MD-11-SP009B4E

Martin O'Malley, *Governor*
Anthony G. Brown, *Lt. Governor*

Beverley K. Swaim-Staley, *Secretary*
Darrell B. Mobley, *Acting Administrator*

STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

COMPREHENSIVE HIGHWAY CORRIDOR PLANNING WITH SUSTAINABILITY INDICATORS

LEI ZHANG
PRINCIPAL INVESTIGATOR

GRADUATE RESEARCH ASSISTANTS:
MINGYANG JI
NICHOLAS FERRARI

UNIVERSITY OF MARYLAND

SP009B4E
FINAL REPORT

October 2011

Technical Report Documentation Page

Report No. MD-11-SP009B4E	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Comprehensive Highway Corridor Planning with Sustainability Indicators		5. **Report Date** October 2011 **6. Performing Organization Code**
7. Author/s Lei Zhang, Principal Investigator Mingyang Ji, Graduate Research Assistant Nicholas Ferrari, Graduate Research Assistant		8. **Performing Organization Report No.**
9. **Performing Organization Name and Address** University of Maryland College Park MD 20742		10. **Work Unit No. (TRAIS)** 11. **Contract or Grant No.** SP009B4E
12. Sponsoring Organization Name and Address Maryland State Highway Administration Office of Policy & Research 707 North Calvert Street Baltimore MD 21202		13. **Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code** (7120) STMD - MDOT/SHA
15. Supplementary Notes		

16. Abstract

The Maryland State Highway Administration (SHA) has initiated major planning efforts to improve transportation efficiency, safety, and sustainability on critical highway corridors through its Comprehensive Highway Corridor (CHC) program. This project developed a Model Of Sustainability and Integrated Corridors (MOSAIC) to assist SHA in selecting the most sustainable corridor improvement option for its Highway Needs Inventory and long range planning processes. Products from this research project will also help SHA achieve its mobility, safety, socio-economic and environmental stewardship objectives.

17. Key Words sustainability, corridor planning, performance measure	18. **Distribution Statement: No restrictions** This document is available from the Research Division upon request.		
19. Security Classification (of this report) None	**20. Security Classification (of this page)** None	**21. No. Of Pages** 60	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.

EXECUTIVE SUMMARY

The Maryland State Highway Administration (SHA) has initiated major planning efforts to improve transportation efficiency, safety, and sustainability on critical highway corridors through its Comprehensive Highway Corridor (CHC) program. It is important for planners to be able to compare various types of highway improvement options during the needs analysis and long-range planning processes to select the best program-level plans for the corridor. To support the CHC and Sustainability Initiatives, SHA funded a research project, titled "Comprehensive Highway Corridor Planning with Sustainability Indicators," to develop a Model Of Sustainability and Integrated Corridors (MOSAIC), which will help SHA estimate the sustainability impact of multimodal highway improvement options early in the transportation planning and environmental screening processes. The results from this research project can also help SHA achieve its mobility, safety, socio-economic and environmental stewardship objectives.

This research project had three specific objectives:

1. Define sustainability indicators that are relevant to SHA's CHC program.
2. Develop a high-level planning model that helps SHA integrate the identified sustainability indicators into the CHC program at the project/corridor level.
3. Provide guidance documents for integrating safety, mobility, and environmental stewardship objectives into SHA's corridor planning process.

Based on these research objectives, a team of researchers at the University of Maryland, College Park, worked closely with SHA's technical liaisons and research staff to successfully develop the MOSAIC tool. 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. The first version of 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. Future research will expand the highway improvement options in MOSAIC to include road diet (i.e. remove auto travel lanes to better accommodate alternative modes of transportation), bus rapid transit, bus-only lanes, high occupancy vehicle lanes, high occupancy toll lanes, freight truck-only lanes, light rail transit, express toll lanes, Intelligent Transportation System (ITS) / Advanced Traffic Information System (ATIS) deployment, and access management.

Various quantitative models have been developed to analyze the impacts of these alternative corridor improvement options on identified sustainability indicators. The impacts on these sustainability indicators are then weighted based on policy considerations and SHA priorities.

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 integrate the existing MOSAIC tool into the SHA Enterprise GIS (eGIS) environment, which will further streamline MOSAIC input and output procedures for state-wide planning applications in Maryland.

The UMD research team, the SHA project champion, technical liaisons, and the SHA advisory committee members for this project share a common vision for MOSAIC: that it will become a flagship application of the SHA CHC Program that not only assists SHA in multimodal highway corridor improvement decision-making but also demonstrates SHA’s commitment to incorporating social, economic, environmental, and sustainability considerations in its transportation planning process.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

In order to improve transportation, environmental, and livability conditions for Maryland residents and visitors, the Maryland State Highway Administration (SHA) has initiated major planning efforts to improve critical highway corridors. The SHA is also committed to integrating safety, mobility, environmental stewardship, and socio-economic objectives in its transportation planning process through its Comprehensive Highway Corridors (CHC) program. To support its sustainability initiatives, SHA has funded the development of a Model Of Sustainability And Integrated Corridors (MOSAIC), which defines sustainability indicators, analyzes the sustainability impact of corridor improvements, and identifies environmental mitigation needs early in the planning process. The sustainability indicators include mobility, safety, air quality, energy consumption, pollution and green house gas emissions, natural resource impact, socio-economic measures, and costs. When implemented at the highway needs assessment and long-range planning stages, MOSAIC can help SHA 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. 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 with minimum requirements on staff time and other resources.

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. For instance, the concept of “environmental banking” allows highway agencies to provide mitigation in advance of the actual needs for replacement/restoration of wetlands and habitat. 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.

This project report summarizes the methods employed in MOSAIC for estimating the sustainability impacts of various corridor improvement options. These impacts are categorized into six major groups: mobility, safety, socio-economic, natural resources, energy and emissions, and cost. In Phase One of the project, the focus was 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. 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.

After an extensive review of the literature and best practices elsewhere as well as several discussions with SHA project liaisons and other SHA staff members, the UMD research team defined a comprehensive set of sustainability indicators that are incorporated and quantitatively evaluated in MOSAIC (see Table 1). For comparison purposes, the sustainability indicators adopted by the Texas DOT for its Sustainability Enhancement Tool (SET) are listed in Table 1.

The remainder of the project report is organized as follows. Chapter 2 summarizes and briefly discusses the major distinguished tools relevant to the comprehensive highway corridor planning discussed. Chapters 3 through 9 document the technical details of various MOSAIC input/output and analysis modules. Chapter 10 presents the findings from a case study that applies MOSAIC to the US 15 corridor between Frederick, MD and the Maryland-Pennsylvania border. Finally, a research roadmap is provided in Chapter 11 to guide future development of the MOSAIC tool.

Table 1. Sustainability Indicators in MOSAIC Compared with SET

MOSAIC		SET (TxDOT)	
Sustainability Categories	**Sustainability Indicators**	**TxDOT Goals**	**Performance Measures**
Mobility	Travel Time Savings	**Reduce Congestion**	Travel Time Index
	Delay		Buffer Index
	Speed		
	Level of Service (LOS)		
	Travel Reliability		
Safety	Accident Counts and Rate	**Enhance Safety**	Annual Severe Crashes per Mile
	Accident Severity		Percentage Lane-miles under Traffic Monitoring/ Surveillance
Socio-Economic Impact	Economic Impact	**Expand Economic Opportunity**	Land-use Balance
	Compatibility with Existing Land Use		Truck Throughput Efficiency
	Within Smart Growth –PFA Boundaries	**Increase the Value of Transportation Assets**	Average Pavement Condition Score
	Livability		Capacity Addition within Available Right of Way
	Noise		Proportion of Non-single-occupant Travel
	Esthetics		
	Compatibility with Sustainable Transportation Modes (Transit/Bike/Walk)		
Cost	Costs		Cost Recovery from Alternative Sources
Energy and Emission	Green House Gas	**Improve Air Quality**	Daily NOx, CO, and VOC Emission per Mile of Roadway
	Pollution emissions		Daily CO2 Emission per Mile of Roadway
			Attainment of Ambient Air Quality Standards
	Fuel Consumption		
Natural Resources	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		

CHAPTER 2: MOBILITY

2.1 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 1.

