Scores_i : The case i's impact on aesthetics along the corridor (the higher the score is, the better effect on the aesthetics' condition);

Rank Score_{ij} : The impact level of case i on the corresponding element j;

Weight Score_j : The importance of element j in determining the aesthetics condition along the corridor.

Chapter 6 Natural Resources

In this version of MOSAIC, the natural resource impacts were measured by the areas of impacted natural resources along a highway corridor. After a comprehensive literature review, a buffer distance was set for the analysis at 1/4 mile for roadway improvements, and 1/2 mile for intersection improvements. The US 15 natural resource maps with these buffer distances are shown in Figures 6 and 7.

Corridor roadway and intersection geometry and GIS shapefiles containing natural resource information are first merged in ArcGIS. Each individual section of the US 15 corridor designated by the MOSAIC user is buffered using the ArcGIS proximity toolset with the given improvement type's impact distance (Figure 6 shows the 1/4 mile buffer for the general purpose lane improvement and Figure 7 shows the 1/2 mile buffer for the grade separated interchange improvement). The area of each natural resource type within the buffer is then computed with ArcGIS query tools.

Once the necessary natural resource information within the buffer zones is obtained in GIS and subsequently imported into MOSAIC, the percentage of impacted land within the buffer area can be computed for each type of natural resource. Higher percentages indicate more severe impact on particular types of natural resources. Impacts on different types of natural resources (e.g. parks, streams, wetlands, historical places, easements) are weighted equally in MOSAIC Beta Version 2. This will be adjusted in future versions based on input from SHA.

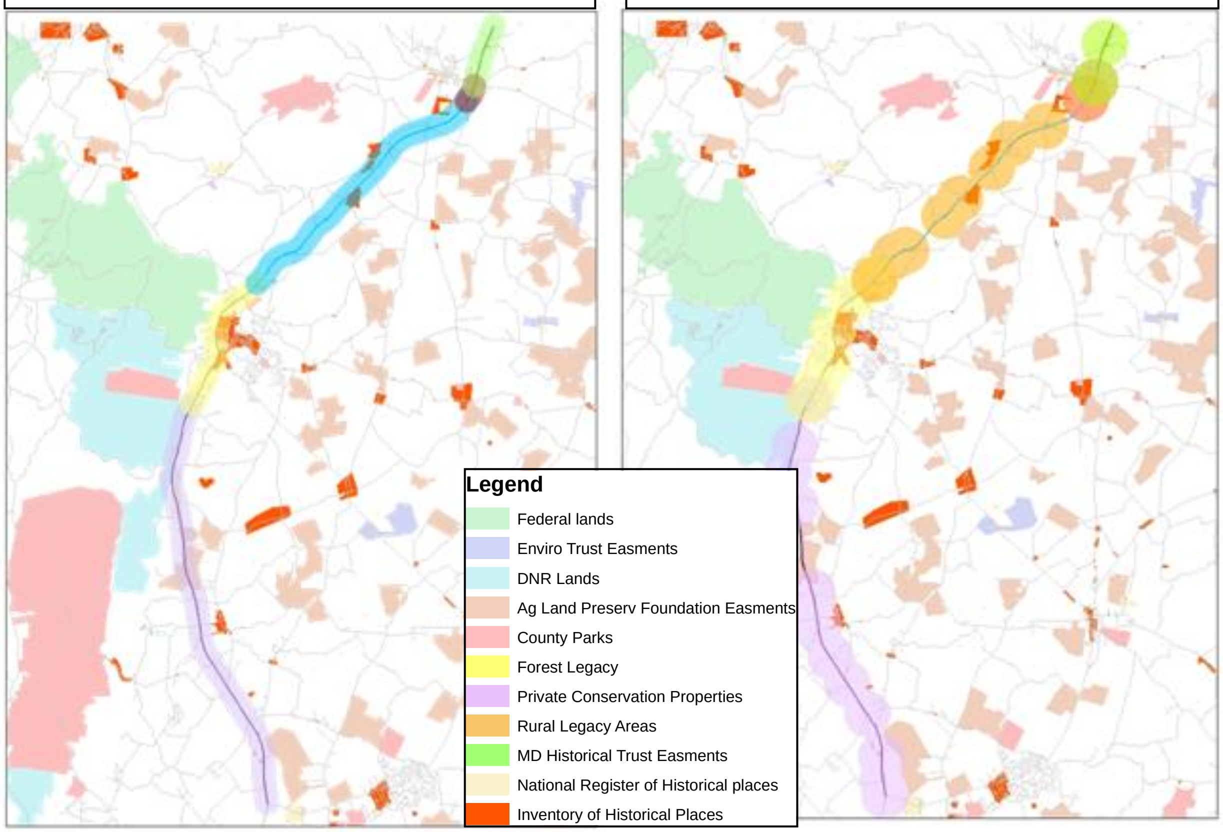
For the two improvement types analyzed in Phase One of the project: adding a general purpose lane and building grade-separated interchanges, the natural resource impact will either be negative or neutral at best. Other multimodal highway improvement types, such as transit investments, HOV/HOT lanes, and road diet to be considered in future project phases, can produce positive impacts on natural resources.

Figure 6. Impact Area of US 15 General Purpose Lane Improvement

(1/4 mile buffer from roadway centerline)

Figure 7. Impact Area of US 15 Grade-Separated Interchanges Improvement

(1/2 mile buffer from intersections)

