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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

COMPREHENSIVE HIGHWAY CORRIDOR PLANNING WITH SUSTAINABILITY INDICATORS

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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.

Phase One of the project focused on defining a comprehensive set of sustainability indicators that could be quantitatively evaluated for major geometric improvement options, such as: adding general purpose lanes and converting at grade intersections to grade separated interchanges. Phase Two of the project focused on extending this quantitative evaluation of sustainability indicators to additional multimodal corridor improvement options, including high occupancy vehicle (HOV) lane, high occupancy toll (HOT) lane, bus rapid transit/bus-only lane, light rail transit, truck-only lane, express toll lane, and road diet (i.e. lane removal).

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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 need analysis and long-range planning processes to select the best program-level plans for the corridor. SHA funded a research project titled "Comprehensive Highway Corridor Planning with Sustainability Indicators" to support the CHC and Sustainability Initiatives and 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 analysis tools for integrating safety, mobility, environmental stewardship, and socio-economic objectives into SHA's corridor planning process with consideration for multimodal corridor improvement options.

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. MOSAIC considers the no-build and ten additional multimodal corridor improvement options, including adding general purpose lanes, upgrading at-grade intersections to grade-separated interchanges, road diet (i.e. lane removal), high occupancy

vehicle (HOV) lane, high occupancy toll (HOT) lane, bus rapid transit/bus-only lane, light rail transit, truck-only lane and express toll lane.

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

After completing the model development, MOSAIC was applied to the US 29 corridor within Maryland, 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 several improvement options would be effective in enhancing sustainability throughout the US 29 corridor.

The current version of MOSAIC runs using a Microsoft Excel spreadsheet and includes: (1) a user input module where users can select a corridor and the 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 share a common vision: that MOSAIC will become a flagship application of the SHA CHC Program by assisting SHA in multimodal highway corridor improvement decision-making and by demonstrating SHA’s commitment to incorporating social, economic, environmental, and sustainability considerations in its transportation planning process.

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CHAPTER 1: INTRODUCTION

The SHA is committed to integrating safety, mobility, environmental stewardship, and socio-economic objectives into 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, natural resource impact, pollution and green house gas emissions, socio-economics and cost. When implemented during the highway needs assessment and long-range planning stages, MOSAIC can help SHA identify the corridor improvement option that best balances these sustainability indicators. Also, it avoids options with major negative environmental impacts that often lead to costly and lengthy environmental screening and mitigation procedures. MOSAIC is 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; instead, MOSAIC integrates sustainability objectives before the selection of an improvement type. Furthermore, it 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 that include problem identification, 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 affected communities and interested stakeholders may also be involved in each corridor-planning step. This is essential because the greatest benefits and the most streamlined process of transportation corridor improvements are obtained when the relevant agencies and stakeholders are involved early in the planning process. Also, the environmental impact mitigation needs to be provided in a proactive and systematic fashion, the multiple corridor projects need to be considered at the program level (instead of on a project-by-project basis), and decisions need to be 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. Phase Two of the project focused on comparing the sustainability impact of both the no-build case and ten additional multimodal corridor improvement options, including adding general purpose lanes, upgrading at-grade intersections to grade-separated interchanges, road diet (i.e. lane removal), high occupancy vehicle (HOV) lane, high occupancy toll (HOT) lane, bus rapid transit/bus-only lane, light rail transit, truck-only lane, and express toll lane.

After an extensive review of the literature and best practices, along with 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 new mode choice models developed in phase two of the MOSAIC project that are necessary for multimodal corridor planning; 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 multimodal MOSAIC to the US 29 corridor between the DC-Maryland border (just south of I-495) and I-70; and finally, Chapter 11 provides a research roadmap to present planned future development of the MOSAIC tool, as well as its integration with the SHA enterprise GIS system for enhanced user friendliness.

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 CO_2 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: PIVOT-POINT MODE CHOICE MODEL

MOSAIC first applies the pivot-point and the enhanced incremental mode choice models in order to analyze the planning-level sustainability impact (i.e. mobility, safety, natural resources, socio-economic factors, cost, and energy and environment) of multimodal improvements on highway corridors, relevant to the SHA's Comprehensive Highway Corridors program. MOSAIC uses these models to generate an updated mode share and ridership to help evaluate improvement options that would produce changes in mode choice. For instance, the model would assist in deciding whether to build light rail transit (LRT) or convert an existing general purpose lane to a high occupancy vehicle (HOV) lane, high occupancy toll (HOT) lane, or bus only lane.

The pivot-point or incremental formulation mode choice model is able to generate the new mode shares in for future years under multiple improvement alternatives. This is done by modifying the existing mode shares based on changes in the characteristics of the transportation networks. While the multinomial mode-choice model requires complete characteristics of the specific transportation system, the pivot-point model only needs the current mode share and the proposed changes of the Level of Service (LOS) variables for each alternative.

2.1. INITIAL PIVOT-POINT MODEL

The initial version of the pivot-point mode choice model is often used for the evaluation of Travel Demand Management (TDM) strategies aimed at reducing vehicle travel during peak periods without introducing any new modes. Early applications include 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 mentioned above, the pivot-point model formulation is 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 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 for LOS variables that MOSAIC uses were obtained from the Home-Based-Work (HBW) mode-choice model specific for Washington, D.C., area provided by the NCHRP report 365, which are -0.017 for $\Delta IVTT_i$, -0.058 for $\Delta OVTT_i$, and -0.004 for $\Delta COST_i$.

2.2. INCREMENTAL LOGIT MODEL

The extended version of the incremental logit model, unlike of the previous version of the pivot-point model, can be used when introducing a new transit service. The extended incremental logit model provides the capability to predict the ridership impact of transit introduction or service changes using only information on existing mode shares and changes in transit service.

The new transit service is expected to attract some riders from the existing transit service and some from other modes. We expect the combined transit services to carry more riders than the existing service. The degree to which the combined transit services will carry more riders than either service alone depends, in part, on the utility between the new and existing services.

The incremental logit equations to predict the proportion of riders using new transit and existing transit, for the case where there are no changes in any of the non-transit modes, are:

$$P'_{NT} = \frac{P_{XT} \times e^{(U'_{NT} - U_{XT})}}{P_{XT} \times [e^{(U'_{NT} - U_{XT})} + e^{(U'_{XT} - U_{XT})}] + [1 - P_{XT}]}$$

$$P'_{XT} = \frac{P_{XT} \times e^{(U'_{XT} - U_{XT})}}{P_{XT} \times [e^{(U'_{NT} - U_{XT})} + e^{(U'_{XT} - U_{XT})}] + [1 - P_{XT}]}$$

Where:

P'_{NT} (P'_{XT}): The expected probability of riders using new and existing transit services, respectively;

P_{XT} : The baseline probability of riders using existing transit services;

U'_{NT} (U'_{XT}): The expected utility measure of new and existing transit services, respectively;

U_{XT} : The baseline utility measure of existing transit services

The following equations can be applied to predict future ridership on each transit mode. This is based on knowledge of the existing transit share, the difference in service provided by the new transit service compared to the existing transit service, and changes in the existing transit service.

The share for other modes is given by:

$$P_i' = \frac{P_i}{P_{XT} \times [e^{(U'_{NT} - U_{XT})} + e^{(U'_{XT} - U_{XT})}] + [1 - P_{XT}]}$$
$$= P_i \times \frac{1 - P_T'}{1 - P_T}$$

Where:

P_i' (P_i) = The probability of riders using other mode i after (before) the transit improvement, respectively;

P_T' (P_T) = The probability of riders using transit after (before) the transit improvement, respectively.

For the specification of the parameters in the transit service function, the incremental prediction models described above can apply the parameter values listed in the following table. Such parameter estimates are generally based on the estimation of disaggregate models.

Table 2. Estimated Level of Service Coefficients for Work Trips

Study area (1)	Parameter Estimates: Out-of-vehicle time, in minutes (2)	In-vehicle time, in minutes (3)	Out-of-pocket costs, in cents (4)	Source reference (5)
San Francisco Bay Area	−0.0343[a]	−0.0224	−0.413/wage[b]	Small (20)
Washington, D.C.	−0.160/DIST[c]	−0.0154	−28.8/income[d]	Atherton, et al. (2)
New Bedford, Mass.	−0.101/DIST[c]	−0.0199	−87.3/income[d]	Atherton and Ben-Akiva (1)
Los Angeles, Calif.	−0.186/DIST[c]	−0.0146	−24.4/income[d]	Atherton and Ben-Akiva (1)
Chicago, Ill.[e]	−0.0201	−0.0082	−0.011	CATS (18)
Chicago, Ill.	−0.040[f]	−0.040[f]	−0.010	Wigner (23)
San Diego, Calif.	−0.0916	−0.0563	−0.0106	PMM (6)
Minneapolis-St. Paul, Minn.	−0.044	−0.031	−0.014	Pratt (4)

c: One way travel distance in miles (multiply parameter by 2.2 for use with kilometers).

d: Annual household income in dollars.

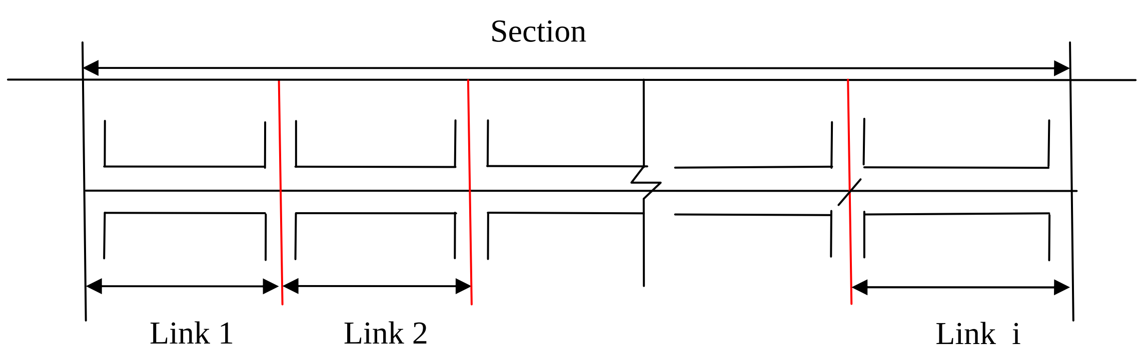
CHAPTER 3: MOBILITY

3.1. TRAVEL TIME SAVINGS

Travel time savings are computed for each improvement scenario by comparing them with the base-case scenario for peak periods. The general steps for the estimation of travel time savings are: (1) dividing the corridor into several sections, (2) calculating the peak-hour travel time for each section, (3) summarizing the total travel time for the whole corridor, and (4) comparing the total travel time for base and improved cases.

The corridor under consideration should first be 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 1). With sections and links defined, the methodology for estimating peak hours' travel time savings can be applied to individual sections in various scenarios. Intersection-level travel time savings are then aggregated to corridor-level estimates.