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 intersection or interchange. Based on intersection/interchange locations, a section is further divided into multiple links (see Figure 2). 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 3). Intersection-level travel time savings are then aggregated to corridor-level estimates.

Figure 1. Estimation of Travel Time Savings

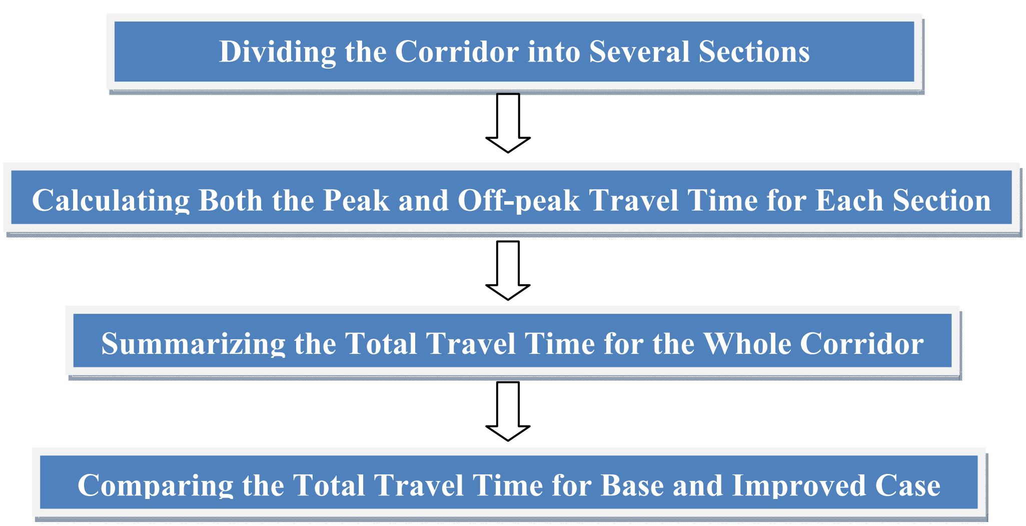


Figure 2. Section and Link Definitions in MOSAIC

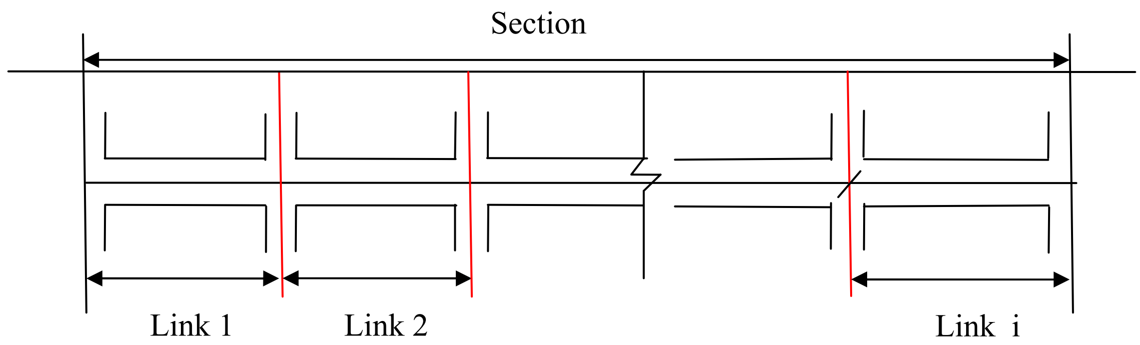
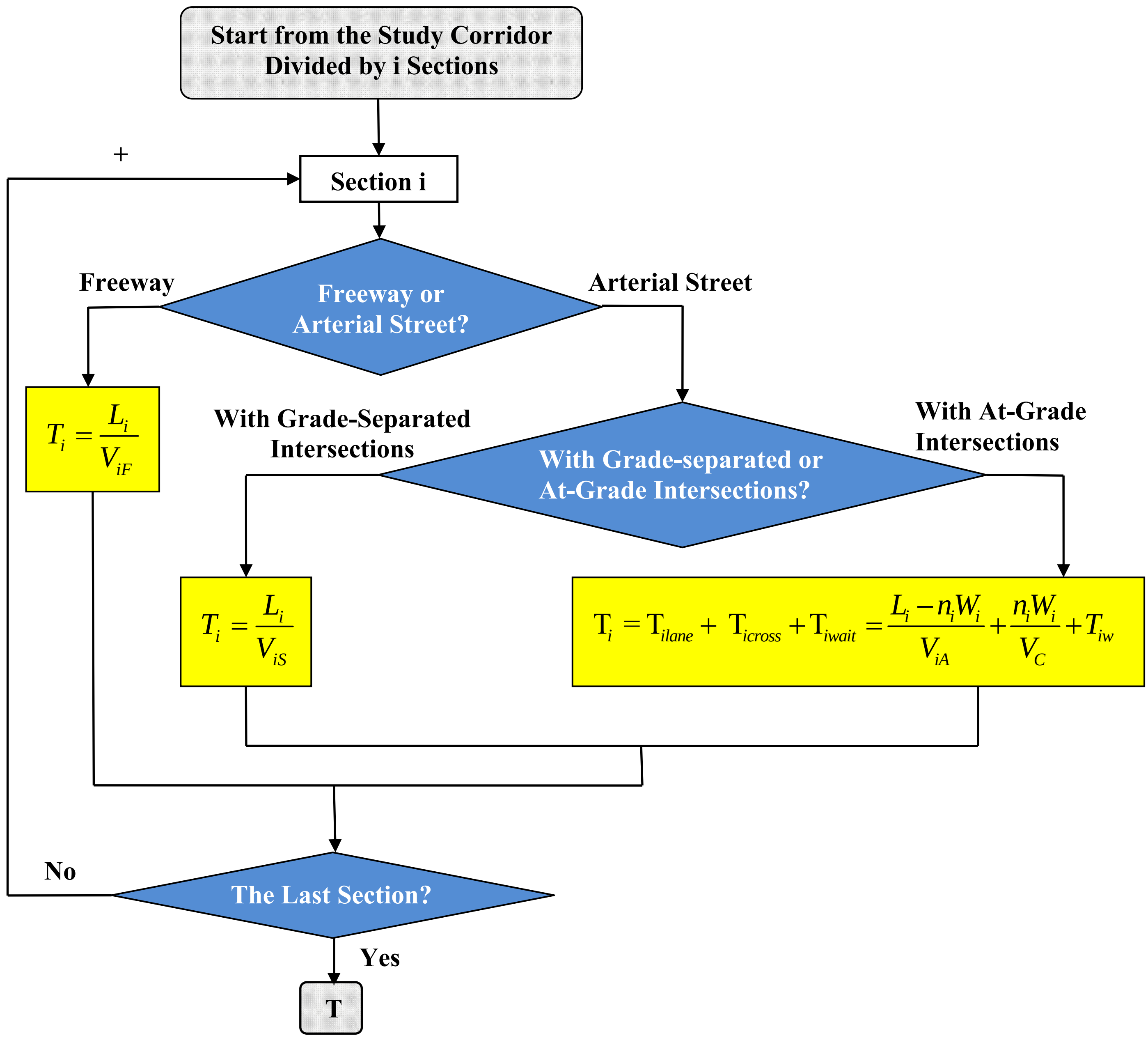


Figure 3. Travel Time Estimation



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 2).