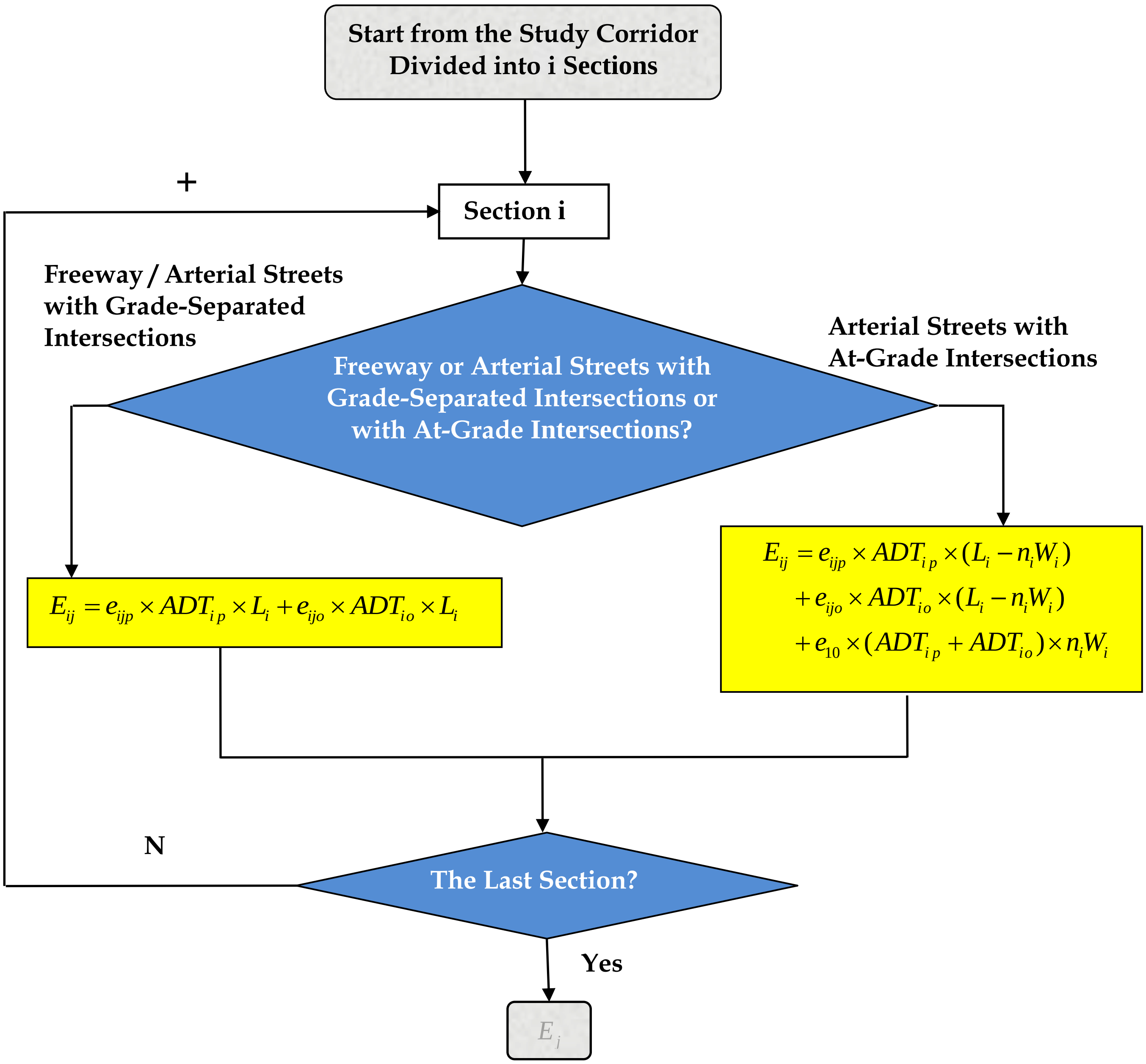


Chapter 7 Energy and Emission

7.1 Pollution Emissions

Pollution emissions for different types of pollutants are computed based on vehicle miles traveled and per-mile emission rates that vary by travel speeds. Inputs for pollution emission estimation include daily traffic volume in peak and off-peak periods, section lengths, and section-by-section travel speeds in peak and off-peak periods. Per-mile emission rates for Maryland, e, at different speeds are obtained by running MOVES2010a, the Motor Vehicle Emission Simulator developed by U.S. Environmental Protection Agency (See Tables 36). The flowchart of our pollution emission estimation module is provided in Figure 8.

Figure 8. Pollution Emission Estimation Flowchart



Where:

E_j: Daily total pollution emission for gas type j along the corridor (grams);

E_{ij}: Daily total pollution emission in section i for gas type j (grams);

ADT_{ip}: Average daily peak hour traffic volume in section i, (vehicles/day);

ADT_{io}: Average daily off-peak hour traffic volume in section i, (vehicles/day);

L_i: Length of the section i (miles).

Wi: The width of the section i (miles);

e_{ijp}: Peak-hour emission rate in section i for gas type j (grams/mile/ADT); (refer to Table 22)

e_{ijo}: Off-peak emission rate in section i for gas type j (grams/mile/ADT); (refer to Table 22)

e_{10}: Emission rate when the speed is 10 mph;

Table 36. MOVES Emissions Rates (Year 2011)

Speed (mph)	Total Emissions per ADT (grams/mile)											
	Rural						Urban					
	Restricted Access			Unrestricted Access			Restricted Access			Unrestricted Access		
	CO	NOx	PM10	CO	NOx	PM10	CO	NOx	PM10	CO	NOx	PM10
2.5	16.55	12.30	0.54	16.30	5.79	0.24	15.39	5.26	0.22	15.39	3.61	0.14
5	9.32	6.49	0.28	9.74	3.21	0.13	8.87	2.94	0.12	9.32	2.12	0.08
10	5.82	4.04	0.17	6.57	2.13	0.08	5.61	1.91	0.07	6.34	1.47	0.05
15	4.67	3.46	0.16	5.55	1.85	0.07	4.50	1.63	0.06	5.37	1.30	0.04
20	3.98	3.08	0.15	4.89	1.68	0.07	3.83	1.44	0.06	4.73	1.19	0.04
25	3.67	2.86	0.14	4.18	1.56	0.06	3.54	1.35	0.05	4.02	1.11	0.03
30	3.59	2.81	0.14	3.89	1.47	0.06	3.49	1.33	0.05	3.74	1.03	0.03
35	3.70	2.54	0.11	3.58	1.35	0.04	3.70	1.27	0.05	3.41	0.96	0.03
40	3.83	2.51	0.11	3.36	1.32	0.04	3.88	1.27	0.05	3.16	0.94	0.02
45	3.90	2.49	0.10	3.19	1.30	0.04	3.99	1.27	0.05	3.00	0.93	0.02
50	3.83	2.43	0.09	3.08	1.28	0.04	3.93	1.25	0.04	2.94	0.93	0.02
55	3.68	2.37	0.08	3.10	1.27	0.03	3.79	1.22	0.04	2.94	0.92	0.02
60	3.57	2.35	0.08	3.10	1.26	0.03	3.68	1.22	0.04	2.99	0.93	0.02
65	3.57	2.46	0.08	3.21	1.31	0.03	3.70	1.26	0.04	3.13	0.97	0.02
70	3.82	2.57	0.08	3.50	1.38	0.03	3.99	1.33	0.04	3.43	1.03	0.02
75	4.41	2.55	0.08	4.34	1.42	0.03	4.69	1.36	0.04	4.30	1.08	0.02
Average Temperature	57.96	57.96	57.96	59.20	59.20	59.20	59.04	59.04	59.04	59.55	59.55	59.55
Average Humidity	61.19	61.19	61.19	61.33	61.33	61.33	61.36	61.36	61.36	61.28	61.28	61.28

7.2 Greenhouse Gas Emissions

The total greenhouse gas emission is estimated with a process similar to that for the pollution emission introduced above. Similarly, the CO_2 emission rates for Maryland at different speeds used in this study are also obtained by running MOVES2010a, the Motor Vehicle Emission Simulator developed by U.S. Environmental Protection Agency (See Tables 37).

Table 37. Emissions Rates for CO^2

Speed (mph)	Total Emissions per ADT (grams/mile)			
	Rural Restricted Access	Rural Unrestricted Access	Urban Restricted Access	Urban Unrestricted Access
2.5	3458.24	2674.44	2629.56	2404.15
5	1846.82	1471.58	1436.65	1340.43
10	1132.40	909.39	869.80	827.15
15	953.55	739.38	706.00	664.14
20	830.49	644.94	600.82	576.62
25	761.74	581.49	543.99	517.59
30	731.71	531.69	514.76	468.12
35	667.43	488.94	488.62	435.33
40	656.98	473.25	480.89	419.80
45	647.91	461.00	473.78	408.23
50	627.04	448.86	460.38	398.50
55	604.02	440.00	446.70	392.26
60	594.56	434.67	439.07	390.63
65	613.94	442.37	448.06	396.86
70	637.72	459.51	463.88	411.65
75	643.59	475.90	477.58	430.31
Average Temperature	57.96	59.20	59.04	59.55
Average Humidity	61.19	61.33	61.36	61.28

7.3 Fuel Consumption

The fuel consumption is evaluated using British Thermal Units (BTUs) based on vehicle activities along a highway corridor. The total fuel consumption is estimated with a process similar to that of the pollution emission discussed above (see Figure 7), except for the e (million BTUs/mile/ADT), which represent the energy consumption rates for Maryland at different speed levels obtained by running MOVES2010a (see Table 38) at the appropriate point. Other inputs for fuel consumption estimation are ADT, section lengths, and lane widths.