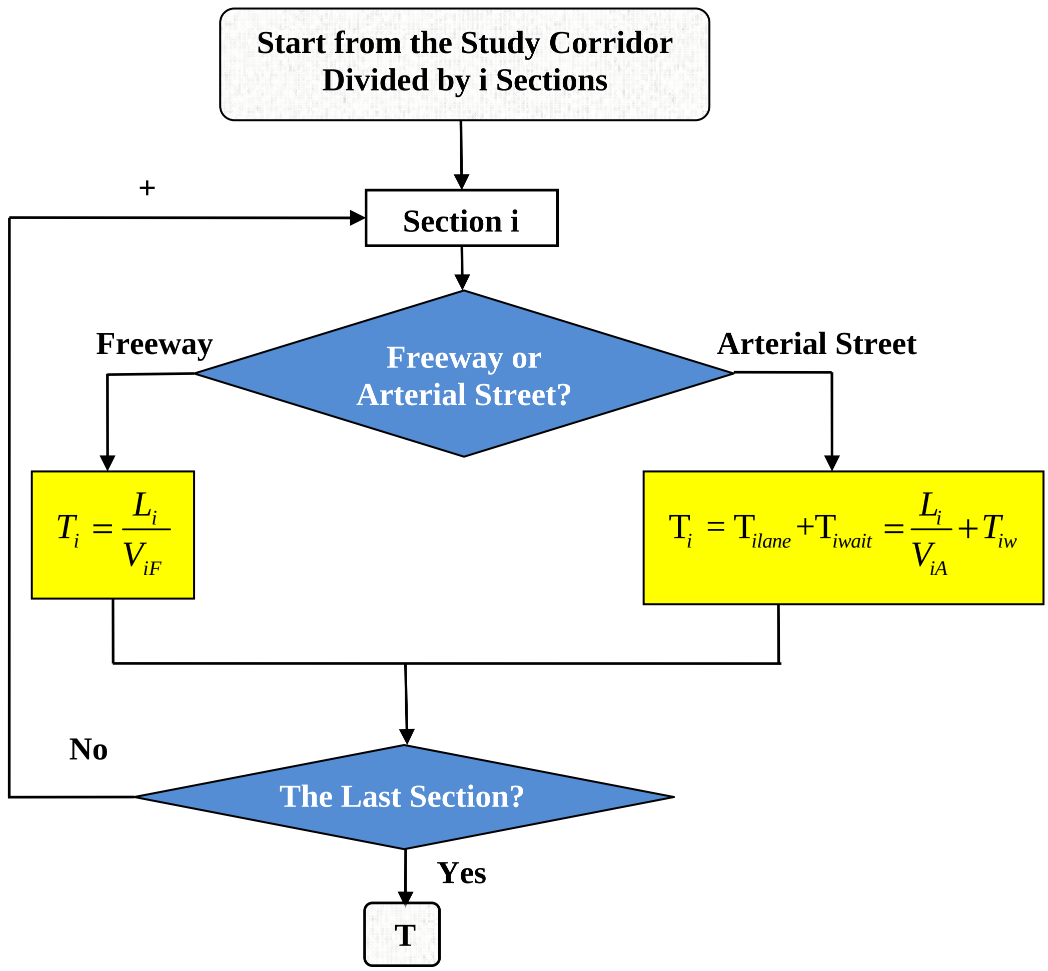
Figure 1. Section and Link Definitions in MOSAIC



3.1.1. TRAVEL TIME FOR GENERAL PURPOSE LANES

To estimate general purpose lanes' speeds during peak periods for both freeway and arterial streets, MOSAIC would follow the flow chart presented in Figure 2.

Figure 2. General Purpose Lane Travel Time Estimation



Notation:

T_{ilane}: Average travel time along the roadway (besides the 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 freeways in section i;

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

L_i : The length of the section i;

n_i : Number of links along section i.

The procedure for estimating freeway and arterial street speeds (V_{iF} and V_{iA}) outlined in the Texas Transportation Institute's Urban Mobility Report (David, 2007) was employed (See Table 3).

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 5).

Table 3. Speed Estimation Based on Daily Traffic Volume per Lane

Facility and Congestion Level	Daily Traffic Volume per Lane	Speed Estimate Equation Peak Speed (mph)
Freeway		
Uncongested	< 15,000	60
Medium	15,001 – 17,500	70-(0.9*ADT/LANE)
Heavy	17,501-20,000	78-(1.4*ADT/LANE)
Severe	20,001-25,000	96-(2.3*ADT/LANE)
Extreme	>25,000	76-(1.46*ADT/LANE)
		Lowest speed is 35 mph
At-grade Arterial Street		
Uncongested	< 5,500	35
Medium	5,501 – 7,000	33.58-(0.74*ADT/LANE)
Heavy	7,001-8,500	33.80-(0.77*ADT/LANE)
Severe	8,501-10,000	31.65-(0.51*ADT/LANE)
Extreme	>10,000	32.57-(0.62*ADT/LANE)
		Lowest speed is 20 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)		

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

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
Medium	15,000-17,500	5,500-7,000	20	15
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)

Table 5. 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)

3.1.2. TRAVEL TIME FOR MANAGED LANES

Three improvement alternatives, High Occupancy Vehicle (HOV) Lanes, High Occupancy Toll (HOT) Lanes and Express Toll Lanes can be categorized as the managed lane improvement types for the travel time saving analysis.

The estimation process of the travel time along HOV is similar to that of the general-purpose lanes as illustrated in Figure 2. As for the proposed AADT per lane in the alternative scenarios, the following functions can be applied in analyzing the process:

$$AADT/lane_{(HOV/HOT)} = \frac{VC_{HOV}/N_{HOV/HOT}}{VC_B/N_B} \times AADT/lane_{(Base)}$$

$$AADT/lane_{(GP)} = \frac{VC_{GP}/N_{GP}}{VC_B/N_B} \times AADT/lane_{(Base)}$$

Notation:

$AADT/lane_{(HOV/HOT)}$: Annual Average Daily Traffic Volume per lane (veh/d/lane) along proposed HOV or HOT lanes;

$AADT/lane_{(GP)}$: Annual Average Daily Traffic Volume per lane (veh/d/lane) along General Purpose (GP) lanes after the proposed improvement;

$AADT/lane_{(Base)}$: Annual Average Daily Traffic Volume per lane (veh/d/lane) in the base case;

$VC_{HOV/HOT}$: Peak-hour vehicle counts along HOV or HOT lanes;

VC_{GP} : Peak-hour vehicle counts along general purpose lanes;

VC_B : Total peak-hour vehicle counts in the base case;

$N_{HOV/HOT}$: Number of proposed HOV or HOT lanes;

N_{GP} : Number of GP lanes after the proposed improvement;

N_B : Total number of lanes in the base case.

The peak-hour vehicle counts can be counted by considering:

$$VC_{HOT} = VC_{NSOV} + VC_{SOV(HOT)}$$

$$VC_{GP} = VC_{SOV(HOV)} + VC_{Truck}$$

Notation:

VC_{NSOV} : Number of carpool vehicles along the section during the peak hours;

$VC_{SOV(HOT)}$: Number of single-occupied vehicles using proposed HOT lane during the peak hours;

$VC_{SOV(HOV)}$: Number of single-occupied vehicles using proposed HOT lane in the corresponding HOV scenario during the peak hours;

VC_{Truck} : Number of trucks along the section during peak hours.

In terms of the number of single-occupied vehicles using a proposed HOT lane, the research team assumes it is equal to the difference between the number of vehicles using a proposed HOT lane and the number of vehicles using a proposed HOV lane in the corresponding HOV scenario during the peak hours. It is presented as:

$$VC_{SOV(HOT)} = VC_{(HOT)} - VC_{(HOV)}$$

All vehicle counts in the proposed scenarios are obtained from the previously introduced pivot-point mode choice models.

3.1.3. TRAVEL TIME FOR BUS/TRUCK ONLY LANES

When building the additional bus-only or truck-only lanes, it is assumed that all buses or trucks will use the new lanes, while other modes will still be using the existing, general-purpose lanes along the roadway.

The corresponding AADT/lane levels are based on the following functions:

$$AADT / lane_{(Bus/Truck)} = \frac{VC_{Bus/Truck} / N_{Bus/Truck}}{VC_B / N_B} \times AADT / lane_{(Base)}$$

$$AADT / lane_{(GP)} = \frac{VC_{GP} / N_{GP}}{VC_B / N_B} \times AADT / lane_{(Base)}$$

Notations:

$AADT / lane_{(Bus/Truck)}$: Annual Average Daily Traffic Volume per lane (veh/d/lane) along proposed bus-only or truck-only lanes;

$VC_{Bus/Truck}$: Peak-hour vehicle counts along bus-only or truck-only lanes;

$N_{Bus/Truck}$: Number of bus-only or truck-only lanes.

3.1.4. TRAVEL TIME FOR LRT

In the LRT scenario, a certain amount of person trips will be attracted to LRT, leaving the remaining person trips on the existing roadway. The exact remaining vehicle counts and the LRT person trips are estimated by applying the extended version of the incremental logit model.

The travel time on the roadway is based on the AADT per lane level deduced from the AADT per lane in the base case. The travel time for the LRT mode is equal to the roadway length divided by the LRT speed. The average LRT speed in our study is 24 miles/hour, in accordance with the Baltimore LRT system.

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:

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

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).

The research team evaluated travel reliability by incorporating Reliability Index and Travel Time Index concepts. These indicate the extent to which the longest travel times (including peak and off-peak) 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):

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

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 2 for travel time estimation. 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.

In terms of the reliability in the LRT scenario, the research team assumes the LRT system has constant speed, and thus should achieve the reliability index as zero in this regard.

CHAPTER 4: SAFETY

4.1. CRASH RATES

Crash Rate is measured as the expected number of crashes per year for a corridor. The research team applied the Safety Performance Function (SPF) method from the most recent FHWA 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 lane widths of 12 feet and a paved shoulder width of 6 feet, with 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 roadways and N_I for 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 5)

Table 6. 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:

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

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 7. 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 FHWA Highway Safety Manual (2010) only provides crash rate estimation procedures for two and four-lane highways, the research team 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.

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 provides multiple CMFs to match various highway conditions.

4.1.2.1. 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 8. 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 9. 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 lanes' 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- lanes and 0.27 for four-lanes) based on the related crash type distributions.

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

The CMFs for shoulder consider both the shoulder width and type. The changes of CMFs with the Shoulder Effective Width (SEW) and ADT are presented both for two-lane and four-lane sections in Table 10. The CMFs for shoulder type are listed in Table 11.

Table 10. 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 11. 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 shoulder-related crash rates will be CMF_{rl} and is calculated with following equation:

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

p_{ra} : Proportion of total crashes constituted by related crashes (default values are 0.574 for two-lanes and 0.27 for four-lanes) 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-foot increments, are shown below in Table 12.

Table 12. 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

- **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 13.

Table 13.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)

- **Adjustment for Right-Turn Lanes**

CMFs for total intersection-related right-turn lanes are found in Table 14.

Table 14. 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 computed as the sum of crash rates by section based on real-world corridor conditions.

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

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).

4.2. 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.

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 15 and 16. To estimate severe crash rates, the total crash rate coefficients in the equations presented in Section 4.1.1 were replaced with these severe crash coefficients. CMFs for severe crash rate estimation are also different from those for total crash estimation. Table 17 summarizes the CMFs resulting from adding left-turn and right-turn lanes at intersections on four-lane, two-way corridors.

Table 15. 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 16. 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 17. 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)

Additionally, 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.

4.3. CRASH RATES FOR PROPOSED ALTERNATIVES

The crash rates and severe crash rates along the proposed roadway improvement scenarios are estimated by applying the same parameters from HSM (2010). However, due to the fact that various AADT levels may occur along different types of lanes within the same section, the research team adjusts the functions from HSM to incorporate each particular situation. Additionally, it is assumed that the LRT mode has no crash rates along the whole corridor.

4.3.1. ROADWAYS

The roadway crash rates of a particular roadway type are sensitive to the corresponding adjusted AADTs obtained from mobility models along with the number of lanes before and after the improvements:

$$N_{Ri} = \exp\ [a + b \times \ln(AADT_i / lane \times n_B) + \ln(L_i)] \times n_r / n_B$$

Notations:

N_{Rri} : Expected number of crashes for a specific roadway type along section i (crashes/yr);

$AADT_i / lane$: Annual Average Daily Traffic Volume per lane (veh/d/lane) for certain proposed roadway type along section i;

n_r : Number of lanes for certain proposed roadway type;

n_B : Existing number of lanes along the section;

L_i : Length of the section i (mile).

4.3.2. INTERSECTIONS

The functions of crash rates at intersections are derived from the HSM similar to roadway crashes; however, minor roads intersecting with the main corridor must also be accounted for:

$$N_{Rii} = \exp\ [a + b \times \ln(AADT_i / lane \times n_B) + c \times \ln AADT_{i\,minor}] \times n_r / n_B$$

Notations:

N_{Rii} : Expected number of crashes for a specific roadway type at intersection i (crashes/yr);

$AADT_{i\min or}$: Annual Average Daily Traffic Volume per lane (veh/d/lane) along minor street at intersection i.

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, and 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 of economies induced by transportation investment. This is a more sophisticated method for economic impact analysis compared to 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 affected 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. Then, the team proceeded to calculate 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

$\mathrm{GDP_j}$: Output per worker in zone j

$\mathrm{E_j}$: 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 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. The land-use types considered are: 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 local traffic accessibility and transit implementation proportion. Based on the team's definition, livability is enhanced if highway corridor improvements are compatible with existing or planned future land use and if they improve accessibility to activity locations.

5.2.1. LAND-USE SCORES

"Land Use Mix" refers to locating different types of land uses close together. Increased land use mix tends to reduce the distances that residents must travel for errands and allows more use of walking and cycling for such trips. Certain combinations of land use are particularly effective at reducing travel, such as incorporating schools, stores, parks and other commonly-used services within residential neighborhoods and employment centers.

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. Land-use types considered in this project include: industrial, commercial, recreational, agricultural, as well as low and high density residential areas.