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. The traffic control delay at the intersections was determined (in Table 4) by employing the LOS method from the Highway Capacity Manual (see Table 3).

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 2. 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 3. 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 4. 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)

2.2. 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).

The research team evaluated travel reliability by incorporating the concepts of Reliability Index and Travel Time Index, which indicates 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 3: SAFETY

3.1. CRASH RATES

Crash Rate is measured as the expected number of crashes per year for a certain corridor. The research team 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.

3.1.1. 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.

3.1.1.1. 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 5)

Table 5. 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)

3.1.1.2. Intersections

The expected crashes rates at the intersections are:

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

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;

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

a, b, c: Regression coefficients. (Refer to Table 6)

Table 6. 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, we set the crash rates for three-lane roadways and intersections 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.

3.1.1.3. 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);

3.1.2. 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.

3.1.2.1. Roadways

- **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 7 and 8 respectively.

Table 7. 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 8. 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.

- **Adjustment for Shoulder Characteristics (CMF_{rs})**

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 9. The CMFs for shoulder type are listed in Table 10.

Table 9. 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 10. 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.

- **Median Width**

The most important 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 11.

Table 11. 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)

3.1.2.2. Intersections

- **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 12.

Table 12.Crash Modification Factors for Installation of Left-turn Lanes on the Major Road Approaches to Intersection

<table>
<tr><th rowspan="2">Roadway Type</th><th rowspan="2">Intersection Type</th><th rowspan="2">Intersection Traffic Control</th><th colspan="4">Number of Approaches with Left-Turn Lane</th></tr>
<tr><th>One Approach</th><th>Two Approaches</th><th>Three Approaches</th><th>Four Approaches</th></tr>
<tr><td rowspan="3">Two-Lane, Two-Way Section</td><td>Tree-leg Intersection</td><td>Minor road stop control</td><td>0.56</td><td>0.31</td><td>--</td><td>--</td></tr>
<tr><td rowspan="2">Four-leg Intersection</td><td>Minor road stop control</td><td>0.72</td><td>0.52</td><td>--</td><td>--</td></tr>
<tr><td>Traffic Signal</td><td>0.82</td><td>0.67</td><td>0.55</td><td>0.45</td></tr>
<tr><td rowspan="2">Four-Lane, Two-Way Section</td><td>Tree-leg Intersection</td><td>Minor road stop control</td><td>0.56</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>Four-leg Intersection</td><td>Minor road stop control</td><td>0.72</td><td>0.52</td><td>--</td><td>--</td></tr>
</table>

(Source: Highway Safety Manual, AASHTO, 2010)

- **Adjustment for Right-Turn Lanes**

CMFs for total intersection-related right-turn lanes are found in Table 13.

Table 13. Crash Modification Factors for Installation of Right-turn Lanes on the Major Road Approaches to Intersection

<table>
<tr><th rowspan="2">Roadway Type</th><th rowspan="2">Intersection Type</th><th rowspan="2">Intersection Traffic Control</th><th colspan="4">Number of Approaches with Right-Turn Lane</th></tr>
<tr><th>One Approach</th><th>Two Approaches</th><th>Three Approaches</th><th>Four Approaches</th></tr>
<tr><td rowspan="3">Two-Lane, Two-Way Section</td><td>Tree-leg Intersection</td><td>Minor road stop control</td><td>0.86</td><td>0.74</td><td>--</td><td>--</td></tr>
<tr><td rowspan="2">Four-leg Intersection</td><td>Minor road stop control</td><td>0.86</td><td>0.74</td><td>--</td><td>--</td></tr>
<tr><td>Traffic Signal</td><td>0.96</td><td>0.92</td><td>0.88</td><td>0.85</td></tr>
<tr><td rowspan="2">Four-Lane, Two-Way Section</td><td>Tree-leg Intersection</td><td>Minor road stop control</td><td>0.86</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>Four-leg Intersection</td><td>Minor road stop control</td><td>0.86</td><td>0.74</td><td>--</td><td>--</td></tr>
</table>

(Source: Highway Safety Manual, AASHTO, 2010)

3.1.2.3. 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 rates along section i (crashes/yr);

L_i: Length of section i (mile);

3.2. CRASH SEVERITY

The research team considered severe crashes as crashes that involve fatalities and/or injuries. The rate of severe crashes can be measured in two ways. The first method uses 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 14 and 15. To estimate severe crash rates, the total crash rate coefficients in equations presented in Section 2.1.1 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 16 summarizes the CMFs resulting from adding left-turn and right-turn lanes at intersections on four-lane, two-way corridors.

Table 14. 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 15. 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 16. 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 4: SOCIO-ECONOMIC IMPACT

4.1. 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 research team applied 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) 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:

$$ED_j = \sum_K E_K T_{jk}^{-1}$$

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 team calculated the base-case effective density (ED) 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.

$$WB = \sum_j [(\frac{\Delta ED_j}{ED_j} \times ElP) \times GDP_j \times E_j]$$

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.

4.2. LIVABILITY

Livability is a socioeconomic indicator that includes a variety of factors that should be considered in analyzing the effectiveness of highway corridor improvements. The research team combined qualitative and quantitative methods 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.

4.2.1. LAND-USE SCORES

The team's land-use scores measure the extent to which 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.

The research team developed an online survey 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 17.

Table 17. 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

4.2.2. 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 18.

Table 18. 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

4.3. 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 4 illustrates the steps for evaluating noise impact.

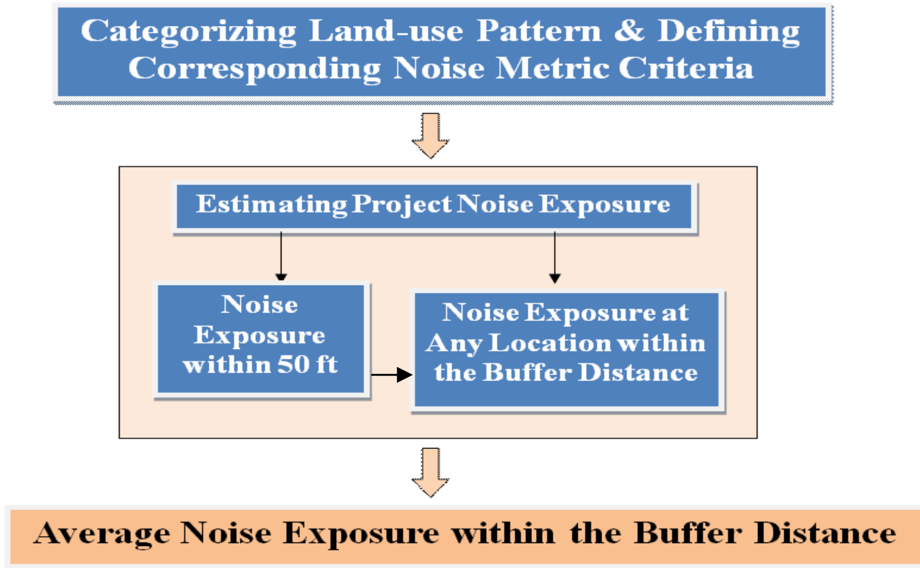


Figure 4. Measuring Noise Impact

4.3.1. LAND USE TYPES AND METRICS FOR TRAFFIC NOISE IMPACT ANALYSIS

The noise metrics used vary by different types of land-use. The research team categorized land-use into three major types, which are described in Table 19 along with the corresponding metrics used for noise impact analysis.

Table 19. 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.

4.3.2. PROJECT NOISE ESTIMATION

3.3.2.1. Project Noise Impact at 50 ft

The research team measured noise impact on different land-use types at the distance of 50 feet 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 noise exposure at 50 feet with the definition as: $SEL = 10\log_{10}\left[\text{Total sound energy during the event}\right]$. The Federal Highway Administration (FHWA) categorized the default value for SEL as Table 20 shows.