Table 38. Fuel Consumption Rates (Year 2011)

Speed (mph)	Energy Consumption per ADT (million BTU/mile)			
	Rural Restricted Access	Rural Unrestricted Access	Urban Restricted Access	Urban Unrestricted Access
2.5	16.55	16.30	15.39	15.39
5	9.32	9.74	8.87	9.32
10	5.82	6.57	5.61	6.34
15	4.67	5.55	4.50	5.37
20	3.98	4.89	3.83	4.73
25	3.67	4.18	3.54	4.02
30	3.59	3.89	3.49	3.74
35	3.70	3.58	3.70	3.41
40	3.83	3.36	3.88	3.16
45	3.90	3.19	3.99	3.00
50	3.83	3.08	3.93	2.94
55	3.68	3.10	3.79	2.94
60	3.57	3.10	3.68	2.99
65	3.57	3.21	3.70	3.13
70	3.82	3.50	3.99	3.43
75	4.41	4.34	4.69	4.30
Average Temperature	57.96	59.20	59.04	59.55
Average Humidity	61.19	61.33	61.36	61.28

Chapter 8 Highway Improvement Cost

To estimate project cost (PC), two Maryland-specific data sources were used. The data came from an SHA maintained website, which includes all in-progress and recently-completed major construction projects (SHA, 2010).

Based on the cost data on the website, cost data was compiled for all projects which include costs for four major categories of the project: planning, engineering, right-of-way, and construction. Based on project descriptions, all relevant projects were divided into three different categories: adding a lane by widening an existing roadway, adding a lane by reconstructing a roadway, and constructing a new interchange on an existing road. The projects were also separated into urban and rural categories. From this dataset, the average costs for projects that have been completed in the last three years were estimated.

The SHA also provides a cost-estimation guide for contractors (SHA, 2009), which provides construction cost estimates of $6 million/lane-mile to add a 12-foot lane, $5.5 million to construct one lane-mile of roadway on a new location, and $40 million to construct a full diamond interchange.

In the end, the cost estimates base on the SHA project database were combined with the cost estimates in the guidelines for contractors to produce cost estimates in MOSAIC (see Table 39).

Table 39. Highway Improvement Costs in Rural and Urban Areas in Maryland

Costs per lane mile or per interchange	Rural	Urban
Widening - Add a lane	$4,500,000	$5,500,000
Reconstruction - Add a lane	$5,500,000	$15,000,000
New Interchange	$35,000,000	$40,000,000

Chapter 9 Pivot-point Mode Choice Model

The pivot-point or incremental formulation mode choice model is able to generate the new mode shares in the future year or under multiple improvement alternatives by modifying the existing mode shares based on changes in the characteristics of the transportation networks. The only data needed for pivot-point model is the current market shares of each mode and the proposed changes of the Level of Service (LOS) variables for each alternative instead of the complete characteristics of the specific transportation system as that was for the multinomial mode-choice model. Therefore, the pivot-point mode choice model is often used for the evaluation of Travel Demand Management (TDM) strategies directed at reducing vehicle travel during peak periods with no new modes introduced. The early applications are the ones such as the Spreadsheet Model for Induced Travel Estimation - Managed Lanes (SMITE-ML 2.2) (FHWA 2000), and the Sketch Planning for Road Use Charge Evaluation (SPRUCE) (Patrick 2003). MOSAIC would apply the logit pivot-point mode choice model on its mode share analysis of the managed lanes including the High Occupancy Vehicle (HOV) Lanes and High Occupancy Toll (HOT) Lanes.

Derived from the standard multinomial logit model, the formulation of the pivot-point model is presented as:

$$P_i^{'} = \frac{P_i \times e^{\Delta U_i}}{\sum_{i=1}^{k} (P_i \times e^{\Delta U_i})}$$

Where

P_i: The baseline probability (share) of using mode i;

$P_i^{'}$: The revised probability of using mode i, and

Δu_i: The changes in utility for mode i.

As aforementioned, the pivot-point model formulations are helpful as it only needs to account for changes in the generalized utility functions, not their complete values. Therefore, if there is no new mode introduced, the mode-specific constants can be ignored as they are canceled out in the changes of the utility. The changes in utility for mode i can be expressed as:

$$\Delta u_i = b_i \times \Delta IVTT_i + c_i \times \Delta OVTT_i + d_i \times \Delta COST_i$$

Where

$\Delta IVTT_i$, $\Delta OVTT_i$, $\Delta COST_i$: The changes in LOS variables for mode i ($IVTT$: In-Vehicle-Travel-Time; $OVTT$: Out-Of-Vehicle-Travel-Time; $COST$: Total Cost); and

b_i, c_i, d_i : The coefficients for each corresponding LOS variables for mode i.

The coefficients on LOS variables that MOSAIC used were from the Home-Based-Work (HBW) mode-choice model specific for Washington D.C. area provided by the NCHRP report 365, which is -0.017 for $\Delta IVTT_i$, -0.058 for $\Delta OVTT_i$, and -0.004 for $\Delta COST_i$.

Chapter 10 MOSAIC Output

10.1 Numerical Output in Separate Databases

MOSAIC compiles separate output databases for each improvement case. These databases contain raw numerical output data organized by corridor section for each of the six MOSAIC modules (Mobility, Safety, Socio-Economics, Natural Resources, Energy and Emissions, and Cost). Table 40 offers an example and displays the impact a particular improvement case (Case 1) on speed and travel on each of the five corridor sections. The impact of each improvement case in the six impact categories is then weighted and scaled based on either default or user-defined weights and scaled to produce a final weighted impact measure. These output databases are used by MOSAIC to run interrelated impact modules (e.g. energy and environmental impact can only be assessed after mobility impact is estimated) and to provide a basis for a variety of graphical and summary outputs, which can be easily incorporated into reports and presentations by MOSAIC users.