The land-use mix score on no-build condition was derived from the average land-use score for all of the traffic analysis zones (TAZs) within 1/4-mile buffer along the corridor, where 0 represents the worst land-use mix situation and 1 represents the best case. The research team then developed an online survey (shown in Appendix I) to obtain land-use scores representing individuals' opinions on how different highway improvement options affect various land-use types along a particular corridor (e.g. US 29) based on the score in the base case. The average scores from the survey are used as default impact scores in the current version of MOSAIC and are presented in Table 18.

Table 18. Impact of Highway Improvements on Land Use

Improvement Types	Land-use Mix Scores
No-build Condition	0.66
Adding one HOV lane or Converting one GP lane into HOV lane	0.65
Adding one HOT lane or Converting one GP lane into HOT lane	0.64
Adding one bus only lane	0.66
Adding one truck only lane	0.61
Building LRT	0.72
Removing one lane	0.70

5.2.2. TRANSPORTATION ACCESSIBILITY

The accessibility measure is the average of the travel time scores and transit implementation scores. The travel time score measures local traffic accessibility. The lower the travel time score, the better the local traffic accessibility will be. The transit implementation score represents the percentage of people using public transit, which includes bus transit and LRT. The higher the score, the better the transit implementation condition will be.

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 3 illustrates the steps for evaluating noise impact.

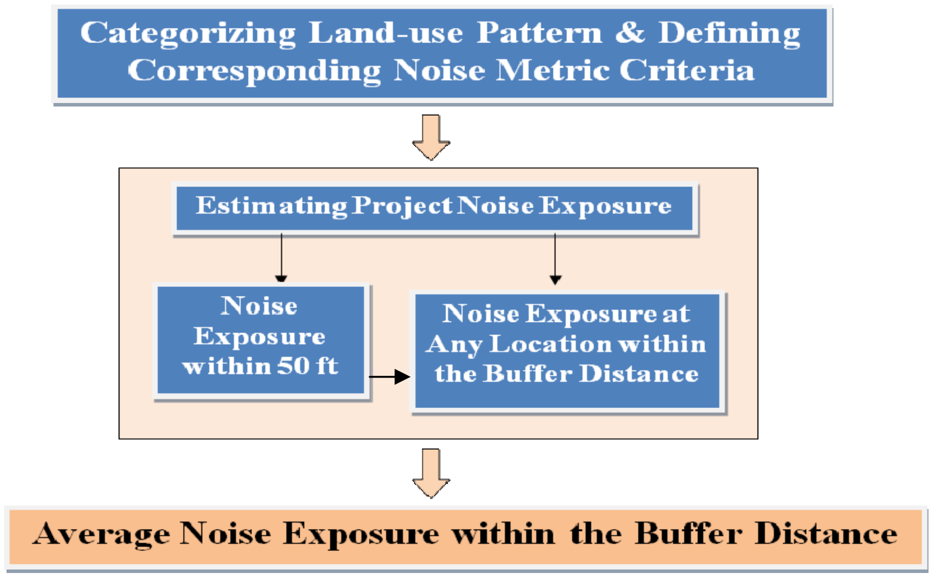


Figure 3. Measuring Noise Impact

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 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.

5.3.2. PROJECT NOISE ESTIMATION

5.3.2.1. Project Noise Impact at 50 ft

The research team adopted the noise methodology and functions from the Federal Transit Administration’s Transit Noise and Vibration Impact Assessment, which uses Manhattan’s existing Light Rail system as a case study (FTA, 2006). This methodology provides roadway noise impact on different land-use types at the distance of 50 feet from the highway centerline as:

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: $SEL = 10\log_{10}[\text{Total sound energy during the event}]$. The Federal Highway Administration (FHWA) categorized the default value for SEL, as shown in Table 20.

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, (vehicles per hour);

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

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

V_n: Average hourly nighttime volume of vehicles of a certain type, (vehicles 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).

The FTA General Noise Assessment procedure was used for calculating noise from transit sources associated with the proposed project. Similar to that of the roadways, the noise impact of LRT is assessed based on a combination of existing ambient noise exposure and the additional noise exposure that will be caused by the proposed project.

The Light Rail Rapid Transit (LRRT) system located on Main Street is the major source of existing noise in the vicinity of the proposed project. The existing Noise Exposure Levels at 50 feet can be estimated by applying the equations as follows:

Hourly L_{eq} at 50ft: $L_{eq} = SEL_{ref} + 10\log(V) + 10\log(N_{cars}) + 20\log(\frac{S}{50}) - 35.6$

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

The reference-sound exposure level (SELref) for Rail Transit at 50 feet from track equals 82 dBA, according to FTA's report (FTA, 2006).

By referring to the Manhattan EIS report, MOSAIC set Vd, which is the average hourly volume of traffic during daytime (7 am to 10 pm), as 4.3 trains/hour; Vn, which is the average hourly volume of traffic during nighttime (10 pm to 7 am) was set as 3.9 trains/hour. S was set as 15 miles per hour across the project corridor. The average number of cars per train, Ncars, is assumed to be three for this analysis (based on two cars during off-peak periods, three cars during peak periods, and four cars during special events).

5.3.2.2. Project Noise Impact at a Certain Arbitrary Receiver

For the distance between the arbitrary receiver and the noise location within the buffer distance, the research team considered that 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 the 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 there is no curve or barrier along the general corridor, this Ground Factor, G, is by default set to 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, and historical roads and historical site protection.

As a part of this project, an online survey was developed and distributed (shown in Appendix I). 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 29 corridor, which can be generalized to other corridors in Maryland. In general, the survey shows that respondents believe six highway improvement types have minimum impact on aesthetics (scores close to 0). However, visual appeal and historical site protection outrank facility compatibility and land use attractiveness in determining aesthetics along the corridor.

Table 21. Impact of Highway Improvements on Aesthetics along the US 29 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	HOV	HOT	Bus only	Truck only	LRT	Road Diet	
Facilities' Compatibility	0.00	1.00	0.67	0.57	1.00	0.71	-0.67	3.83
Land Use Attractiveness	0.14	0.75	0.75	0.43	0.50	1.38	-0.50	3.67
Visual Appeal	0.43	0.57	0.25	0.50	0.00	0.88	0.50	5.33
Historical Road and Sites Protection	0.43	0.00	0.00	0.25	-0.38	-0.63	0.75	5.00

Notes:

1) Facilities' Compatibility: Including traffic control devices, lighting, channelizing islands and roundabout design, markings, etc;
2) Land Use Attractiveness: Including transportation network land use, landscaping, median, shoulder and other roadside design features, etc;
3) Visual Appeal: Including visual friction (various interesting views as opposed to uninteresting ones), view 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 sites.

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 : 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, areas of affected natural resources along a highway corridor were used to measure natural resource impacts. After a comprehensive literature review, a set of buffer distances have been set for the analysis listed in Table 22. The US 29 natural resource map is shown in Figure 4.

Table 22. Buffer Distances for Each Improvement Alternative

<table>
<tr><th>Section</th><th># Lanes</th><th>HOV</th><th>HOT</th><th>Express</th><th>Bus Only Lane</th><th>Truck Only Lane</th><th>LRT</th></tr>
<tr><td rowspan="2">1</td><td>2</td><td colspan="3">Adding One HOV / HOT/ Express Toll Lane (1/4 miles)</td><td rowspan="7">Adding One Bus Only Lane (1/4 miles)</td><td rowspan="7">Adding One Truck Only Lane (1/4 miles)</td><td rowspan="7">Adding LRT Mode Choice (1/8 miles)</td></tr>
<tr><td>3</td><td colspan="3" rowspan="2">Converting One GP Lane to HOV / HOT/ Express Toll Lane (0)</td></tr>
<tr><td rowspan="2">2</td><td>3</td></tr>
<tr><td>2</td><td colspan="3" rowspan="2">Adding One HOV / HOT/ Express Toll Lane (1/4 miles)</td></tr>
<tr><td rowspan="2">3</td><td>2</td></tr>
<tr><td>3</td><td colspan="3" rowspan="2">Converting One GP Lane to HOV / HOT/ Express Toll Lane (0)</td></tr>
<tr><td>4</td><td>3</td></tr>
</table>

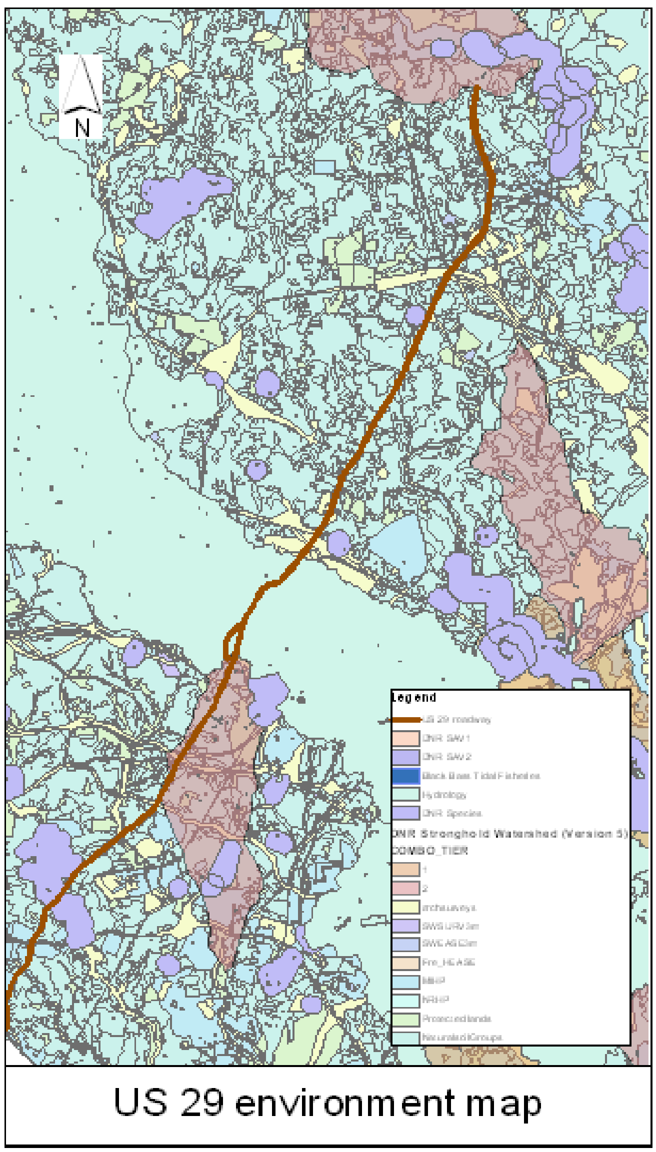
<table>
<tr><th>Section</th><th># Lanes</th><th>Adding Lanes</th><th>Road Diet</th><th>Grade-Separated Interchanges</th></tr>
<tr><td rowspan="2">1</td><td>2</td><td rowspan="2">Adding One GP Lane (1/4 miles)</td><td>--</td><td>--</td></tr>
<tr><td>3</td><td>--</td><td>--</td></tr>
<tr><td rowspan="2">2</td><td>3</td><td>--</td><td>Removing One GP Lane</td><td>--</td></tr>
<tr><td>2</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td rowspan="2">3</td><td>2</td><td>--</td><td>--</td><td rowspan="3">Building Interchanges for all the intersections (1/2 miles at intersections)</td></tr>
<tr><td>3</td><td>--</td><td>Removing One GP Lane</td></tr>
<tr><td>4</td><td>3</td><td>Adding One GP Lane (1/4 miles)</td><td>Removing One GP Lane</td></tr>
</table>

Corridor roadway, intersection geometry and GIS shapefiles containing natural resource information are first merged in ArcGIS. Each individual section of the US 29 corridor designated by the MOSAIC user is buffered using the ArcGIS proximity toolset with the given improvement type's impact distance. 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 affected land within the buffer area can be computed for each type of natural resource. Higher percentages indicate more severe impact to surrounding natural resources. Impacts on different types of natural resources (e.g. parks, streams, wetlands, historical places, easements) are weighted equally in this version of MOSAIC. This will be adjusted in future versions based on input from SHA.

For the six improvement types analyzed in Phase Two of the project, the natural resource impact will either be negative or neutral at best.

Figure 4. Impact Area of US 29 Corridor



CHAPTER 7: ENERGY AND EMISSIONS

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. The roadway per-mile emission rates for Maryland, e, at different speeds are obtained by running MOVES2010a, the Motor Vehicle Emission Simulator developed by the U.S. Environmental Protection Agency (EPA) (See Table 21). In addition, MOSAIC obtains LRT emission rates from EPA's National Emission Trends (NET) database (See Table 24).