Table 20. 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-axle 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).

4.3.2.2. 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 L_{dn} and L_{eq} can be obtained from L_{dn} and L_{eq} at 50 feet developed above, by using the following equation:

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

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.

4.3.3. 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:

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

4.4. 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 21. 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 5: 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 5 and 6.

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 5 shows the 1/4 mile buffer for the general purpose lane improvement and Figure 6 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 5. Impact Area of US 15 General Purpose Lane Improvement

(1/4 mile buffer from roadway centerline)

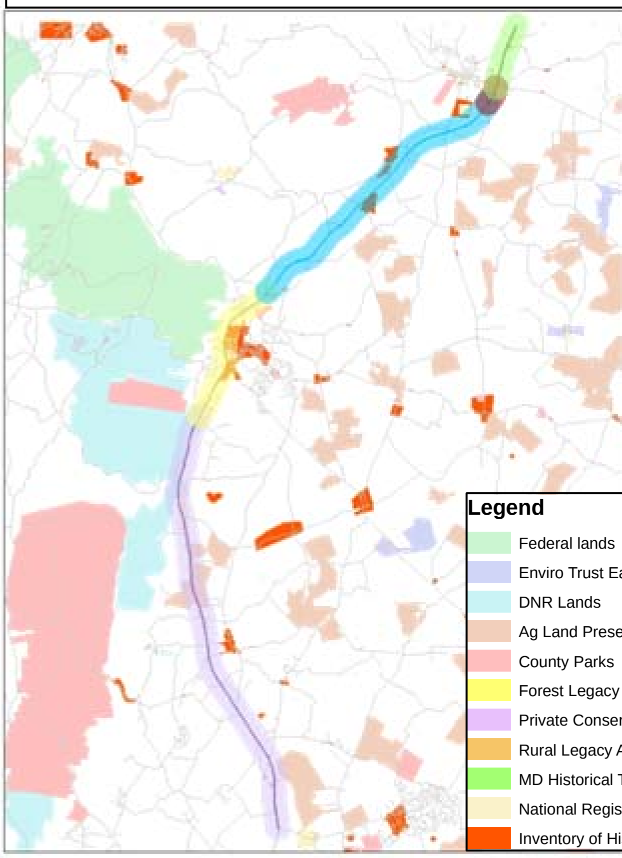
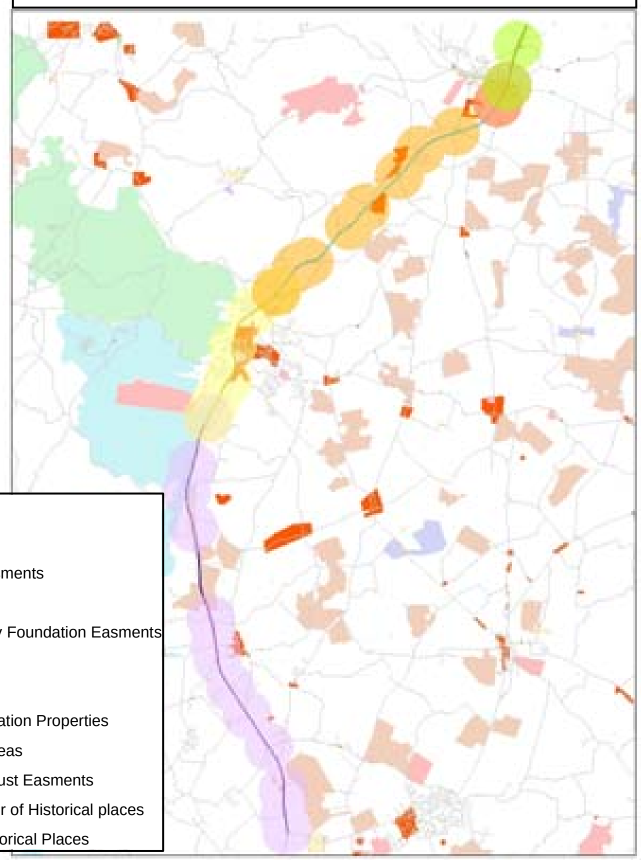


Figure 6. Impact Area of US 15 Grade-Separated Interchanges Improvement

(1/2 mile buffer from intersections)

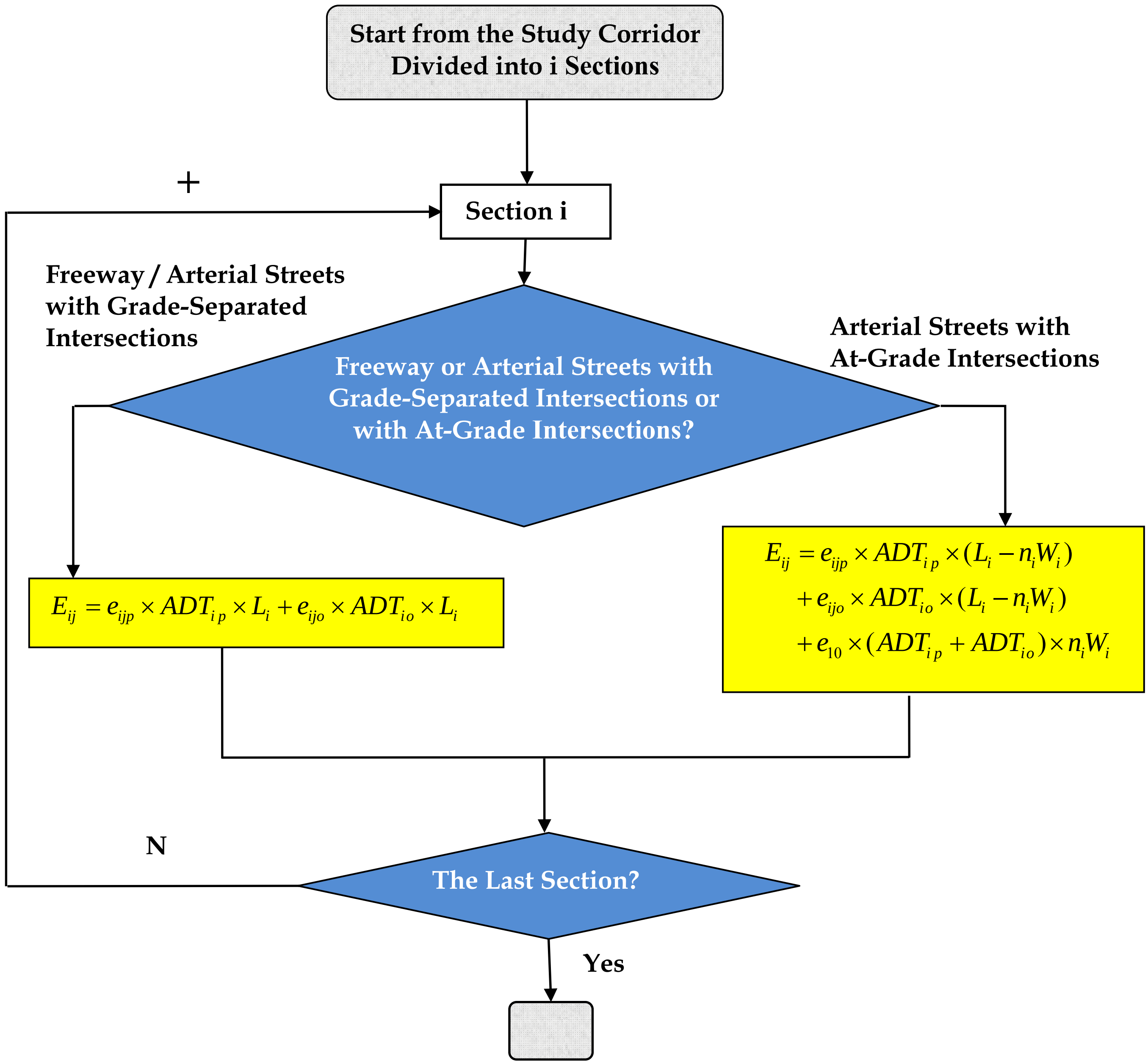


CHAPTER 6: ENERGY AND EMISSIONS

6.1. 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 22). The flowchart of the pollution emission estimation module is provided in Figure 7.