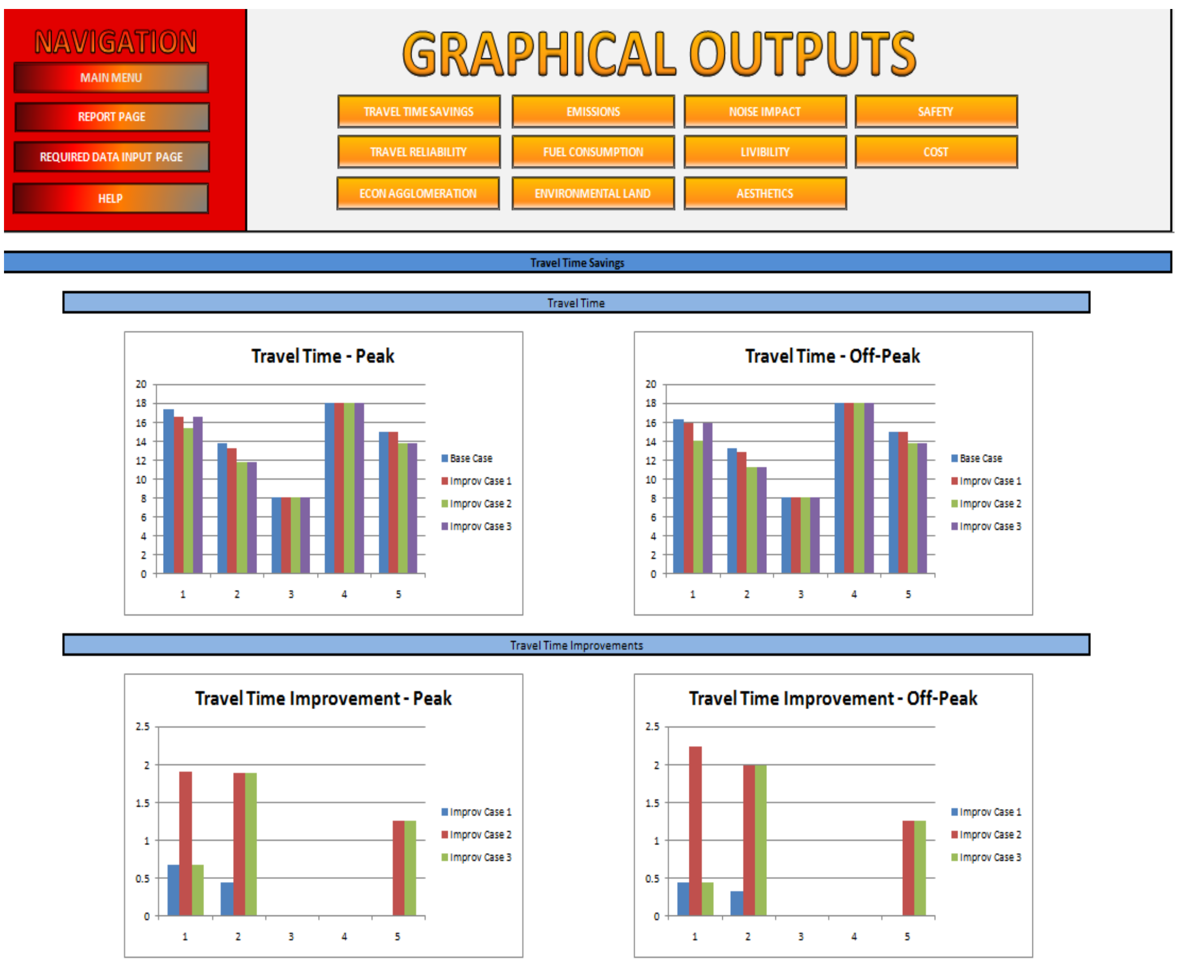
Table 40. MOSAIC Output Database

Section #	**Base Vij Speed**		**Improved Vij Speed 1**	
	Peak Speed	Off-Peak Speed	Peak Speed	Off-Peak Speed
1	26.99625	28.73125	28.179	29.593
2	28.450875	29.7305625	29.4767	30.54845
3	60	60	60	60
4	60	60	60	60
5	35	35	35	35
Section #	**Base Travel Time**		**Improved Travel Time 1**	
	BASE Peak	BASE Off-Peak	Improved Peak1	Improved Off-Peak1
1	17.28846234	16.32211762	16.61679459	15.88426461
2	13.71971712	13.17662676	13.28061482	12.8533547
3	8	8	8	8
4	18	18	18	18
5	14.96618238	14.96618238	14.96618238	14.96618238

10.2 Graphical Output

MOSAIC automatically creates customized graphs for each of the six impact categories. This provides one location where users can check and analyze the performance of all improvement cases against the base-case scenario. All improvement cases and the base case are compared side-by-side (see Figure 9). Both un-weighted and weighted impact scores are presented. These graphs can also be directly exported from MOSAIC as needed for use in project reports or presentations.

Figure 9. MOSAIC Graphical Output View

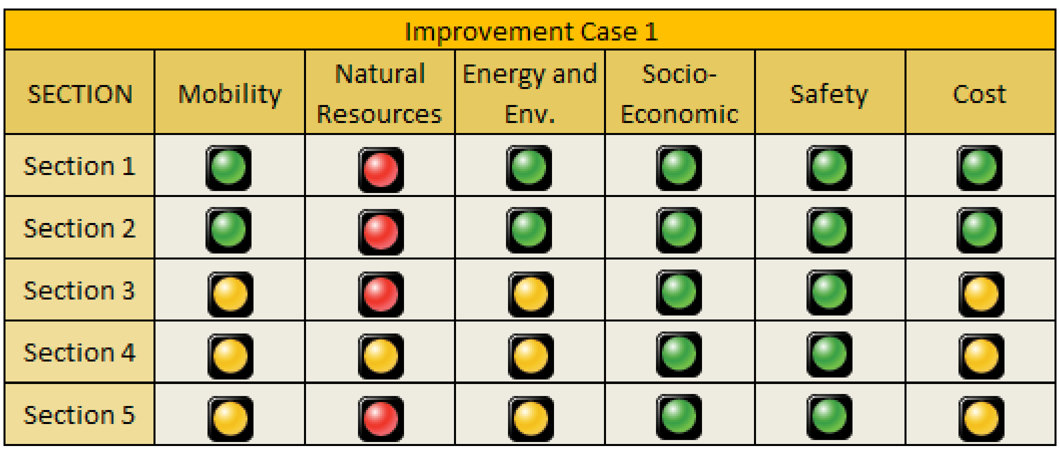


10.3 Final Summary

MOSAIC also provides a final summary, which includes graphical visualizations of the impact of each improvement case at both the section and corridor levels. A final corridor score is also calculated based on weighted averages of corridor-level indicator scores using either default or user-defined weights. The user-defined weights represent how users value the relative importance of the six impact categories. For instance, certain users may value mobility and safety highly, while other users may give priorities to natural resources, energy, and environmental impact mitigation.

10.3.1 Section Level Summary Output

Figure 10. MOSAIC Section-Level Summary Output



Improvement Case 1						
SECTION	Mobility	Natural Resources	Energy and Env.	Socio-Economic	Safety	Cost
Section 1						
Section 2						
Section 3						
Section 4						
Section 5						

The figure above shows the section-level analysis summary for one improvement case. In general, "green" implies positive impact and benefit from the corridor improvement scenario, "yellow" indicates neutral impact, and "red" implies negative impact. The table below lists both how the impact score for each of the six impact categories is computed based on the large number of performance measures introduced in previous chapters. Note that all impact scores are normalized to the same -10 to 10 scale for comparison purposes.

Table 41. Computation and Normalization of Impact Scores

Mobility	Based on Travel Time Savings and Travel Reliability Scores	Average of the % Improvement Scaled from -10 to +10
Natural Resources	Based on Environmental Land Impacts score	Sum of Environmental Area Within Impact Area/Total Improvement Impact Area Scaled from -10 to +10
Energy and Emissions	Based on Fuel Consumption and Pollutant Discharge Scores	Total of the % Improvement Scaled from -10 to +10
Socio-Economic	Based on Aesthetics, Economic Agglomeration, Noise, and Livability Scores	Total of the % Improvement Scaled from -10 to +10
Safety	Based on Severe and Normal Crash Scores	Average of the % Improvement of Normal Crash rates and Severe Crash Rates Scaled from -10 to +10
Cost	Based on benefit cost analysis of Travel Time Savings and estimated Project Cost	Total Yearly Travel Time Savings/Improvement Cost Scaled from -10 to +10 based on the maximum ratio

10.3.2 Corridor-level Summary Output

The corridor-level impact scores are weighted averages of section-level impact scores. The weights for each section are based on vehicle miles traveled on that section. A custom graph is provided to visualize the corridor level impact (see Figure 11 for an example). These weighted average scores are scaled similarly to the section-level summary output, with +10 indicating the highest level of positive impact, 0 indicating no impact and -10 indicating the worse possible impact from improvement.

Figure 11. MOSAIC Corridor-Level Summary Output

MOE	Mobility	Natural Resources	Energy and Env.	Socio-Economic	Safety	Cost
Score	0.874	-4.452	0.834	0.871	1.423	3.195

10.3.3 Final Corridor Scores and Weighting System

Figure 12. MOSAIC Final Improvement Case Scores

Improvement Case 1	
Final Score	0.458

Improvement Case 2	
Final Score	2.317

MOSAIC provides a final score for each improvement case, which is determined as the weighted average of the six impact scores for the six impact categories. By default, the weights for each impact category are equal. However, MOSAIC provides an option for users to define the weights of these indicators. Shown below in Figure 13, the weighting system allows users to easily scale final scores to help identify the best improvement case according to users' goals (different SHA divisions may have different goals). Individual weights are numerically shown to the left, while relative weights are shown to the right.