The roadway daily total pollution emission for each emission type can be expressed as:

$$E_j = \sum_i E_{ij} \text{ and } E_{ij} = e_{ijp} \times ADT_{ip} \times L_i + e_{ijo} \times ADT_{io} \times L_i$$

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).

e_{ijp}: Peak-hour emission rate in section i for gas type j (grams/vehicle/mile); (refer to Table 23)

e_{ijo}:   Off-peak emission rate in section i for gas type j (grams/vehicle/mile); (refer to Table 23)

Since some managed lane improvement alternatives such as HOV, HOT, and the express toll lanes mostly operate during peak-hours and act as general purpose lanes during off-peak hours, the research team only analyzed pollution emissions for peak hour traffic volumes. In addition, different types of lanes may have different ADT as obtained from the mobility analysis.

Table 23. Roadway Emissions Rates from MOVES (Year 2011)

Speed (mph)	Total Emissions per vehicle (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

Table 24. Emission Rates for LRT

CO (g/p-m)	NOx (g/p-m)	PM10 (g/p-m)
0.0355	0.6123	0.0232

7.2. GREENHOUSE GAS EMISSIONS

The total greenhouse gas (GHG) emission is estimated with a process similar to that of the pollution emission introduced above. Similarly, the roadway GHG emission rates for Maryland at different speeds are obtained by running MOVES2010a, the Motor Vehicle Emission Simulator developed by the EPA (See Tables 25). The rate for LRT was also obtained from EPA's National Emission Trends (NET) database, which is 284.66 grams per person mile.

Table 25. Roadway GHG Emissions Rates from MOVES (Year 2011)

Speed (mph)	Total Emissions per Vehicle (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 research team evaluated fuel consumption using British Thermal Units (BTUs) based on vehicle activities along a highway corridor. The total roadway fuel consumption is estimated with a process similar to that of the pollution emission discussed above, except for the e (million BTUs/mile/ADT). Here it represents the energy consumption rates for Maryland at different speed levels obtained by running MOVES2010a (see Table 26) at the appropriate point. We set the LRT's fuel consumption rate to 2,516 BTU/ (p-m), by referring to the Transportation Energy Data Book: Edition 30. Other inputs for fuel consumption estimation are ADT, section lengths and lane widths.

Table 26. Roadway Fuel Consumption Rates from MOVES (Year 2011)

Speed (mph)	Energy Consumption per Vehicle (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

8.1. COSTS FOR GENERAL PURPOSE LANES

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

Cost data was compiled for all projects that included costs for four major categories of the project: planning, engineering, right-of-way acquisition 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 27).

Table 27. 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

8.2. COSTS FOR OTHER ALTERNATIVES

In order to estimate the costs for the HOV or HOT scenario, the research team did a comprehensive literature review and regarded the I-395/I-95's construction report from the Financially Constrained Long-Range Transportation Plan for 2040, which was published by the National Capital Region Transportation Planning Board, as one that fits the costs analysis best. In the I-95 project, fourteen miles of HOV lanes were widened from two lanes to three lanes and two more nine-mile long HOV lanes were built along each direction. The total cost of this project was $1.01 billion. Thus, the research team set the construction costs of adding two-way HOV or HOT lanes as $31.56 million per mile. Since the construction of the two-way general-purpose lanes costs $30 million per mile, the research team set the costs of converting two-way GP lane to two-way HOV or HOT lane as $1.56 million per lane.

The research team set the cost rate for truck-only lane construction by referring to the I-70 Dedicated Truck Lanes Feasibility Study. This study included analysis on the Washington Commerce Corridor (WCC) a proposed North-South (N-S) alternative to Interstate-5 beginning in Lewis County, Wash., and extending north to the Canadian border that facilitates the movement of freight, goods, people and utilities. The WCC was estimated to cost between $42 billion and $50 billion if built for the full complement of passenger cars, rail transport, energy infrastructure and recreational trails. The associated cost for constructing dedicated truck-only lanes for the full 270-mile route was approximately $14.7 billion, or $18 million/lane-mile. From this, the research team set the construction costs of the two-way, truck-only lane as $36 million per mile. Meanwhile, since there are no major changes between general-purpose lanes and bus-only lanes, the research team assumed the construction cost of two-way, bus-only lanes to be the same as general-purpose lanes at $ 30 million per mile.

Construction costs for LRT were established based on Maryland's Purple Line project. By referring to MTA's South Maryland Transit Corridor Preservation Study, the two-way LRT's construction cost was set to $120.6 million per mile. In addition, the LRT vehicle cost was set to $131 million per train.

CHAPTER 9: MOSAIC OUTPUT

9.1. 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 28 offers an example and displays the effect a particular improvement case has on speed and travel in each of the five corridor sections. The effect of each improvement case in the six impact categories is then weighted and scaled based on either default or user-defined weights 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.

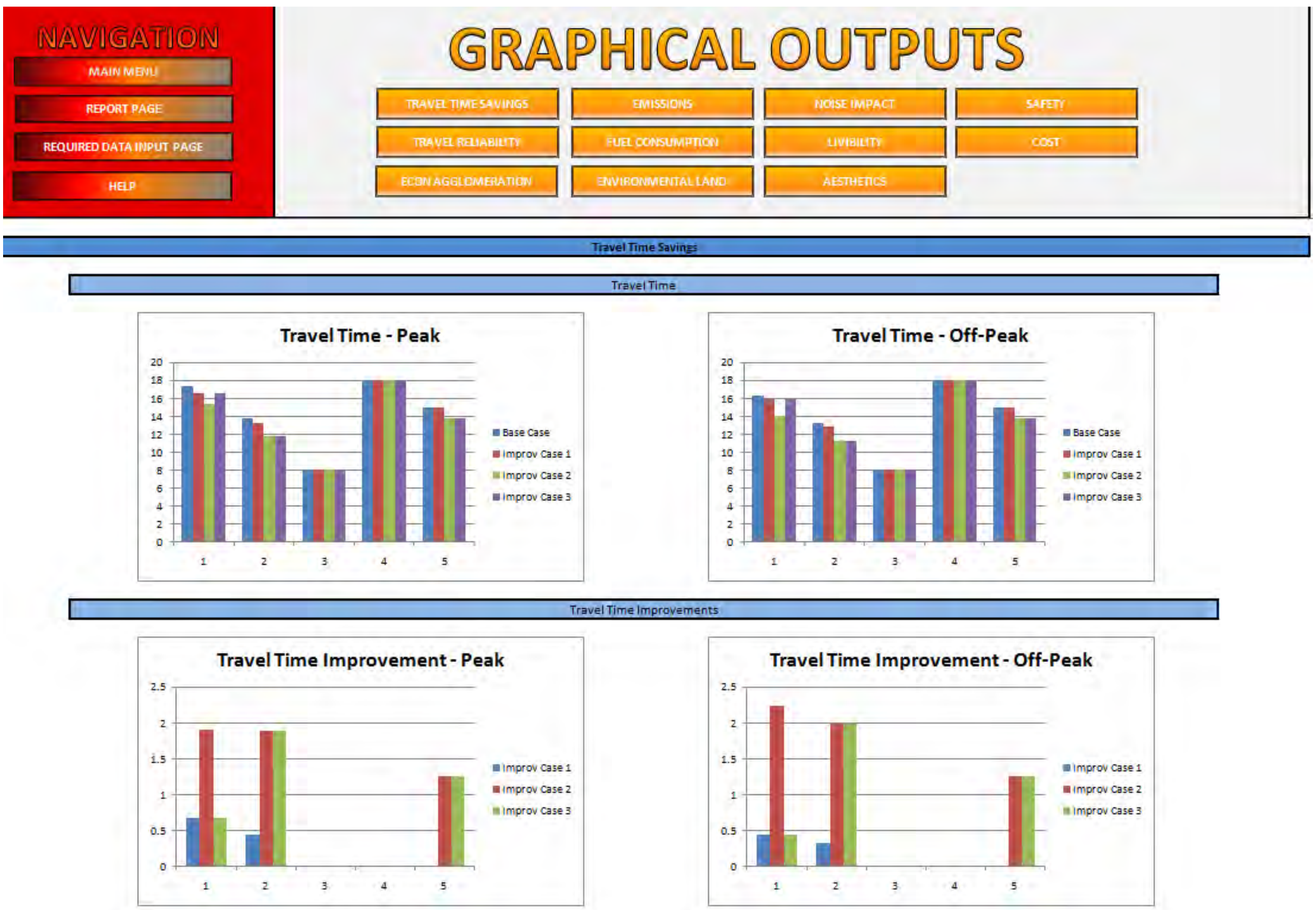
Table 28. MOSAIC Output Database

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

9.2. GRAPHICAL OUTPUT

MOSAIC automatically creates customized graphs for each of the six impact categories. This provides one location where users can check and compare the performance of all improvement cases with the base-case scenario. All improvement and base cases are compared side by side (see Figure 5). Also, 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 5. MOSAIC Graphical Output View

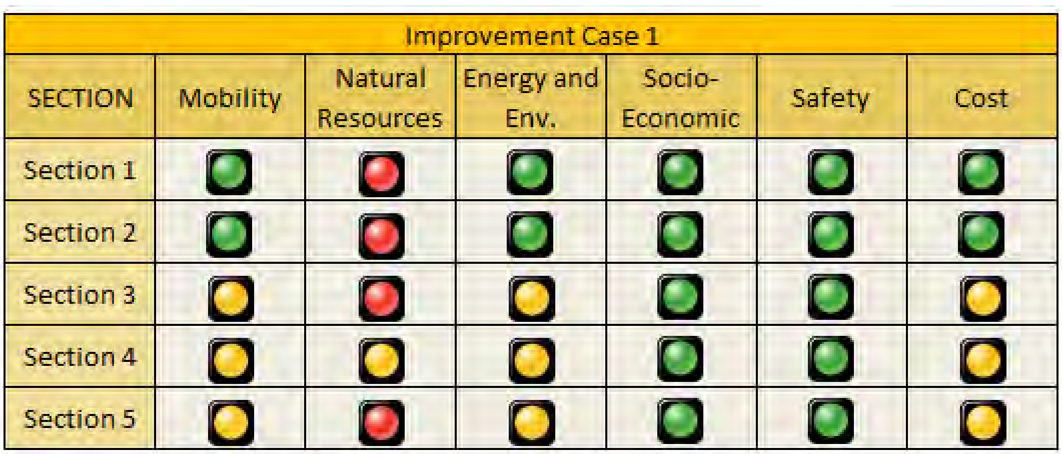


9.3. FINAL SUMMARY

MOSAIC also provides a final summary, which includes graphical visualizations of the impact of each improvement case at both the section and corridor levels. As previously stated in Section 3.1-Travel Time Savings, each section represents a portion of the corridor where there are uniform traffic-flow characteristics such as traffic volume, number of lanes, etc. 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 highly value mobility and safety, while other users may prioritize natural resources, energy, and environmental impact mitigation.

9.3.1. SECTION LEVEL SUMMARY OUTPUT

Figure 6. MOSAIC Section-Level Summary Output



The figure above shows the section-level analysis summary for one improvement case. In general, “green” implies positive effect and benefit from a corridor improvement scenario, “yellow” indicates neutral effect and “red” implies negative effect. The table below shows how the impact score for each of the six 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.

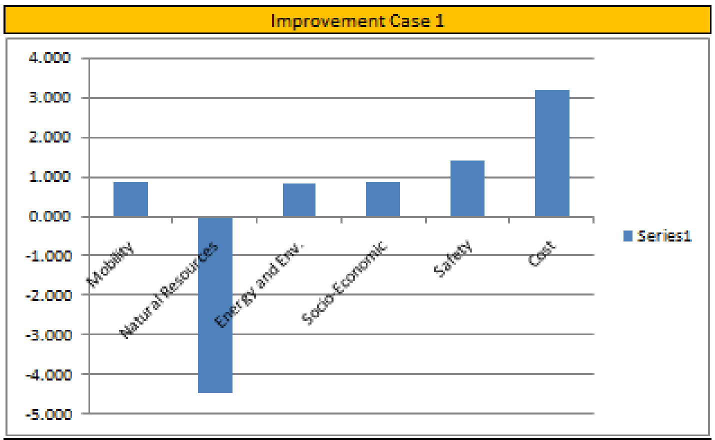
Table 29. Computation and Normalization of Impact Scores

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

9.3.2. 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 7 for an example). These weighted average scores are scaled similarly to the section-level summary output, with +10 indicating the highest level of positive effect, 0 indicating no effect, and -10 indicating the worse possible effect from improvement.