Figure 7. 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 22. 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

6.2. 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 23).

Table 23. 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

6.3. FUEL CONSUMPTION

The research team evaluated fuel consumption 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 24) at the appropriate point. Other inputs for fuel consumption estimation are ADT, section lengths, and lane widths.

Table 24. 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 7: 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 based on the SHA project database were combined with the cost estimates in the guidelines for contractors to produce cost estimates in MOSAIC (see Table 25).

Table 25. 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 8: MOSAIC OUTPUT

8.1. 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 26 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.

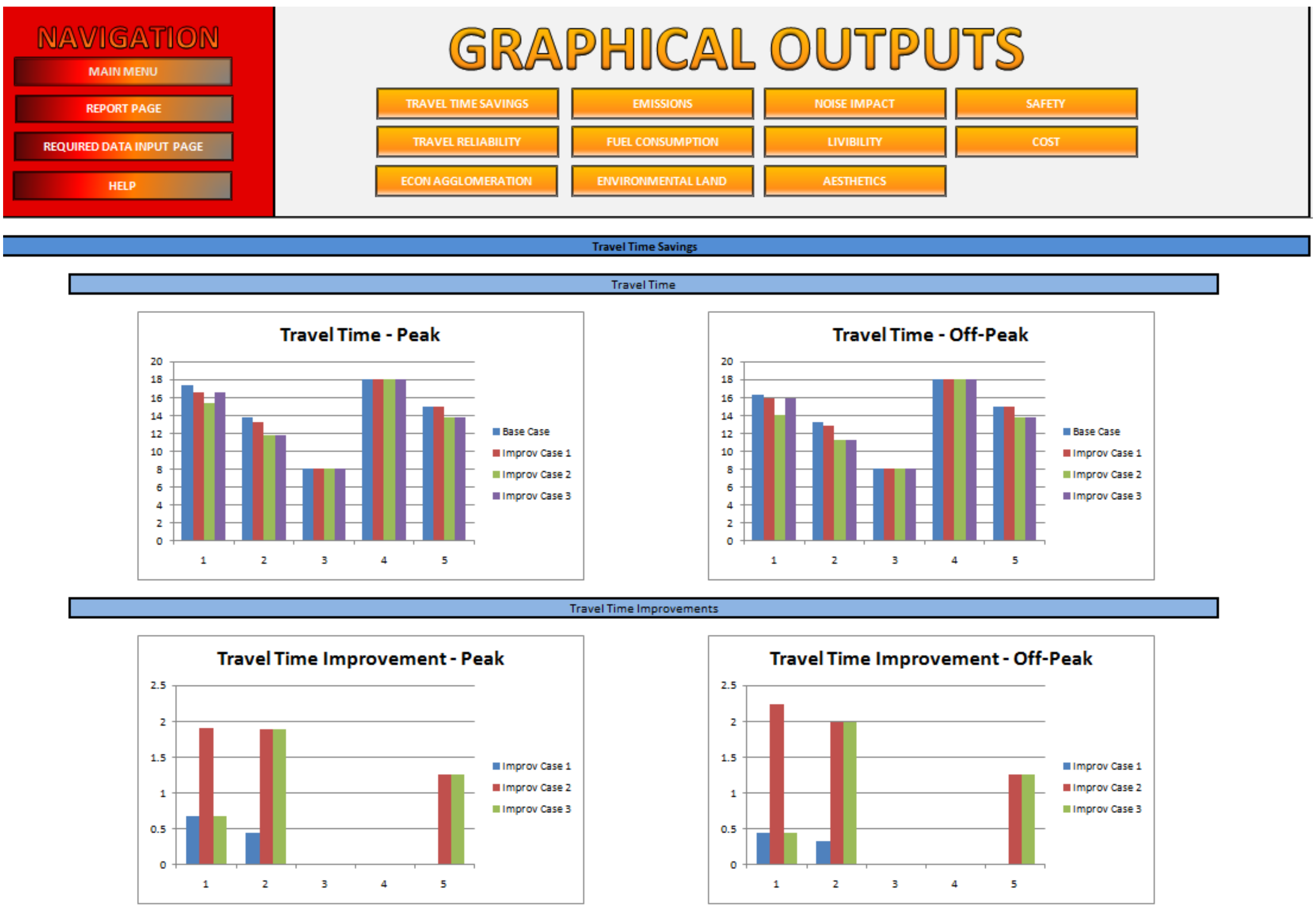
Table 26. MOSAIC Output Database

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

8.2. 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 8). 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 8. MOSAIC Graphical Output View

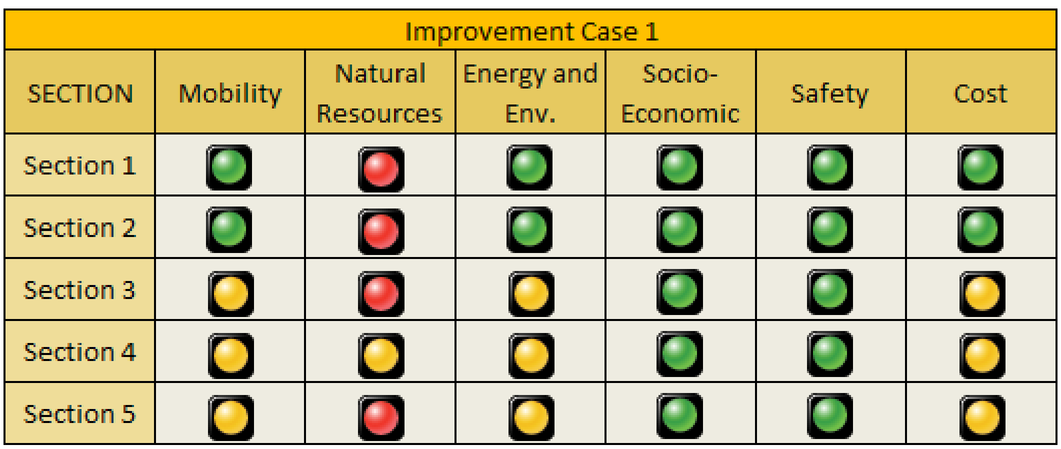


8.3. FINAL SUMMARY

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.

8.3.1 SECTION LEVEL SUMMARY OUTPUT

Figure 9. MOSAIC Section-Level Summary Output



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.