Figure 13. MOSAIC Impact Score Weighting System

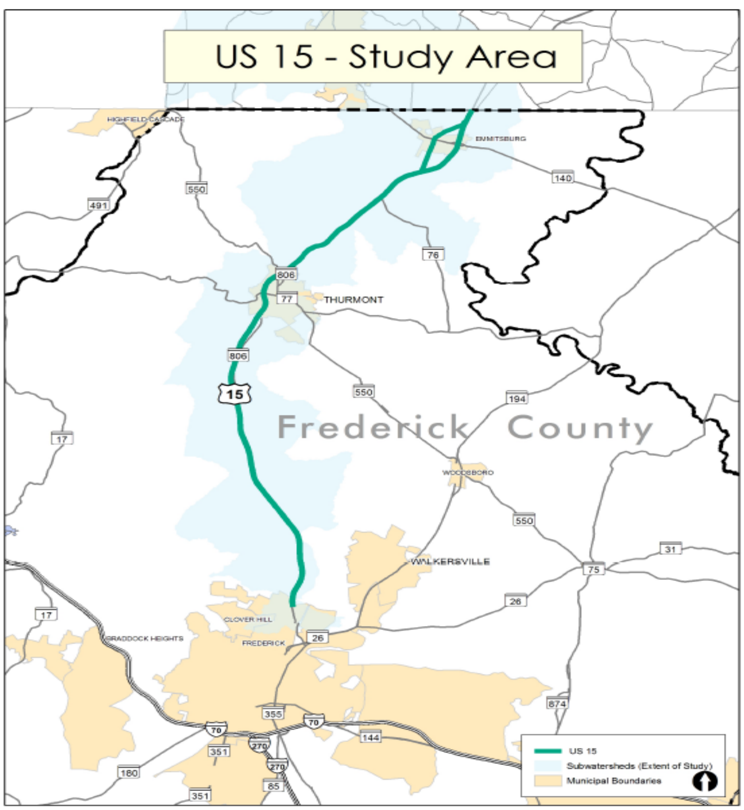
Weighting System		
MOBILITY	8	2.96
NATURAL RESOURCES	3	1.11
ENERGY AND ENVIROMENT	5	1.85
SOCIO-ECONOMIC	2	0.74
SAFETY	7	2.59
COST	2	0.74

RESTORE DEFAULT WEIGHTS

Chapter 11 U.S.-15 Corridor Case Study

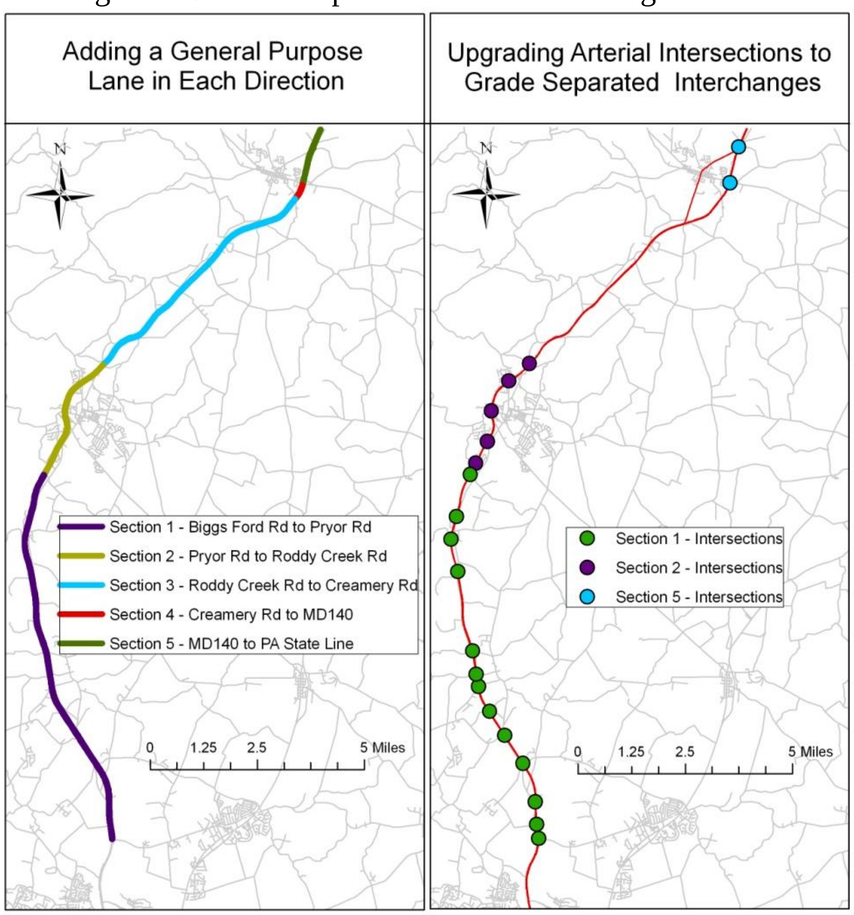
In Maryland, the highway runs 37.85 miles (60.91 km) from the Virginia state line at the Potomac River in Point of Rocks north to the Pennsylvania state line near Emmitsburg. US 15 is the primary north–south highway of Frederick County. The highway connects the county seat of Frederick with Point of Rocks and Leesburg to the south and with Thurmont, Emmitsburg, and Gettysburg to the north. US 15 is a four-lane divided highway throughout the state except for the portion between the Point of Rocks Bridge and the highway's junction with US 340 near Jefferson. The U.S. Highway is a freeway along its concurrency with US 340 and through Frederick, where the highway meets US 40 and Interstate 70 (I-70). The segment of US 15 from Biggs Ford Road to PA-MD border line was selected as the candidate corridor for case study, which is shown in Figure 14.

Figure 14. US 15 Study Area



The study area was divided into five sections according to SHA's short-term comprehensive highway corridor planning study. Section 1 is a 7-mile rural arterial with seven intersections and four lanes in each direction; Section 2 is also a 6-mile rural arterial with four lanes each way and has six intersections; Sections 3 and 4 are rural freeways with two interchanges each respectively measuring 8-miles and 18 miles long; Section 5 is an 8-mile rural freeway with seven intersections and four lanes each way. Two improvement plans, shown below in Figure 15, were applied to this corridor: (1) Adding one general purpose travel lane in each direction on all roadway sections and (2) Upgrading all at-grade interchanges to grades-separated interchanges for arterial sections with no change to freeway sections.

Figure 15. US 15 Improvement Plans and Segmentation



11.1 Case Study Inputs

The required input data for each section along the selected US 15 corridor is presented in Table 42. Certain input information is optional in MOSAIC as discussed in previous chapters. The default values for all optional input variables by section are summarized in Table 43.

Table 42. Required Input Data

		Section 1	Section 2	Section 3	Section 4	Section 5
GENERAL DATA	Section Length (miles)	7.22	6	8	18	8
	Section Width (miles)	0.002841	0.002841	0.002841	0.002841	0.002841
	Number of Lanes	4	4	4	4	4
	Roadway Type	Arterial Street	Arterial Street	Freeway	Freeway	Arterial Street
	Average Daily Traffic	36500	27725	23800	18450	11850
	Number of Intersections	7	6	2	2	7
	Rural/Urban	Rural	Rural	Rural	Rural	Rural
ECONOMIC DATA	Work-based Employment	23000	23000	23000	23000	23000
	GDP Per Worker	12000	12000	12000	12000	12000
LAND USE AND TRANSPORT DATA	Study Area (square miles)	15.71	7.34	11.67	0.94	3.51
	Recreational (square miles)	1.571	0.367	3.501	0.0282	0.351
	Agricultural (square miles)	9.426	5.138	3.501	0.6674	0.1755
	Low Density Residential (square miles)	1.571	1.468	3.501	0.094	0
	High Density Residential (square miles)	0	0	0	0.0376	1.5795
	Commercial (square miles)	1.571	0.367	1.167	0.094	1.2285
	Industrial (square miles)	1.571	0	0	0.0188	0.1755
	High Density Mixed Use	0	0	0	0	0
	Med Density Mixed Use	0	0	0	0	0
	Transit Oriented Dev	0	0	0	0	0
AESTHETICS DATA	Facility Compatability	-3	0	1	1	2
	Land Use Attractive	2	-1	2	4	1
	Visual Appeal	0	-2	3	5	3
	Historical Roads/Sites	1	3	1	11	1
ECOLOGICAL/HISTORICAL IMPACT DATA (square miles)	Cultural/Historical Sites	1.420,0.550	1.000,0.565	0.800,0.079	0.000,0.094	0.015,0.660
	Steep Slopes	1.000,0.000	2.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000
	Highly Erodible Soils	0.500,0.660	0.000,0.613	0.000,0.110	0.000,0.157	0.000,0.660
	Wetlands	1.230,0.495	0.000,0.094	1.000,0.016	0.000,0.141	0.200,0.440
	Waterways	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000
	Floodplains	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000
	Forests	1.000,0.330	1.200,0.047	2.100,0.016	0.000,0.016	1.200,0.055
	Critical Areas	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000
	Springs/Seeps	1.210,1.100	0.000,0.942	0.000,0.314	0.000,0.314	0.000,1.100