Figure 7. 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

9.3.3. FINAL CORRIDOR SCORES AND WEIGHTING SYSTEM

Figure 8. 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 9, 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 9. 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 10: US 29 CORRIDOR CASE STUDY

US 29 is a United States highway that runs for 1,036 miles (1,667 km) north-south from the western suburbs of Baltimore, Md., to Pensacola, Fla. In the state of Maryland, US 29 is a major highway that emerges from Washington, D.C., and runs north into eastern Montgomery County and Howard County, stretching over 25.86 miles (41.62 km) through the state and terminating at MD 99 just north of Interstate 70 outside of Ellicott City. It serves the cities of Columbia and Ellicott City and provides the westernmost north–south route between Washington, D.C., and Baltimore.

The research team's study area is a segment of US 29 stretching from Interstate 70 toward the Washington, D.C. line, which is highlighted in Figure 10. The study area was divided into four sections according to AADT per-lane levels and roadway configurations. Section 1 and 2 are freeways with full access control. Section 1 begins at Interstate 70 and ends at MD 175. Section 2 begins at MD 175 and ends at the Montgomery County line. Section 3 and 4 are arterial streets with signalized intersections. Section 3 runs from the Montgomery County line to Dale Drive, and Section 4 runs from Dale Drive to the Washington, D.C. line. The study period is from 6:00 a.m. through 9:00 a.m., the morning peak hours. Five improvement plans were analyzed for this corridor as listed in Tables 30 and 31. Detailed roadway information for US 29 was derived from the 2010 Highway Location Reference for Howard and Montgomery Counties and the SHA's Internet Traffic Monitoring System (I-TMS) website, and that data is presented in Table 32.

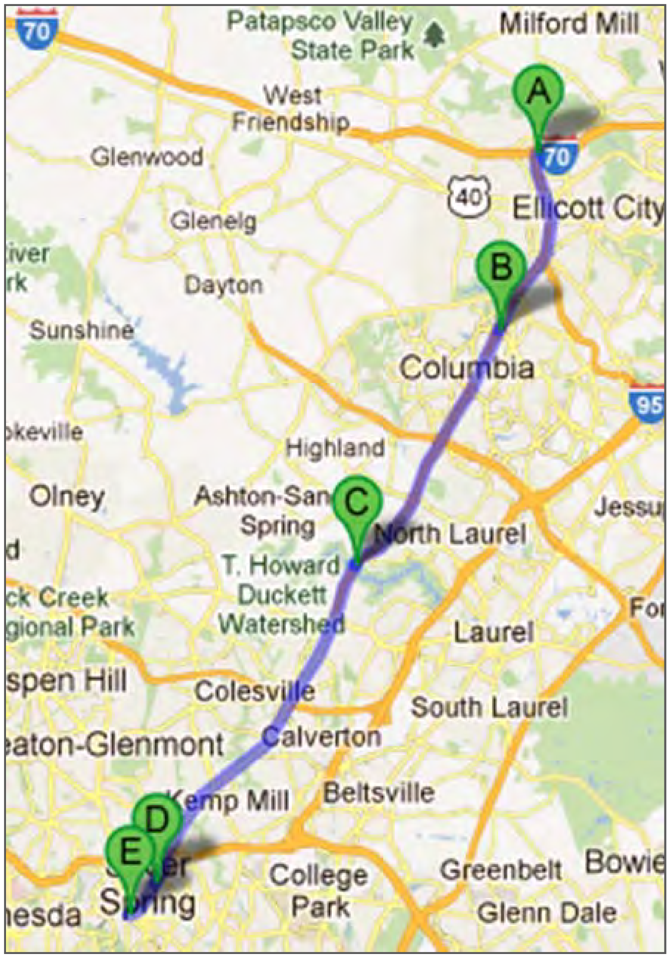


Figure 10. US 29 Roadway Map

Table 30. US 29 Improvement Alternatives 1

<table>
<tr><th>Section</th><th># Lanes</th><th>HOV</th><th>HOT</th><th>Express</th><th>Bus Only Lane</th><th>Truck Only Lane</th><th>LRT</th></tr>
<tr><td rowspan="2">1</td><td>2</td><td colspan="3">Adding One HOV / HOT/ Express Toll Lane</td><td rowspan="7">Adding One Bus Only Lane</td><td rowspan="7">Adding One Truck Only Lane</td><td rowspan="7">Adding LRT Mode Choice</td></tr>
<tr><td>3</td><td colspan="3" rowspan="2">Converting One GP Lane to HOV / HOT/ Express Toll Lane</td></tr>
<tr><td rowspan="2">2</td><td>3</td></tr>
<tr><td>2</td><td colspan="3" rowspan="2">Adding One HOV / HOT/ Express Toll Lane</td></tr>
<tr><td rowspan="2">3</td><td>2</td></tr>
<tr><td>3</td><td colspan="3" rowspan="2">Converting One GP Lane to HOV / HOT/ Express Toll Lane</td></tr>
<tr><td>4</td><td>3</td></tr>
</table>

Table 31. US 29 Improvement Alternatives 2

Section	# Lanes	Adding Lanes	Road Diet	Grade-Separated Interchanges
1	2	Adding One GP Lane	--	--
	3	Adding One GP Lane	--	--
2	3	--	Removing One GP Lane	--
	2	--	--	--
3	2	--	--	Building Interchanges for all the intersections
	3	--	Removing One GP Lane	
4	3	Adding One GP Lane	Removing One GP Lane	Building Interchanges for all the intersections

Table 32. US 29 Roadway Information

Section	# Lanes	Mileage (miles)	AADT/Lane	Peak-hour Person Trips	Peak-hour Vehicle Counts	Congestion Level
1	2	1.35	20969	21894	17263	Severe
	3	4.08				
2	3	6.36	13469	14614	11523	Uncongested
	2	2.91				
3	2	3.79	11127	11302	8912	Uncongested
	3	6.95				
4	3	1.51	6029	5963	4702	Medium

10.1. MODE CHOICE ANALYSIS

The outputs generated from the mode choice models are the inputs for travel-time models and are the prerequisites for travel-time analysis.

10.1.1. CASE STUDY INPUT

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

10.1.1.1. Base Mode Shares

Existing mode shares can be computed by applying existing mode-share data derived from the traffic-count data for the previous case study along US 29. The 2010 vehicle-counts data for each traffic mode along each lane was obtained from the Vehicle Occupancy Count Report generated from SHA's hourly I-TMS. The research team assumed the mode shares were the same for sections 1 and 2. The mode ">=5" was assumed to load five people, "vanpool" seven people, and "truck" one person. The "bus" mode has a design load factor of 1.2 and thus is able to load an average of 48 people per vehicle.

10.1.1.2. LOS Variables

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

All three improvement types need to consider the changes of IVTT as part of the variance of the LOS variables. The HOV, HOT, express, and bus-only lanes are assumed to operate at free-flow conditions with uncongested travel times. The average speed of LRT was set to 24 mph, according to the LRT report from MTA (2001). 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-495.

Therefore, the changes in IVTT for managed-lane improvement options would be the difference between congested and uncongested travel times. MOSAIC assumes there will be no change in travel time for the remaining GP lanes. After the new shares and number of drive-alone vehicles are estimated, the updated congested travel time for the GP lanes was computed. For LRT, the changes in IVTT are computed as the difference between congested highway travel time and the LRT travel time.

There will be no changes in OVTT at this point for the five improvement types. The HOT and Express Toll Lane (ETL) alternatives will result in higher user costs due to tolling. The toll payments were assumed to be $1.45 for HOT lanes and $4.20 for ETLs during the peak hours, according to the toll used on the newly opened MD 200. As contained in the Maryland Statewide Transportation Model report, the auto operating costs were set at $0.099/mile in the year 2000. As such, the team assumed no changes occurred to the total cost between the base and LRT scenarios.

10.1.2. MODE CHOICE ANALYSIS PROCEDURE

It was assumed that this mode share analysis procedure would have no impact on truck-vehicle trips or person trips. Both the vehicle and person trips of the mode "truck" suffered change before and after the mode choice analysis. In this way, the initial mode shares were adjusted without considering the percentage of trucks during the analysis. The "truck" person trips were later added after completing the first iteration of the analysis.

10.1.2.1. Alternative 1: HOV Lanes

The procedure for the pivot-point mode shares analysis of the first alternative was as follows: build one new HOV lane or convert one GP lane into one HOV lane for the corresponding section. Since single-occupancy vehicles are forbidden in HOV lanes, it was assumed that there would be no change to their IVTT and thus no utility changes to 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 were obtained at this point.

After the first iteration, the new volume-to-capacity (v/c) ratios both for the HOV lanes and non-HOV lanes were computed. The v/c ratio for the HOV lane is equal to the number of two-person and greater capacity vehicles divided by the HOV lanes' capacity. The ratio for the non-HOV or GP lanes is equal to the number of single-user vehicles plus 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 resulting 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 traffic equilibrium across HOV and general-purpose lanes is achieved. In this way, the process ends when between two iterations, the difference in travel times between the non-HOV lanes and the initial existing travel time is within one minute.

10.1.2.2. Alternative 2: HOT Lanes

The procedure for the pivot-point mode shares analysis of the second alternative was as follows: build one new HOV lane or convert one GP lane into one HOV lane for the corresponding section - similar to the first alternative. However, there is one difference in the analysis: the changes to the utility functions include a cost associated with the toll.

In the second alternative, the single-occupancy vehicles would be allowed to use the HOT lane only if the drivers were willing to pay the toll. Thus, the Δu_i is equal to the product of the $\Delta IVTT_i$ and its corresponding coefficients, plus the product of the $\Delta COST_i$ and its corresponding coefficient. For each of the other modes, the Δu_i is still equal to the product of the $\Delta IVTT_i$ and its corresponding coefficient.

10.1.2.3. Alternative 3: Express Toll Lanes

The procedure for the pivot-point mode shares analysis of the third alternative was as follows: build one new express toll lane or convert one GP lane into one express toll lane for the corresponding section - similar to the second alternative. There are two differences within the mode share analysis: one changes toll rates and the other allows any person in any vehicle mode to use the express toll lane as long as the person pays the corresponding toll.

10.1.2.4. Alternative 4: Bus Only Lanes

The procedure for the pivot-point mode shares analysis of the fourth alternative was as follows: build one new bus only lane along the whole corridor. The users save travel time both along the uncongested bus-only lane by taking buses to destinations and by moving bus traffic out of general-purpose lanes.

10.1.2.5. Alternative 5: LRT

The method for LRT analysis is based on the extended incremental logit formulations for mode choice. The expected probability of riders using new or existing transit services both depend on the baseline probability and changes to the transit LOS.

10.1.3. MODE CHOICE RESULTS AND FINDINGS

The vehicle volumes for the base case and for each improvement alternative generated from the mode choice model are listed in Table 33 for comparison. The number of person Trips Transferred to LRT in the LRT Scenario calculated from extended incremental mode choice models are presented in Table 34.