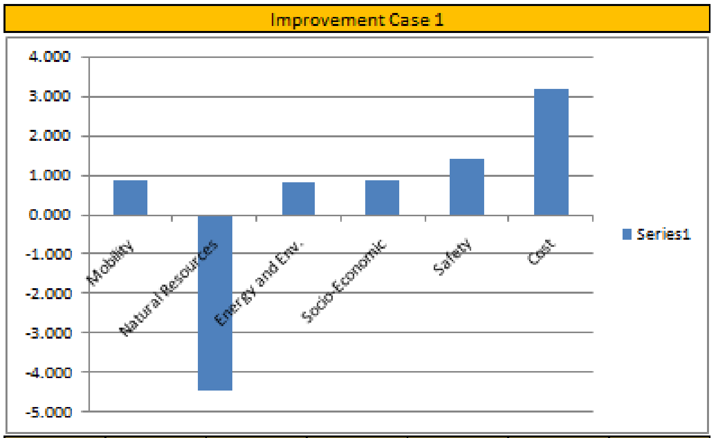
Table 27. Computation and Normalization of Impact Scores

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

8.3.2 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 10 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 10. 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

8.3.3 FINAL CORRIDOR SCORES AND WEIGHTING SYSTEM

Figure 11. MOSAIC Final Improvement Case Scores

Improvement Case 1	
Final Score	0.458

Improvement Case 2	
Final Score	2.317

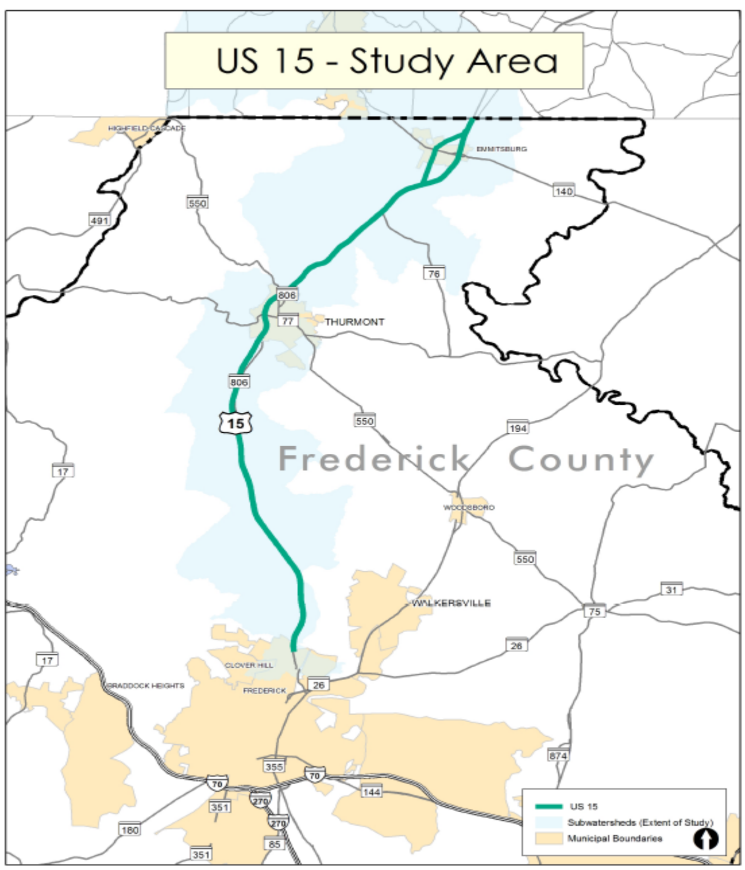
MOSAIC provides a final score for each improvement case, which is determined as the weighted average of the six impact scores for the six impact categories. By default, the weights for each impact category are equal. However, MOSAIC provides an option for users to define the weights of these indicators. 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 12. MOSAIC Impact Score Weighting System

CHAPTER 9: US 15 CORRIDOR CASE STUDY

In Maryland, US 15 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 where it is two lanes. The US 15 Highway classified as a Urban Freeway/Expressway along its concurrency with US 340 and through Frederick, where the highway meets US 40 and Interstate 70 (I-70). US 15 south of US 340 and north of Frederick is classified as a Rural Other Principal Arterial. The segment of US 15 from Biggs Ford Road to PA-MD border line was

Figure 13. US 15 Study Area

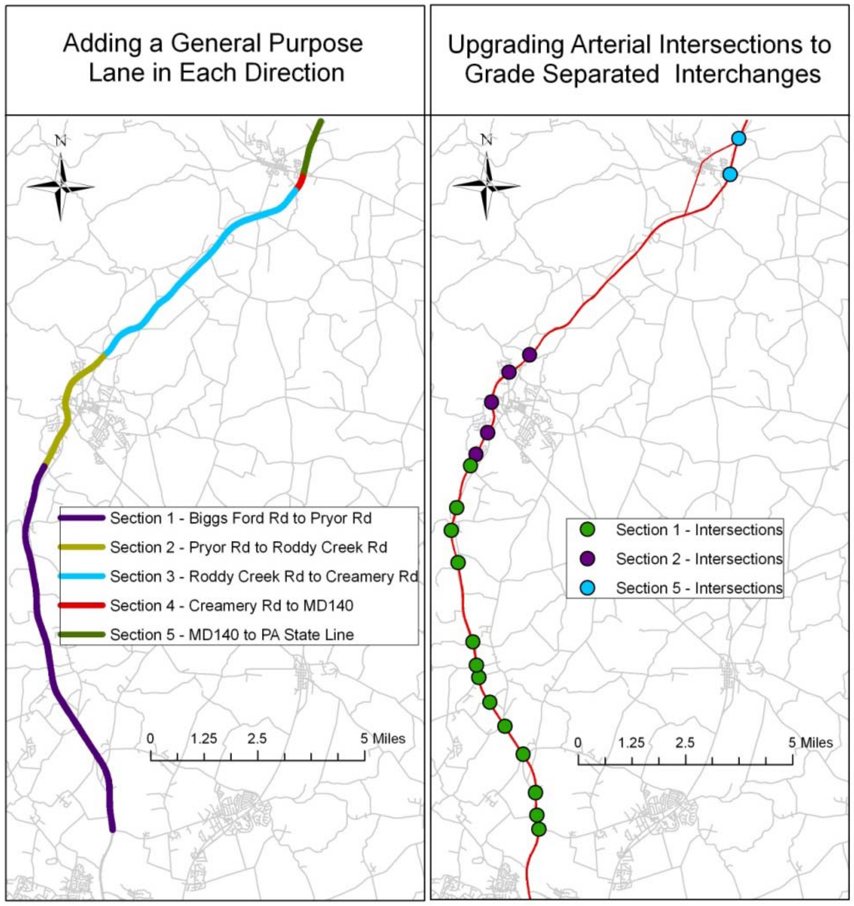


selected as the candidate corridor for case study, which is shown in Figure 13.

The study area was divided into five sections based on traffic volume characteristics according to SHA's short-term comprehensive highway corridor planning study. Section 1, Biggs Ford Road to Pryor Road, is a 7-mile rural arterial with seven intersections and four lanes in each direction; Section 2, Pryor Road to Roddy Creek Road, is also a 6-mile rural arterial with four lanes each way and six intersections; Sections 3, Roddy Creek Road to Creamery Road, and 4, Creamery Road to MD 140 are rural freeways with two interchanges each respectively measuring 8 miles and 18 miles long; Section 5, MD 140 to Pennsylvania state line, is an 8-mile rural freeway with seven intersections and four lanes each way. Section 1 was classified as severe congested segment according to the category of travel speed of arterial streets, while section 2 was medium congested segment in the base condition, leaving the rest of the sections as uncongested segments. Various types of ecological or historical areas exist within the study buffer distance along the corridor mainly in seven categories: cultural/historical sites, steep slopes, highly erodible soils, wetland, forests, springs/steeps, and natural species, which will be impacted by the traffic condition and roadway's configurations of the corridor.

Two improvement plans, shown below in Figure 14, 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 14. US 15 Improvement Plans and Segmentation



9.1 CASE STUDY INPUTS

The required input data for each section along the selected US 15 corridor is presented in Table 28. 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 29.