	Bedrock/Geo Areas	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000
	Natural Species	1.500,0.275	0.000,0.236	1.200,0.079	0.000,0.079	1.100,0.275
	Storm Water Facilities	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000	0.000,0.000
TYPICAL INTERSECTION DATA	ADT on Minor Streets	12000	12000	12000	12000	12000
	Approaches With Left Turn Lanes	One Approach	One Approach	One Approach	One Approach	One Approach
	Approaches With Right Turn Lanes	Two Approaches	Two Approaches	Two Approaches	Two Approaches	Two Approaches
	Number of 3-Leg Intersections	4	4	4	4	4
	Number of 4-Leg Intersections	2	2	2	2	2
	Divided/Undivded	Undivided	Undivided	Divided	Divided	Undivided

Table 43. Optional Input Data

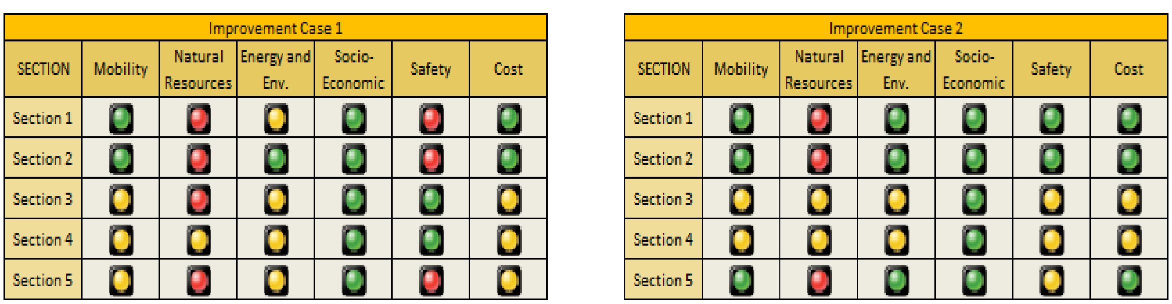
OPTIONAL GENERAL DATA	Fraction Peak Hour ADT	0.90
	Fraction Off-Peak Hour ADT	0.10
	Corridor Terrain	Flat
	Corridor Type	Principal Arterial
	Lane Width	9
OPTIONAL ECONOMIC DATA	Cost of travel	15
	Productivity Elasticity with respect to Employment Density	0.04
	Effective Density of Employment	0.125
OPTIONAL NOISE DATA	Noise Source Type	Automobiles and Vans
	Distance to Noise Source	250
	Large Ground Factors	0

11.2 Case Study Findings

After submitting the input data and running MOSAIC analysis modules, model outputs were generated as described in Chapter 8: (1) Numerical outputs in separated databases; (2) Graphical outputs; and (3) Final summary reports.

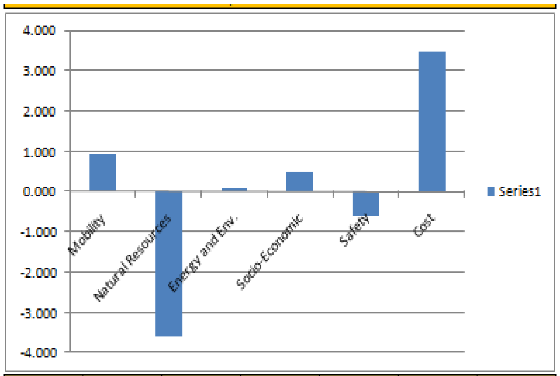
Results from the section-by-section analysis show that improvement plan 2, upgrading intersections to grade-separated interchanges, has fewer negative and more positive impacts on sustainability indicators related to mobility and cost in section 5; energy, and pollution/GHG emissions in sections 1 and 5; and the safety in sections 1, 2, and 5, compared to adding improvement case 1, adding one general purpose travel lane in each direction. The corridor-level analysis results categorized by the six sustainability indicator groups demonstrate that both improvement types have overall positive impact on mobility, energy and emissions, socio-economics, and cost for the study area along US 15, and both have moderate negative impact on natural resources. As for safety, improvement plan 2 will benefit while improvement plan 1 will have negative impacts on safety. Therefore, converting arterial street at-grade intersections to grade-separated interchanges along US 15 is a more desirable corridor improvement option than building more capacity on this corridor according to the six sustainability indicator categories (see Figure 16 and 17). If equal weights are given to all six sustainability indicator categories (e.g. mobility is equally as important as safety, as energy and emissions, as natural resources, and so on), the research shows the final overall sustainability score for improvement plan 1 to be 0.127, and 2.006 for improvement plan 2. This finding remains valid for most combinations of weights assigned to different sustainability indicator categories.

Figure 16. Section Analysis Results

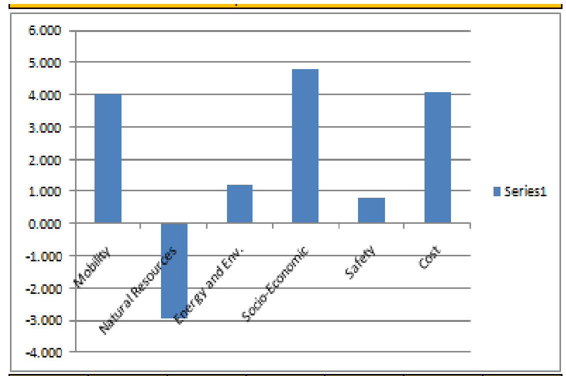


Note: Green means the impact is significant and desirable. Red means the impact is significant but undesirable. Yellow means the impact (either positive or negative) is insignificant.

Figure 17. Corridor Analysis Results



MOE	Mobility	Natural Resources	Energy and Env.	Socio-Economic	Safety	Cost
Score	0.911	-3.611	0.097	0.493	-0.593	3.466



MOE	Mobility	Natural Resources	Energy and Env.	Socio-Economic	Safety	Cost
Score	4.024	-2.928	1.203	4.810	0.820	4.106

Note: Unweighted scores for each indicator are scaled on a range of -10 to +10, where -10 represents a 100% deterioration and +10 represents a 100% improvement over the do-nothing scenario.

Chapter 12 Interstate 270 Mode Choice Case Study

Interstate 270 in Maryland is a major connector route between Interstate 70 in Frederick and Interstate 495 (Capital Beltway). As the main connector between the Capital and transcontinental Interstate 70, Interstate 270 provides access to points west out of Washington D.C. Southbound Interstate 270 splits, with the left lanes providing high occupancy vehicles direct access to Interstate 495/Capital Beltway because of the high traffic demand along the corridor several years ago, and the right lanes splitting into Spur Interstate 270 south to Interstate 495/Capital Beltway south and Interstate 270 southeast to Interstate 495/Capital Beltway east. (SHA, 2003) The southbound HOV lane extends from MUDDY BRANCH to the I-495, and is operational during the morning peak period from 6:00a.m.to 9:00a.m, with the general traffic using these lanes at all other times. The study area, a segment of I 270 oriented from CO4556 FATHER HURLEY BLVD toward the CO164 TUCKERMAN LA, is highlighted in Figure 18. The study period is from 6:00 a.m. through 9:00 a.m., i.e. the morning peak hours.