Table 33. Pivot-Point Mode Choice Model Vehicle Volumes Results

Modes	Section 1 (2 lanes)					
	Base	HOV	HOT	Express	Bus	LRT
1	13547	12299	13035	13,497	9850	11581
2	1044	1290	1145	1,049	1772	893
3	42	52	46	43	72	36
4	13	16	14	13	21	11
>=5	1	1	1	1	2	1
Vanpool	21	26	23	21	36	18
Bus	60	74	66	61	102	51
Truck	655	655	655	655	655	655
Total	15384	14413	14986	15340	12509	13246

Modes	Section 1 (3 lanes)					
	Base	HOV	HOT	Express	Bus	LRT
1	15750	9910	10390	15,691	14582	13640
2	1214	2363	2269	1,220	1444	1052
3	49	96	92	49	58	43
4	15	29	28	15	18	13
>=5	1	2	2	1	1	1
Vanpool	25	48	46	25	29	21
Bus	70	136	131	71	83	61
Truck	761	761	761	761	761	761
Total	17885	13345	13718	17834	16977	15591

Modes	Section 2 (3 lanes)					
	Base	HOV	HOT	Express	Bus	LRT
1	10716	9474	9484	10,677	10598	9434
2	826	1071	1069	830	849	727
3	33	43	43	34	34	29
4	10	13	13	10	10	9
>=5	1	1	1	1	1	1
Vanpool	17	22	22	17	17	15
Bus	48	62	62	48	49	42
Truck	518	518	518	518	518	518
Total	12169	11204	11211	12134	12077	9434

Modes	Section 2 (2 lanes)					
	Base	HOV	HOT	Express	Bus	LRT
1	8900	8799	8778	8,867	8746	7752
2	686	706	710	689	716	598
3	28	29	29	28	29	24
4	8	9	9	8	9	7
>=5	1	1	1	1	1	1
Vanpool	14	14	14	14	14	12
Bus	40	41	41	40	41	34
Truck	430	430	430	430	430	430
Total	10106	10028	10011	10077	9986	8859

Modes	Section 3 (2 lanes)					
	Base	HOV	HOT	Express	Bus	LRT
1	7916	7855	7865	7,887	7823	6921
2	610	622	620	613	629	534
3	25	25	25	25	25	22
4	7	8	8	7	8	6
>=5	1	1	1	1	1	1
Vanpool	12	13	13	12	13	11
Bus	35	36	36	36	36	31
Truck	383	383	383	383	383	383
Total	8990	8942	8950	8964	8917	7907

Modes	Section 3 (3 lanes)					
	Base	HOV	HOT	Express	Bus	LRT
1	7810	7620	7681	7,781	7797	6898
2	602	639	627	605	605	532
3	24	26	25	25	24	22
4	7	8	8	7	7	6
>=5	1	1	1	1	1	1
Vanpool	12	13	13	12	12	11
Bus	35	37	36	35	35	31
Truck	377	377	377	377	377	377
Total	8869	8721	8768	8843	8858	7877

Modes	Section 4					
	Base	HOV	HOT	Express	Bus	LRT
1	4141	4140	4127	4,125	4141	3606
2	319	319	322	321	319	278
3	13	13	13	13	13	11
4	4	4	4	4	4	3
>=5	0	0	0	0	0	0
Vanpool	6	6	7	7	6	6
Bus	18	18	19	19	18	16
Truck	200	200	200	200	200	200
Total	4702	4702	4691	4689	4702	4121

Table 34. Person Trips Transferred to LRT in the LRT Scenario

Section	# Lanes	LRT PT	Total PT	%
1	2	2736	19511	14.02%
	3	2937	22683	12.95%
2	3	1785	15434	11.57%
	2	1597	12817	12.46%
3	2	1386	11401	12.16%
	3	1270	11248	11.29%
4	3	744	5963	12.48%

The results demonstrated that LRT will encourage ridesharing to a larger extent, compared to other improvement options. This would better reduce highway congestion along the study area. The second best choice was to construct bus-only lanes. The third best choice would be the HOV-lane scenario; however, as severe congestion problems appear, HOV lanes would show limitations and shortcomings that are visible in the results. One typical example is the inefficient usage of road space, where it appears that few drivers take advantage of fast lanes and large amounts of single-occupancy vehicle drivers must endure adjacent GP lanes with poor traffic conditions. The HOT scenario performs well in the uncongested sections, such as Section 4, mainly because the toll lane may continue to restrict the usage of single-occupied vehicles.

10.2. MOBILITY ANALYSIS RESULTS

The research team applied the travel time estimation and reliability analysis models with vehicle count and person trip data, which was generated by mode choice models. The resulting average per-person trip travel time along with the average roadway reliability index are listed in Tables 35 and 36, respectively. Meanwhile, Figure 11 presents the comparison of the final results by sections.

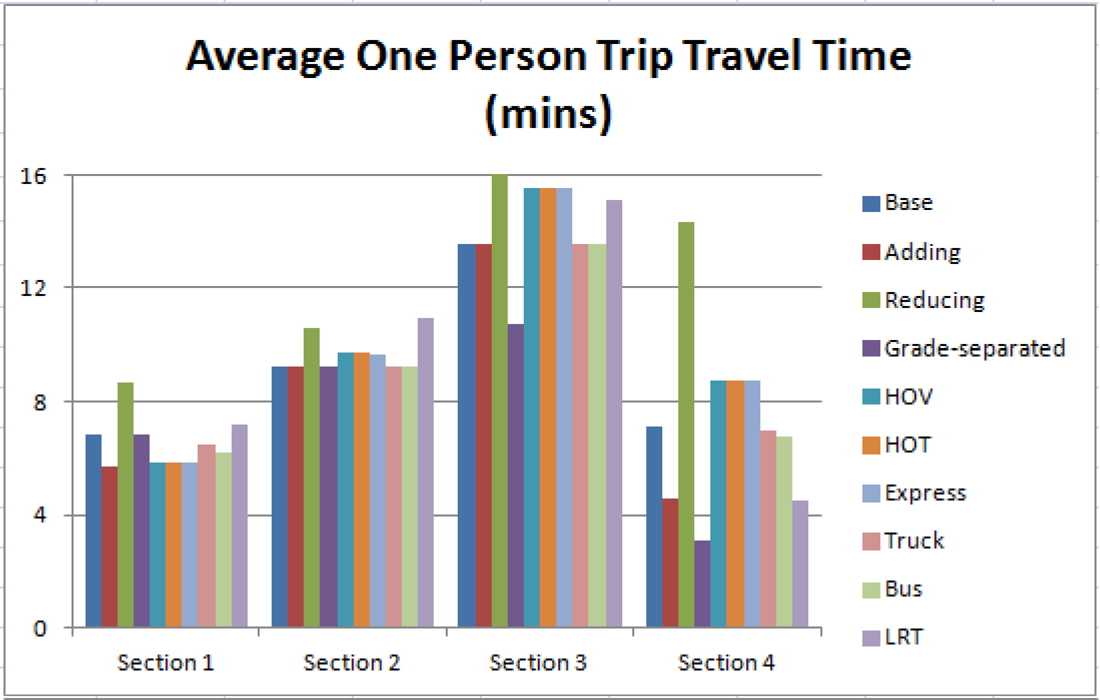
Table 35. Average One Person Trip Travel Time (mins)

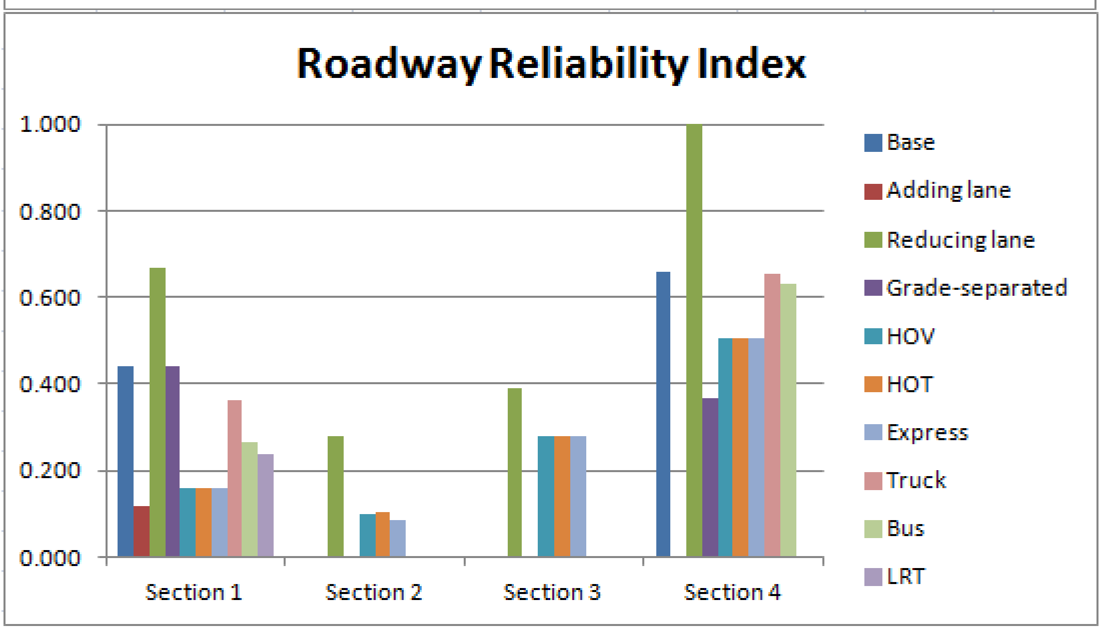
Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	6.820	5.733	8.690	6.820	5.850	5.850	5.850	6.502	6.177	7.181
2	9.269	9.269	10.614	9.269	9.700	9.726	9.647	9.270	9.270	10.917
3	13.573	13.573	16.541	10.740	15.543	15.543	15.543	13.573	13.573	15.117
4	7.111	4.589	14.351	3.111	8.753	8.753	8.753	7.007	6.744	4.487
Total	36.773	33.164	50.196	29.940	39.845	39.872	39.792	36.353	35.765	37.703

Table 36. Roadway Reliability Index

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	0.442	0.117	0.666	0.442	0.159	0.159	0.159	0.267	0.362	0.239
2	0.000	0.000	0.280	0.000	0.098	0.104	0.086	0.000	0.000	0.000
3	0.000	0.000	0.393	0.000	0.280	0.280	0.280	0.000	0.000	0.000
4	0.660	0.000	1.000	0.369	0.505	0.505	0.505	0.631	0.654	0.000
Average	0.126	0.024	0.443	0.110	0.205	0.207	0.201	0.089	0.110	0.048

Figure 11. Mobility Results comparison

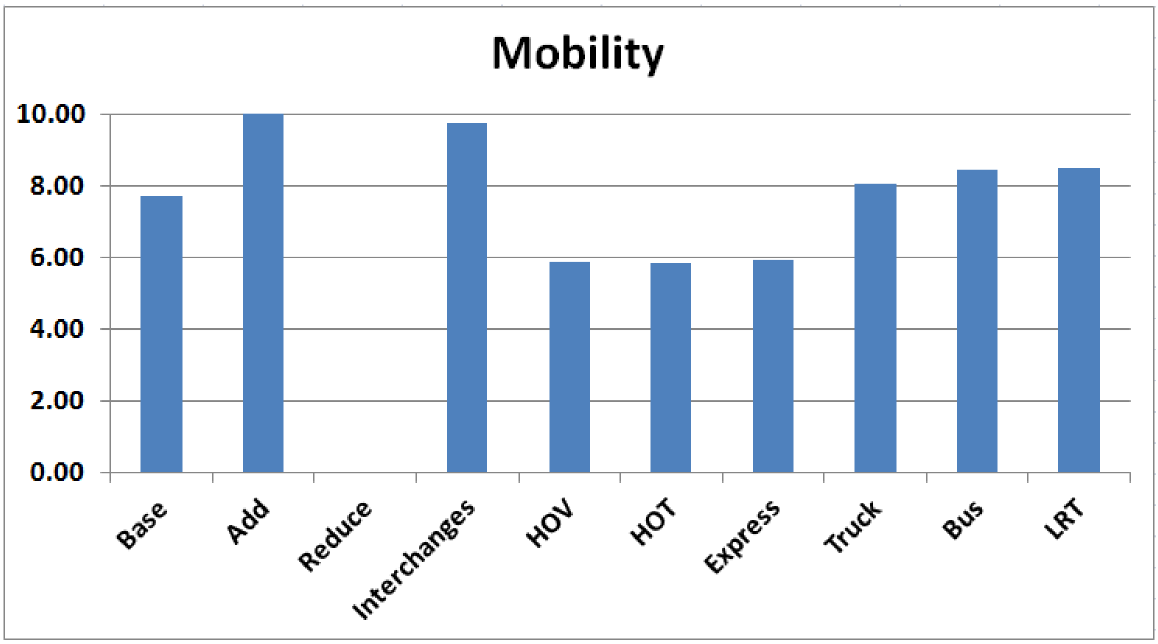




The results indicate that building grade-separated intersections best improved mobility along arterial sections. In less congested sections, such as Sections 2 and 3, building one additional bus-only or truck-only lane would be more effective and efficient in reducing the travel time and increasing the reliability, compared to managed lanes improvement options. For arterial streets with low-travel speed limits and many at-grade intersections, such as Section 4, the LRT scenario can achieve the best performance in both travel time savings and reliability improvement. This may result from the travel time savings at intersections.

The mobility scores, including indicators such as travel time and average roadway reliability index along the Study Area, are presented in Figure 12. The graph illustrates that the bus-only lane improvement option can reduce the travel time to the largest extent among the managed lane improvement alternatives, while adding one general-purpose lane alternative performs best in enhancing the travel reliability along the entire study area.