Table 28. 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	ADT on Minor Streets	12000	12000	12000	12000	12000

INTERSECTION DATA	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 29. 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

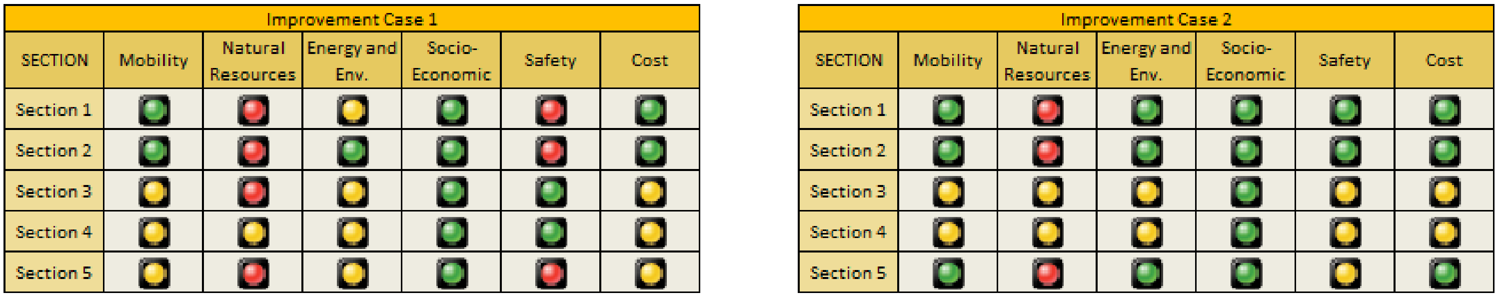
9.2 CASE STUDY FINDINGS

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.

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 15 and 16). 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.

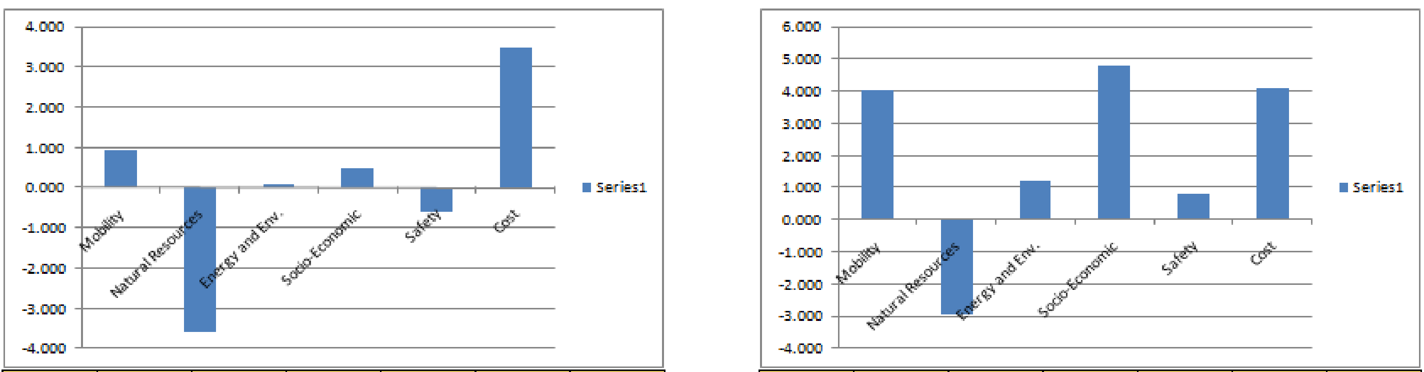
Results from the section-by-section analysis show that improvement plan 2, upgrading intersections to grade-separated interchanges, has fewer negative and more positive impacts on sustainability indicators related to mobility and cost in Section 5; energy, and pollution/GHG emissions in sections 1 and 5; and on safety in sections 1, 2, and 5, compared to adding improvement case 1, adding one general purpose travel lane in each direction. For sections 3 and 4, where improvement plan 1 adds general purpose lanes, the analysis shows minor improvement to safety versus a large negative impact on natural resources, making improvement plan 2 a better option.

Figure 15. 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 16. 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

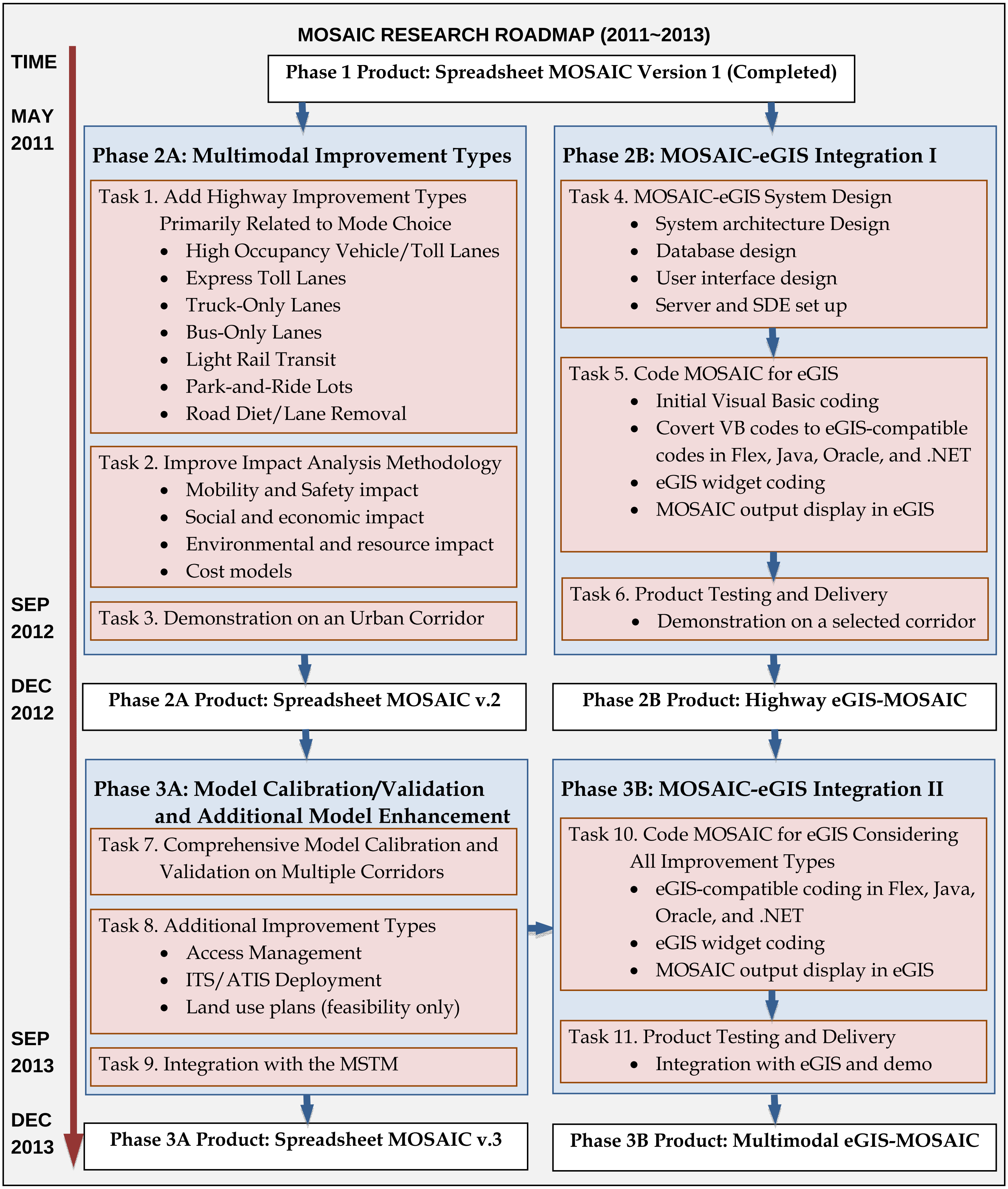
Note: Unweighted scores for each indicator are scaled on a range of -10 to +10, where -10 represents a 100% deterioration and +10 represents a 100% improvement over the do-nothing scenario.