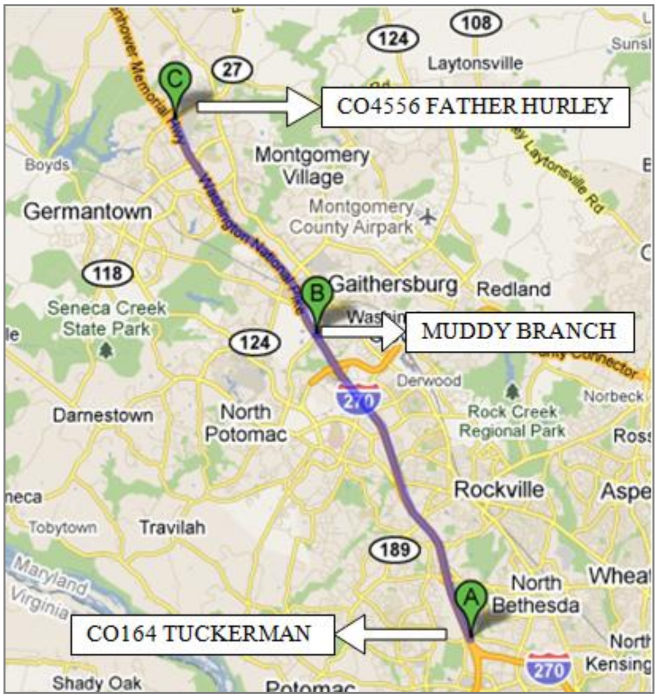


Figure 18 I 270 Study Area

The study area was divided into two sections according to AADT level and the roadway configurations. Section 1 is a 7.41-mile highway with one HOV lane and 5 General Purpose (GP) lanes from MUDDY BRANCH RD toward CO164 TUCKERMAN LA, while section 2 is a 5.61-mile highway with 4 GP lanes. Two improvement plans, were applied to this corridor: (1) Converting one GP lane to one HOV lane for the entire corridor; and (2) Replacing one HOV lane with one HOT lane for section 1 and converting one GP lane to one HOT lane for section 2.

12.1 Case Study Input

As mentioned above, the pivot-point mode choice model would require the existing mode shares, along with the changes of the LOS variables, along the corridor.

12.1.1 Base Mode Shares

The existing mode shares can be computed by applying the existing traffic count data. The 2008 count data for each traffic mode along each lane of the study corridor was obtained from the Vehicle Occupancy Count Report generated from SHA's hourly Internet Traffic Monitoring System (I-TMS). The count data for section 1 was from the monitor location: S1997150042; while the data for section 2 was from the location: S1997150044. The mode ">=5" was assumed to load 5 persons, "vanpool" loads 7 persons, "truck" loads 1 person, and the "bus" has the designed load factor as 1.2 and thus, is able to load 48 persons per time on average. The cumulative existing mode shares as well as the traffic counts for the whole study area are presented in Table 44 for section 1 while Table 45 for section 2.

Table 44 Section 1 Traffic Counts and Mode Shares

	HOV Lane			GP Lane		
Modes	3-h VC	3-h PT	3-h MS	3-h VC	3-h PT	3-h MS
1	207	207	2.77%	19129	19129	78.37%
2	2313	4626	61.98%	1060	2120	8.69%
3	47	141	1.89%	85	255	1.04%
4	14	56	0.75%	13	52	0.21%
>=5	0	0	0.00%	8	40	0.16%
Vanpool	31	217	2.91%	56	392	1.61%
Bus	46	2208	29.58%	38	1824	7.47%
Truck	9	9	0.12%	597	597	2.45%
Total	2667	7464	100.00%	20986	24409	100.00%

Table 45 Section 2 Traffic Counts and Mode Shares

Modes	3-h VC	3-h PT	3-h MS
1	12828	12828	69.43%
2	989	1978	10.71%
3	40	120	0.65%
4	12	48	0.26%
>=5	1	5	0.03%
Vanpool	20	140	0.76%
Bus	57	2736	14.81%
Truck	620	620	3.36%
Total	14567	18475	100.00%

12.1.2 LOS Variables

As aforementioned, MOSAIC takes into account three types of LOS variables on its mode choices analysis: In-Vehicle-Travel-Time ($IVTT$), Out-Of-Vehicle-Travel-Time ($OVTT$), and Total Cost ($COST$).

Both improvement types one and two need to consider the changes of IVTT as part of the variance of the LOS variables. The HOV and the HOT lanes are assumed to operate at free-flow conditions and the travel times under these two scenarios are the uncongested travel time. For the GP lanes, the travel times are based on the BPR function and its corresponding coefficients were introduced in NCHRP Report 365, which is presented as:

$$T_c = T_f \times (1 + 0.83 \times (\frac{v}{c})^{5.5})$$

Where

T_c : Congested link travel time;

T_f : Link free-flow travel time;

v : Assigned link traffic volume (vehicles); and

c : Link capacity, which is 1800 vehicles / lane for I 270.

Therefore, the changes in IVTT for either HOV or HOT lanes would be the changes between the congested and the uncongested travel time. MOSAIC assumes there will be no change on travel time for the remaining GP lanes. After the new shares and number of drive-alone vehicles are estimated, the congested updated travel time for the GP lanes will be computed.

Assuming there will be no changes on OVTT at this point for the two improvement types, as for the changes on the total costs, the HOT alternative would require the extra payment on the tolls for the single-occupy vehicles. The payment was assumed to be 1.45 dollars according to the amount that newly opened MD 200 charged.

12.2 Case Study Procedure

I assumed this mode shares analysis procedure would have no impact on the trucks' vehicle trips and person trips. That is to say, both the vehicle trips and person trips of the mode "truck" will have no change before and after the mode choice analysis. In this way, the initial mode shares was adjusted without considering the percentage of trucks during the analysis, and the "truck" person trips were added on after completing the first iteration of the analysis.

12.2.1 Alternative 1: HOV Lanes

The procedure of the pivot-point mode shares analysis for the alternative 1: converting one GP lane to one HOV lane for the entire corridor started from the existing person trips presented in Table 44 and 45 aforementioned. Since the single-occupancy vehicles are forbidden in using the HOV lanes, it was assumed that there would be no changes on IVTT and thus, no utility changes for the mode "1" in the first iteration. For each of the other modes, the Δu_i is equal to the product of the $\Delta IVTT_i$ and its corresponding coefficient. Based on the changes of utilities, the person trips and vehicle counts can be obtained at this point.

After the first iteration, the new volume-to-capacity ratios both for the HOV lanes and non-HOV lanes can be figured out. The v/c ratio for the HOV lane is equal to the two-person and above vehicles divided by the HOV lanes' capacity; while the one for the non-HOV or GP lanes is equal to the drive-alone vehicles plus the trucks divided by the remaining lanes' capacity. In this way, the congested travel time for the GP lanes can be updated based on the non-HOV travel time resulted from the first iteration.

Since the travel time for the GP lanes will increase after introducing the HOV lane, the increase in congestion for the drive-alone mode makes the HOV modes even more attractive. Therefore, the process should be iterated until the resulting shares for drive-alone produce a v/c ratio that is in balance with the time used for input to the change in IVTT for drive-alone. In this way, the iteration ends were set when the changes of travel times along the non-HOV lanes compared with the initial existing travel time vary within one minute between two iterations.

12.2.2 Alternative 2: HOT Lanes

The procedure of the pivot-point mode shares analysis for the alternative 2: replacing one HOV lane with one HOT lane for section 1 and converting one GP lane to one HOT lane for section 2, is similar to the one for the alternative 1. The differences exist in two aspects: changes on utility function and adding the process for reversing the existing HOV lane's person trips back to the GP lane's corresponding person trips.