Figure 12. Mobility Scores for Each Improvement Option along the Study Area



10.3. SAFETY ANALYSIS RESULTS

By applying the safety analysis models based on the US 29 traffic information and roadway configurations, the unit crash rates as well as the severe crash rates for every mode along each section were calculated and are listed in Tables 37 and 38. The comparison of the safety condition for each alternative is presented in Figures 13 and 14. It is necessary to mention that

MOSAIC estimated the total crash number as 996, with a severe crash number of 53 per year along US 29. In 2010, the same data type reported from the police was 660 total crashes, with 23 considered severe. This proves that MOSAIC can be a useful tool to predict both the total number and number of severe crashes accurately.

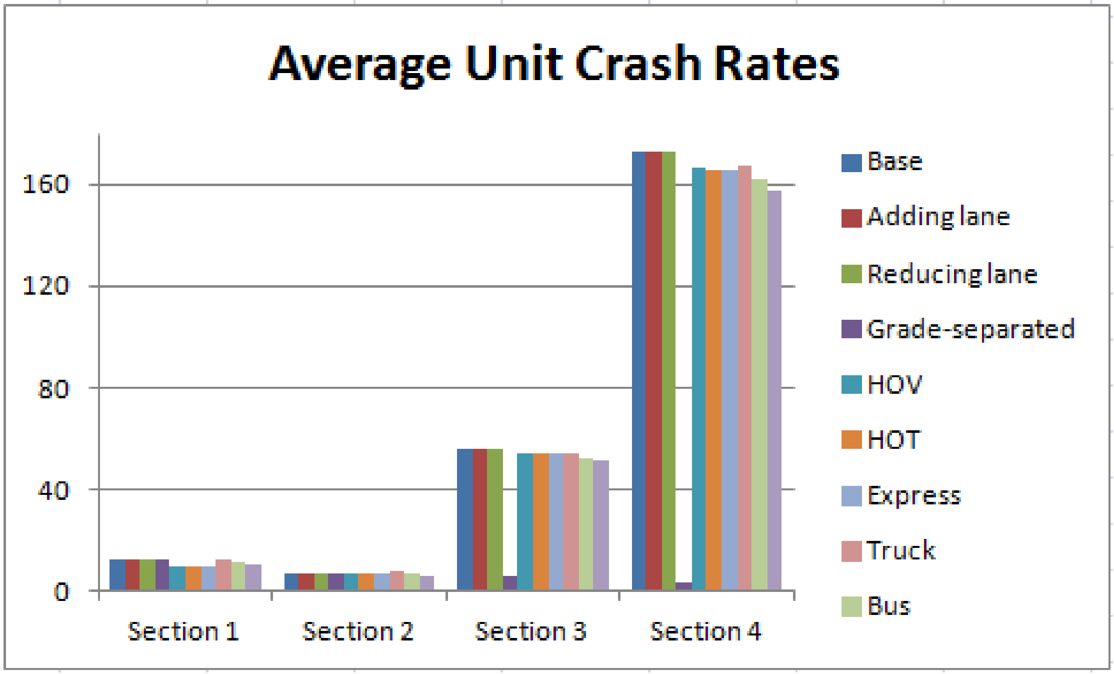
Table 37. Unit Crash Rates along Each Section

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	11.891	11.891	11.891	11.891	9.196	9.481	9.393	11.996	11.110	10.273
2	7.290	7.290	7.290	7.290	6.861	6.868	6.852	7.356	7.329	6.401
3	56.120	56.120	56.120	5.875	53.606	53.879	53.634	54.217	52.552	51.250
4	173.189	173.189	173.189	3.519	166.209	165.808	165.185	167.145	161.837	157.323
Average	36.972	36.972	36.972	7.442	34.889	35.035	34.879	35.919	34.770	33.511

Table 38. Unit Severe Crash Rates along Each Section

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	2.930	2.930	2.930	2.930	2.345	2.413	2.391	2.870	2.642	2.594
2	1.949	1.949	1.949	1.949	1.811	1.807	1.806	1.907	1.865	1.748
3	1.628	1.628	1.628	1.628	1.575	1.582	1.577	1.592	1.565	1.464
4	1.065	1.065	1.065	1.065	1.042	1.039	1.036	1.045	1.030	0.949
Average	1.969	1.969	1.969	1.969	1.782	1.797	1.789	1.927	1.855	1.760

Figure 13. Safety Results comparison



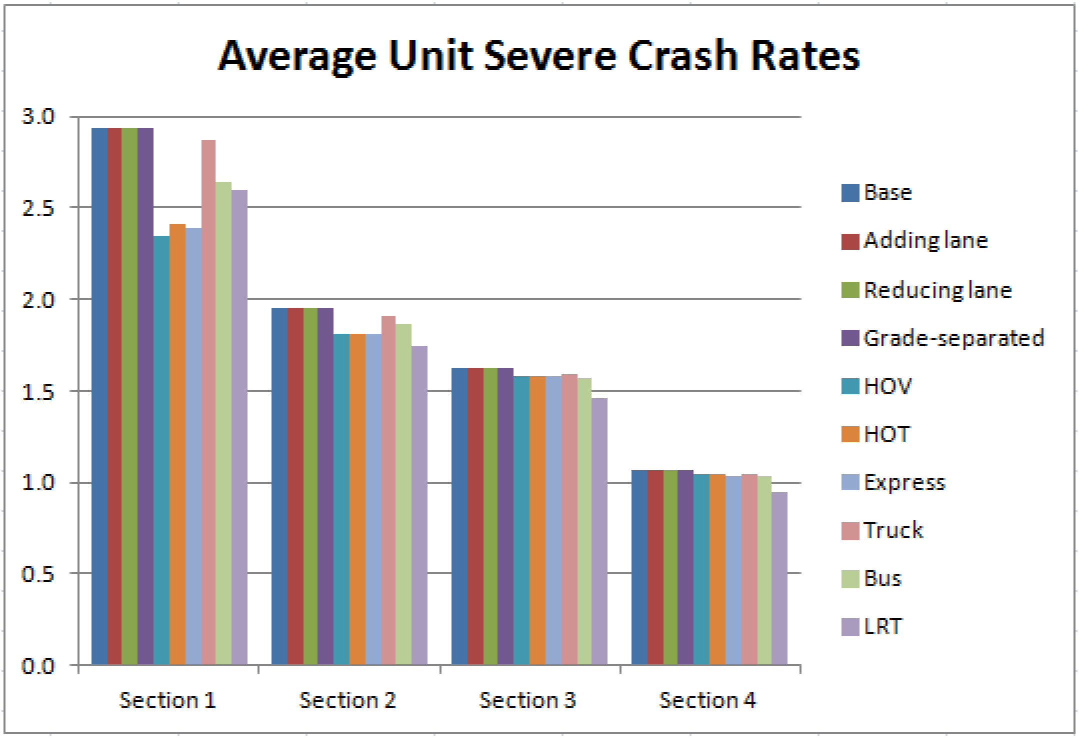
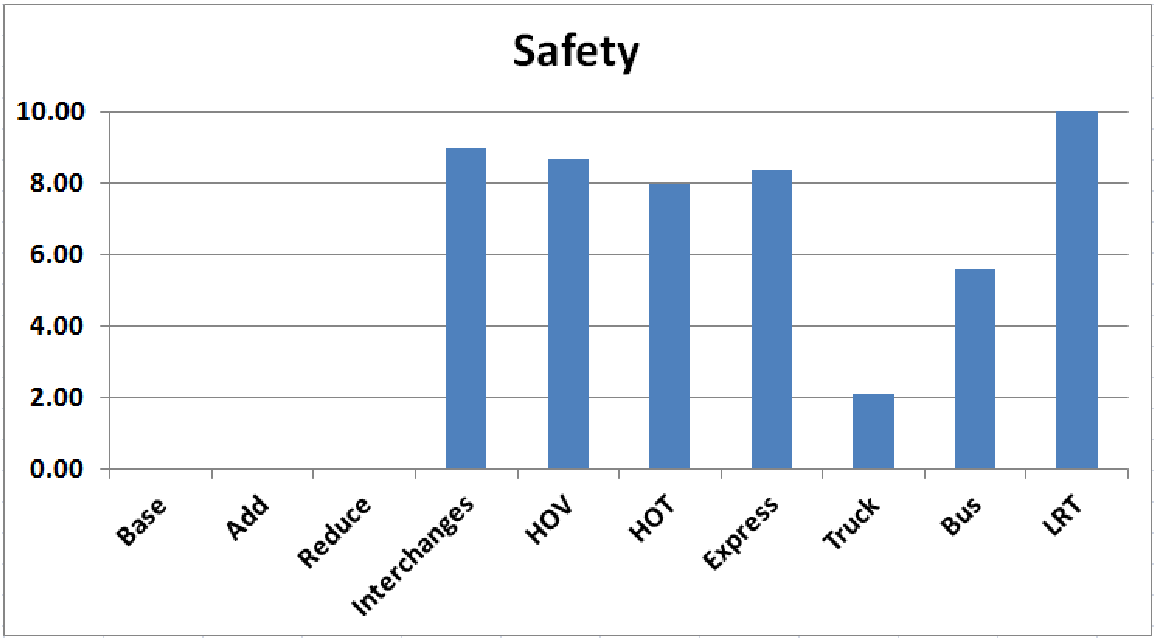


Figure 14. Average Safety Scores along the Study Corridor



The model results indicate that the sections with intersections have much higher total crash rates than freeway sections. Meanwhile, congested sections, such as Section 1 (which displayed a higher incidence of severe crashes) and Section 4 (which displayed a higher rate of total crashes), will model more total and severe crash rates than less congested sections, such as Section 2 and 3, respectively.

As for each modeled improvement scenario, the LRT will be more effective in reducing the crash rates, while adding or removing general purpose lanes will not significantly reduce crashes.

10.4. SOCIOECONOMIC ANALYSIS RESULTS

10.4.1. ECONOMICS MODEL RESULTS

10.4.1.1. Agglomeration Economic Benefits

Economic benefits from agglomeration effects were calculated as the sum of the change in effective density of employment multiplied by the productivity elasticity, output per worker, and employment. The team also evaluated the alternatives' economic benefits by comparing the proportion of economic improvements from agglomeration effects to GDP per worker for each section. The results for the economic benefits as well as the rates of the benefits are listed in Tables 39 and 40. Figure 15 demonstrates the features of each improvement option.

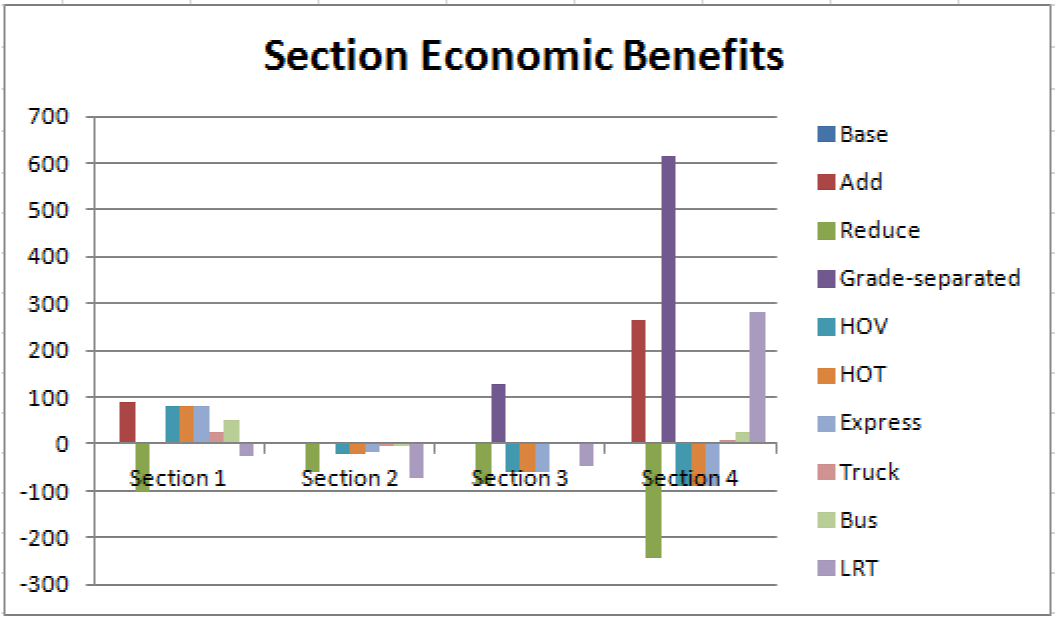
Table 39. Economic benefits from agglomeration effects

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	0.000	90.961	-103.286	0.000	79.597	79.597	79.597	23.488	49.935	-24.133
2	0.000	0.000	-60.830	0.000	-21.305	-22.567	-18.803	-0.052	-0.052	-72.468
3	0.000	0.000	-86.129	126.629	-60.825	-60.825	-60.825	0.000	0.000	-49.023
4	0.000	263.909	-242.141	617.082	-90.006	-90.006	-90.006	7.130	26.127	280.739
Average	0.000	354.870	-492.385	743.711	-92.539	-93.801	-90.037	30.566	76.010	135.115

Table 40. Percentage of Total Economic Benefits Compared with GDP per Worker

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	0.000	0.758	-0.861	0.000	0.663	0.663	0.663	0.196	0.416	-0.201
2	0.000	0.000	-0.507	0.000	-0.178	-0.188	-0.157	0.000	0.000	-0.604
3	0.000	0.000	-0.718	1.055	-0.507	-0.507	-0.507	0.000	0.000	-0.409
4	0.000	2.199	-2.018	5.142	-0.750	-0.750	-0.750	0.059	0.218	2.339
Average	0.000	0.739	-1.026	1.549	-0.193	-0.195	-0.188	0.064	0.158	0.281

Figure 15. Economic Impacts Results



10.4.2. LIVABILITY MODEL RESULTS

The livability model results are composed of three major scores: land-use mix scores, travel time and transit usage.