CHAPTER 10: MOSAIC RESEARCH ROADMAP

The final chapter of the project report presents a research roadmap for further developing MOSAIC into a GIS-based tool that can be fully integrated into the SHA eGIS (Enterprise Geographical Information System). 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. Individual research tasks, as well as their interdependencies, are identified in this roadmap. Although the current MOSAIC tool is already fully functional, future phases of this research project will complete the research tasks outlined in this research roadmap and deliver an eGIS-based MOSAIC tool that considers multimodal highway improvement options and has been comprehensively tested and validated.

The UMD research team, the SHA technical liaisons, and the SHA advisory committee members for this project share a common vision for MOSAIC: That it will become a flagship application of the SHA CHC Program and Sustainability Initiatives that not only assists SHA in multimodal highway corridor improvement decision-making but also demonstrates SHA's commitment to incorporating social, economic, environmental, and sustainability considerations in its transportation planning process.

Figure 17. MOSAIC Research Roadmap



REFERENCES

AASHTO, Highway Safety Manual, 2010;

Alaska Department Of Natural Resources, Division Of Oil And Gas [Online], Nenana Basin exploration licence, Department of Natural Resources, 2002; www.dog.dnr.state.ak.us/oil/products/publications/nenana/nenana_TOC.html,

Bellomo-McGee Inc., Midwest Research Institute, Highway Safety Manual, Two-Lane Highways, NCHRP Project 17-18(4), February 2003;

Ciccone, A. and Hall, R.E.. Productivity and the Density of Economic Activity, The American Economic Rveiw, Vol. 86, No. 1, pp 54-70, Mar., 1996;

Dane Westerdahl, Lead Investigator of California Air Resources Board, and Costantinos Sioutas, Lead investigator of Los Angeles PM Center/Supersite, Take a Supersite on the Road: monitoring particulate matter in community air, 2010;

David G. Penney, Ph.D., Professor of Physiology, Wayne State University School of Medicine, Detroit, MI, and Director of Surgical Research, Providence Hospital, Southfield, MI, Co Exposures And Scale Of Effects From Zero To One Million Parts Per Million, Carbon Monoxide (Co) Headquarters, 2002;

David Schrank, Tim Lomax, The 2007 Urban Mobility Report, Texas Transportation Institute, The Texas A&M University System, September 2007; http://mobility.tamu.edu;

Department of Transport. Transport, Wider Economic Benefits, and Impact on GDP. Discussion Paper. July, 2005;

Federal Highway Administration, GIS- based crash referencing & analysis system, Highway Safety Information System, North Carolina Center for Geographic Information, North Carolina DOT, University of North Carolina Highway Safety Research Center (UNC-HSRC), No. FHWA-RD-99-081, February 1999;

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

Girouard, P., M.E. Walsh, and D.A. Becker, BIOCOST-Canada: a new tool to evaluate the economic, energy, and carbon budgets of perennial energy crops. In Proceedings of the Fourth Biomass Conference of the Americas, Pp. 85-90., Elsevier Science, Ltd., Oxford, UK, 1999;

Guang qing Chi and Brian Stone Jr., Sustainable Transport Planning: Estimating the Ecological Footprint of Vehicle Travel in Future Years, Journal of Urban Planning and Development, Vol. 131, No.3, ©ASCE, ISSN 0733-9488/2005/3-170–180, 2005;

Highway Research Program, Performance Measurement Framework for Highway Capacity Decision Making Strategic, SHRP 2 Report S2-C02-RR, 2009;

IHSDM, Crash Prediction Module Engineer's Manual, USA, 2004;

James M. Witkowski, Benefit Analysis for Urban Grade Separated Interchanges, ASCE, Journal of Transportation Engineering, Vol. 114, No.1, January, 1988;

James R. Schutt, Kimberly L. Phillips and Harlow C. Landphair, Guidelines For Aesthetic Design In Highway Corridors: Tools And Treatments For Texas Highways, Texas Transportation Institute, The Texas A&M University System, 2001;

J. Bonneson and D. Lord, Role and Application of Accident Modification Factors in the Highway buy Design Process, Texas Transportation Institute, The Texas A&M University System, 2005;

J. Bonneson, K. Zimmerman, and K. Fitzpatrick, Interim Roadway Safety Design Workbook, May 2005; http://tti.tamu.edu/documents/0-4703-P4.pdf

J. Bonneson and K. Zimmerman, Procedure For Using Accident Modification Factors In The Highway Design Process, Texas Transportation Institute , 2007;

Joshua h. Schmidt1, Mark s. Lindberg, devin s. Johnson, and joel A. Schmutz, Environmental And Human Influences On Trumpeter Swan Habitat Occupancy In Alaska, Department of Biology and Wildlife and Institute of Arctic Biology, University of Alaska, National Marine Mammal Laboratory, Alaska Fisheries Science Center, NOAA, Seattle, U.S. Geological Survey, Alaska Science Center, AK, 2009;

K. Max Zhang, Oliver Gao, Cornell University, Development of Advanced Modeling Tools for Hotpot Analysis of Transportation Emissions, UTC Center Report, 2009;

Lardner/Klein Landscape Architects, P.C. in Association with Oldham Historic Properties, Inc, Context Sensitive Solutions for the Maryland Historic National Road Scenic Byway, The Maryland State Highway Administration, Feb 2006;

Lena, T. S., V. Ochieng, M. Carter, J. Holguín-Veras, and P. L. Kinney. Elemental Carbon and $PM_{2.5}$ Levels in an Urban Community Heavily Impacted by Truck Traffic. *Environmental Health Perspectives*, Vol. 110, pp. 1009-1015, 2002;

Maged Hamed, Waleed Effat, A GIS-based approach for the screening assessment of noise and vibration impacts from transit projects, Journal of Environmental Management 84, 305–313, 2007;

Mark A. Marek, P.E., Landscape and Aesthetics Design Manual, TxDOT online Manual System, 2009;

Maryland Department of Transportation, Maryland Transit Administration, Purple Line alternatives analysis, September 2008;

McCarthy Hyder Consultants N22 Baile Bhuirne - Macroom (Baile Bhuirne to Coolcour) Environmental Impact Statement , financed by the Irish Government under the National Development Plan (NDP) 2007 - 2013 and part financed by the European Union, Oco 2009;

M. Dietz, D. Ebersbach, Ch. Lippold (TUD), K. Mallschutzke (INECO), G. Gatti (POLOBA), A. Wieczynski (PIAP), Road Safety Performance Function, 2005;

Richard T. T. Forman and Lauren E. Alexander, Roads And Their Major Ecological Effects, Harvard University Graduate School of Design, Cambridge, Massachusetts 02138, Annu. Rev. Ecol. Syst. 29:207–31, 1998;

Ron Pfefer, Chair, TRB Task Force for the Development of a Highway Safety Manual, Road Safet Analysis Methods and Procedures, 2004;

Skatteudvalg, T., Modtaget via elektronisk Post. Der Tages forbehold for evt. fejl , July 11, 2002;

State Highway Administration (SHA), Highway Development Project Information, 2010; http://apps.roads.maryland.gov/WebProjectLifeCycle/ProjectHome.asp

State Highway Administration, Maryland Department of Transportation, Highway Construction Cost Estimating Manual, 2009;

Statistics Canada., Energy supply and demand, July 11, 2002;

Tara Ramani, Josias Zietsman, William Eisele, Duane Rosa, Debbie Spillane and Brian Bochner, Developing Sustainable Transportation Performance Measures For TxDOT's Strategic Plan: Technical Report, Texas Transportation Institute The Texas A&M University System, October 2008;

Transportation Research Board, Impact of Shoulder Width and Median Width on Safety, National Cooperative Highway Research Program, Report 633, 2009;

Trinh Pham, David Ragland, Summary of Crash Prediction Models Also known as Safety Performance Functions (SPFs), December 2005;

Wada, Y., Biophysical productivity data for ecological footprint analysis, UBC Task Force on Healthy and Sustainable Communities, 1994.