In alternative 2, the single-occupancy vehicles are allowed in using the HOT lane only if the drivers would like to pay the toll. Thus, the Δu_i is equal to the product of the $\Delta IVTT_i$ and its corresponding coefficients plus product of the $\Delta COST_i$ and its corresponding coefficient. And for each of the other modes, the Δu_i is still equal to the product of the $\Delta IVTT_i$ and its corresponding coefficient.

The existing person trips along section 1 need to be reversed back to the scenario that 6 lanes are all GP lanes to consistent with the model formulation. The amount of single-occupancy vehicles that would use the HOT lane by paying the toll can be calculated by comparing the difference of the total amount of single-occupancy vehicles between scenario 1 and 2. Thus, the traffic volume along HOT lane after the first iteration should not only include the two-person and above vehicle amount but also the amount of single-occupancy vehicle that would pay for the toll.

12.3 Case Study Results and Findings

After complete the pivot-point mode choice analysis on the two improvement options applied to the study corridor: (1) Converting one GP lane to one HOV lane for the entire corridor; and (2) Replacing one HOV lane with one HOT lane for section 1 and converting one GP lane to one HOT lane for section 2, the final vehicle count and mode share results for each section can be obtained, which were listed in Table 46. Table 47 is also presented to compare the traffic count differences among each improvement type with the existing scenario.

Table 46 Pivot-Point Mode Choice Model Results

	Section 1				Section 2			
	Scenario 1: HOV		Scenario 2: HOT		Scenario 1: HOV		Scenario 2: HOT	
Modes	VC	MS	VC	MS	VC	MS	VC	MS
1	18810	80.84%	19403	81.87%	12604	87.57%	12786	87.97%
2	3492	15.01%	3354	14.15%	1033	7.18%	997	6.86%
3	142	0.61%	131	0.55%	42	0.29%	40	0.28%
4	28	0.12%	27	0.11%	13	0.09%	12	0.08%
>=5	9	0.04%	8	0.03%	1	0.01%	1	0.01%
Vanpool	93	0.40%	87	0.37%	21	0.15%	20	0.14%
Bus	88	0.38%	84	0.35%	60	0.41%	57	0.40%
Truck	606	2.60%	606	2.56%	620	4.31%	620	4.27%
Total	23268	100.00%	23699	100.00%	14393	100.00%	14534	100.00%

Table 47 Traffic Count Differences

	Section 1				Section 2	
Modes	Scenario 1-E	Scenario 2-E	Scenario 2-1	Scenario 2-GP	Scenario 1-E	Scenario 2-E
1	-526	67	593	-85	-224	-42
2	119	-19	-138	24	44	8
3	10	-1	-10	1	2	0
4	1	0	-2	0	1	0
>=5	1	0	-1	0	0	0
Vanpool	6	0	-7	1	1	0
Bus	4	0	-5	1	3	0
Truck	0	0	0	0	0	0
Total	-385	46	431	-59	-174	-33

Table 47 indicates that the improvement type one: converting one GP lane to one HOV lane for the entire corridor would reduce the total traffic counts to a larger amount both compared to the existing traffic count and the one for the improvement 2: replacing one HOV lane with one HOT lane for section 1 and converting one GP lane to one HOT lane for section 2. The improvement 2 would increase the traffic amount compared to the existing scenario for section 1 mainly because the HOT lane would attract more single-occupancy vehicles in using the fast-speed lane by paying for the toll. But if compared with the traffic counts that reversed to the GP lanes' scenario from the existing one for section 1, the total traffic count for improvement type 2 was still reduced by 59 at this point.

For other characteristics of performances on the two improvement types are presented in Table 48 and 49 for section 1 and 2 respectively. These performances include the travel time and v/c ratio along the non-HOV and non-HOT lanes, or GP lanes, v/c ratio for the HOV and HOT lanes, and the vehicle occupancy for the whole study area.

Table 48 Other Performances along Section One

	Existing Scenario	scenario 1	Scenario 1-E	Scenario 2	Scenario 2-E	Scenario 2-1
Non-HOV or Non-HOT (mins)	9.762	11.594	1.832	9.351	-0.411	-2.243
HOV or HOT v/c	0.494	0.377	-0.117	0.696	0.202	0.319
Non-HOV or Non-HOT v/c	0.777	0.889	0.112	0.739	-0.039	-0.150
VO	1.186	1.197	0.011	1.185	-0.001	-0.013

Table 49 Other Performances along Section Two

	Existing Scenario	scenario 1	Scenario 1-E	Scenario 2	Scenario 2-E	Scenario 2-1
Non-HOV or Non-HOT (mins)	6.702	7.784	1.082	7.784	1.082	0.000
HOV or HOT v/c	n/a	0.216	n/a	0.243	n/a	0.026
Non-HOV or Non-HOT v/c	0.674	0.816	0.142	0.816	0.142	0.000
VO	1.088	1.094	0.005	1.089	0.001	-0.004

Table 48 and 49 indicate that compared with improvement type one, the improvement type two performs better in increasing the fast-lane's v/c ratio and would increase less travel time along the non-HOV and non-HOT lanes. However, the improvement type one acted better in increasing the GPs' v/c ratio and would increase the vehicle occupancy along the whole corridor to a larger extent.

The results demonstrate that HOV lanes would encourage ridesharing to a larger extent compared with HOT lanes and thereby better reduce highway congestion along the study area. However, as more and more severe congestion problem appeared, HOV lanes would show their limitations and shortcomings derived from our results. One typical example among them is the inefficient usage of the road space. It appeared that few drivers take advantage of fast lanes, while a large amount of single-occupancy vehicle drivers must endure the adjacent GP lanes with the worse traffic condition.

12.4 Case Study Summary

The study indicated it would be quite convenient to apply the pivot-point mode choice model for the evaluation of Travel Demand management (TDM) strategies with no new modes introduced. The model would also preserves the current (or base) matrices, therefore retaining any special associations detected in the data but never completely accounted for in a model. However, the restrictions for this model lie in the fact that the operation of each mode should strictly obey the rules of HOV and HOV lanes, where no trucks or the single-occupancy vehicles is allowed to use HOV lanes and no trucks is allowed to enter HOT lanes, which is quite unrealistic in the real life. Thus, our future study will conduct the mode choice analysis by also applying the nested logit model from Maryland Statewide Model (MSTM), to compare the results from two models to analyze the impacts of TDM strategies on the mode shares.

Chapter 13 Conclusion and Future Study

The case study results of US 15 within Maryland demonstrate that MOSAIC performs well when applied in analyzing two existing highway improvement types: adding a general-purpose lane and converting at-grade intersections to grade-separated interchanges. MOSAIC is also able to provide numerical and graphical outputs for users after estimating the impact of these improvement types on six categories of measures of effectiveness: mobility, safety, socio-economics, natural resources, energy and environment, and cost. MOSAIC benefit not only in multimodal highway corridor improvement decision-making, but also in demonstrating transportation agencies' commitment to incorporating social, economic, environmental, and sustainability considerations in its transportation planning process.

Future study will include model validation after collecting corresponding data from corridors which had similar improvement types with the ones that MOSAIC considered. Besides, although the current MOSAIC tool is already fully functional, future phases of this research project will complete the research tasks to deliver an eGIS (Enterprise Geographical Information System)-based MOSAIC tool that considers multimodal highway improvement options. The multimodal improvements in highway projects that MOSAIC will incorporate in phase two include improvement types such as road diet (i.e. reduce number of lanes), bus rapid transit, light rail, bus-only lane, HOV/HOT operations, park-and-ride, express toll lanes, truck-only lane, bike/pedestrian facilities, ITS/ATIS deployment, access management, and local land use plans. MOSAIC will also be further developed into the GIS-based tool that can be fully integrated into the SHA eGIS. This MOSAIC-eGIS integration will produce a user interface that is easy to understand, easy to use, and ready to be incorporated into various existing SHA processes, which will further streamline MOSAIC input and output processes, making the tool ready for state-wide applications in Maryland.

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