As mentioned previously, 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. The land-use mix score on a no-build condition was derived from the average land-use score for all the TAZs within 1/4-mile buffer along the corridor, where 0 represents the worst land-use mix situation and 1 is the best case. The research team then developed an online survey to obtain land-use scores representing individuals' opinions. The purpose was to observe how different highway improvement options affect various land-use types along a particular corridor (e.g. US 29), based on the score in the base case. The average scores from the survey were used as the default impact scores in the current version of MOSAIC and are presented below in Table 41.

Table 41. Impact of Highway Improvements on Land Use

Improvement Types	Land-use Mix Scores
No-build condition	0.66
Adding one GP Lane	0.76
Removing one GP lane	0.55
Building the grade-separated interchanges along arterial sections	0.66
Adding one HOV lane or converting one GP lane into HOV lane	0.65
Adding one HOT lane or converting one GP lane into HOT lane	0.64
Adding one truck only lane	0.61
Adding one bus only lane	0.66
Building LRT	0.72

Travel time scores were calculated based on the roadway's travel time. Here, 1 represents the worse condition, while 10 is the best condition. The final scores were then added into the final livability scores.

The transit usage score is represented by the percentage of people using public transit, which includes bus transit and LRT. A higher number of person trips using public transit will achieve a higher score. The number of person trips using each mode is listed below in Table 42.

Table 42. Person trips by mode

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	6240	6240	6240	6240	10080	9456	6332	8880	6240	11049
2	4224	4224	4224	4224	4944	4944	4237	4320	4224	7065
3	3360	3360	3360	3360	3504	3456	3397	3408	3360	5632
4	864	864	864	864	864	912	894	864	864	1512

10.4.3. NOISE MODEL RESULTS

As basic inputs for noise models, the US 29 roadway speeds and AADT levels are listed in Tables 43 and 44 for preparing the case study.

Table 43. Roadway Speed along US 29 (mph)

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	47.771	57.767	40.906	47.771	55.844	55.844	55.844	50.166	53.880	52.553
2	60.000	60.000	54.281	60.000	58.254	58.124	58.216	60.000	60.000	60.000
3	60.000	60.000	57.506	60.000	58.748	58.748	58.748	60.000	60.000	60.000
4	29.119	35.000	27.038	29.119	29.449	29.449	29.449	29.499	29.985	35.000

Table 44. AADT Level along US 29

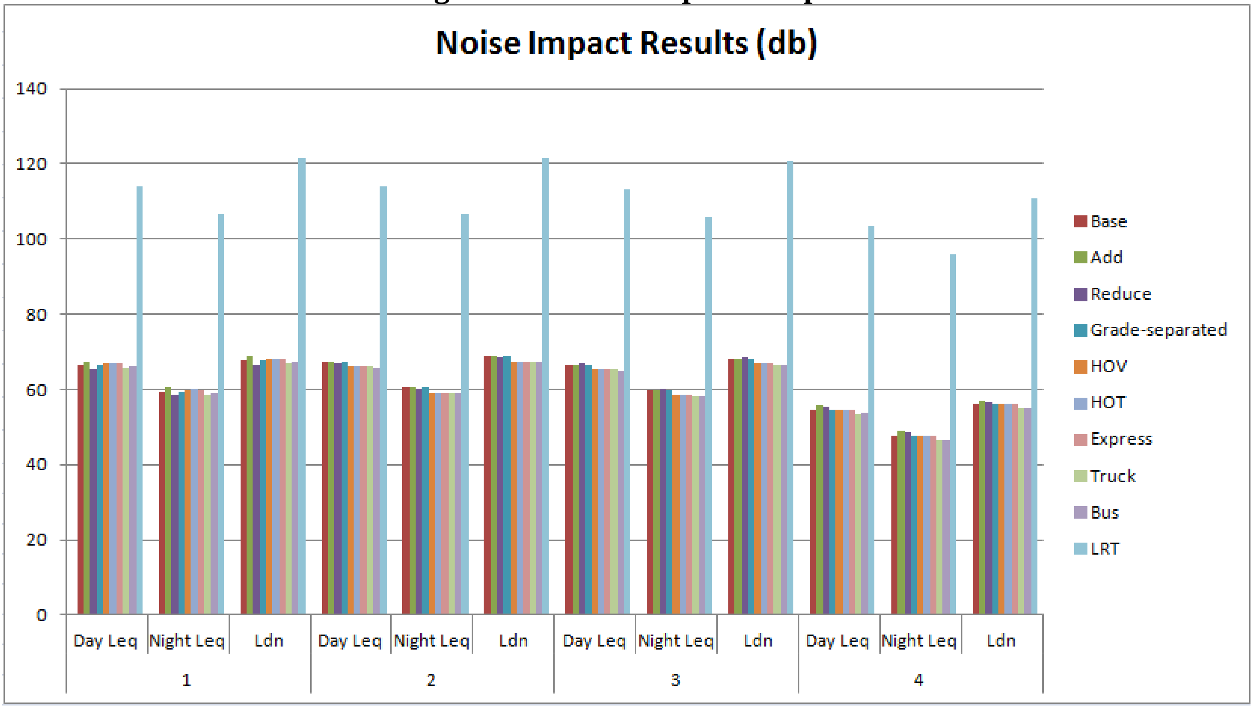
Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	20969	14978	26211	20969	14372	14850	14597	14978	13402	18190
2	13469	13469	16836	13469	10655	10652	10622	9621	9531	11878
3	11127	11127	13909	11127	9160	9193	9172	7948	7916	9844
4	6029	4522	9044	6029	6028	6015	5995	4522	4522	5284

The results are presented in Table 45 in terms of daytime hourly Leq, nighttime hourly Leq, and daytime-nighttime hourly Ldn at 50 feet. Figure 16 indicates that the LRT scenario will contribute a much more significant noise impact compared to other alternatives. In addition, Section 4 had the lowest noise impact, compared to other sections.

Table 45. Noise Impact Results

Section	Leq	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	Day Leq	66.43	67.44	65.38	66.43	66.82	66.96	66.89	65.60	66.05	114.10
	Night Leq	59.44	60.45	58.39	59.44	59.83	59.97	59.90	58.61	59.06	106.68
	Ldn	67.81	68.83	66.76	67.81	68.21	68.35	68.27	66.99	67.44	121.54
2	Day Leq	67.47	67.47	67.14	67.47	66.07	66.04	66.05	66.01	65.97	113.98
	Night Leq	60.49	60.49	60.15	60.49	59.08	59.05	59.06	59.02	58.98	106.56
	Ldn	68.86	68.86	68.52	68.86	67.46	67.43	67.44	67.40	67.36	121.41
3	Day Leq	66.65	66.65	67.06	66.65	65.53	65.54	65.53	65.18	65.17	113.16
	Night Leq	59.66	59.66	60.07	59.66	58.54	58.55	58.54	58.19	58.18	105.74
	Ldn	68.03	68.03	68.45	68.03	66.91	66.93	66.92	66.57	66.55	120.60
4	Day Leq	54.57	55.71	55.36	54.56	54.71	54.70	54.69	53.48	53.70	103.44
	Night Leq	47.58	48.72	48.37	47.57	47.72	47.71	47.70	46.49	46.71	96.02
	Ldn	55.95	57.10	56.74	55.95	56.10	56.09	56.07	54.87	55.08	110.87

Figure 16. Noise Impact Graph



10.4.4. AESTHETICS ANALYSIS RESULTS

As a part of this project, an online survey was developed and distributed for the aesthetics analysis along US 29. The following table shows the survey results for the US 29 corridor, which can be generalized to other corridors in Maryland. In general, the survey showed that the impact of the six highway improvement types had minimum effects on aesthetics (scores close to 0). On the other hand, the survey revealed that visual appeal and historical site protection were more significant in determining the aesthetics along the corridor.

Table 46. Impact of Highway Improvements on Aesthetics along the US 29 Corridor

Elements	Average Rating Scores for the Aesthetics of Base and Improved Cases along US 29 (-3 ~ +3)									Average Weighting Scores (1 ~ 7)
	Base Case	HOV	HOT	Bus only	Truck only	LRT	Road Diet	Add	Interchanges	
Facilities' Compatibility	0.00	1.00	0.67	0.57	1.00	0.71	-0.67	1	1.29	3.83
Land Use Attractiveness	0.14	0.75	0.75	0.43	0.50	1.38	-0.50	0.71	0.43	3.67
Visual Appeal	0.43	0.57	0.25	0.50	0.00	0.88	0.50	0.29	0.43	5.33
Historical Road and Sites Protection	0.43	0.00	0.00	0.25	-0.38	-0.63	0.75	-0.33	0	5.00

10.5. NATURAL RESOURCES ANALYSIS RESULTS

As for the roadway improvement alternatives' effects on natural resources, the research team applied ArcGIS to calculate the areas of the natural resources that were covered within each improvement's impact buffer distance. The area coverage for each improvement alternative is listed in Table 47.

Table 47. Natural Resources Area Coverage for Each Improvement Alternative (Square Miles)

Add	Reduce	Interchanges	HOV	HOT	Express	Truck	Bus	LRT
0.106	0	1.810	2.002	2.002	2.002	2.834	2.834	1.438

10.6. ENERGY AND EMISSIONS ANALYSIS RESULTS

As mentioned previously, the specific energy consumption rate for fuel (given in British Thermal Units per mile) and pollutant emission rates (given in grams per mile) for carbon monoxide (CO), nitrogen oxides (NOx), particulate matter less than 10 micrometers (PM_{10}) and carbon dioxide (CO_2) are required prior to running further energy and emission models. The specific rates for

US 29 were obtained from EPA's MOVES and additional literature review for LRT's rates. These rates are summarized in Table 48.

Table 48. Energy and Emission Rates for LRT Mode

CO	NOx	PM_{10}	CO_2	Fuel
(g/p-m)	(g/p-m)	(g/p-m)	(g/p-m)	(BTU/p-m)
0.0355	0.6123	0.0232	284.66	2.516

10.6.1. POLLUTION EMISSION ANALYSIS RESULTS

Roadway pollution emissions for different types of pollutants were computed based on vehicle miles traveled and per-mile emission rates that vary by travel speeds. By taking into account the updated AADT level for each improvement option, the team obtained the total pollution emissions shown in Tables 49, 50, and 51. Meanwhile, Figure 17 shows the graphs presenting the quantitative results.

The trends in the graphs demonstrate that the LRT scenario can reduce pollution emission for all four sections. The HOV and HOT scenarios, where one HOV/HOT lane would be added or one general-purpose lane would be converted to either of these lanes act more effectively and efficiently to reduce the pollution emissions along more congested sections.

Table 49. CO Emissions along US 29 corridor (Million Grams)

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	1.24	1.14	1.11	1.24	0.88	0.91	0.88	1.20	1.04	1.05
2	1.23	1.23	1.19	1.23	1.10	1.10	1.10	1.21	1.20	1.09
3	0.95	0.95	0.89	0.95	0.88	0.88	0.88	0.93	0.93	0.84
4	0.10	0.09	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.08
Total	3.52	3.41	3.29	3.52	2.97	3.00	2.97	3.44	3.27	3.06

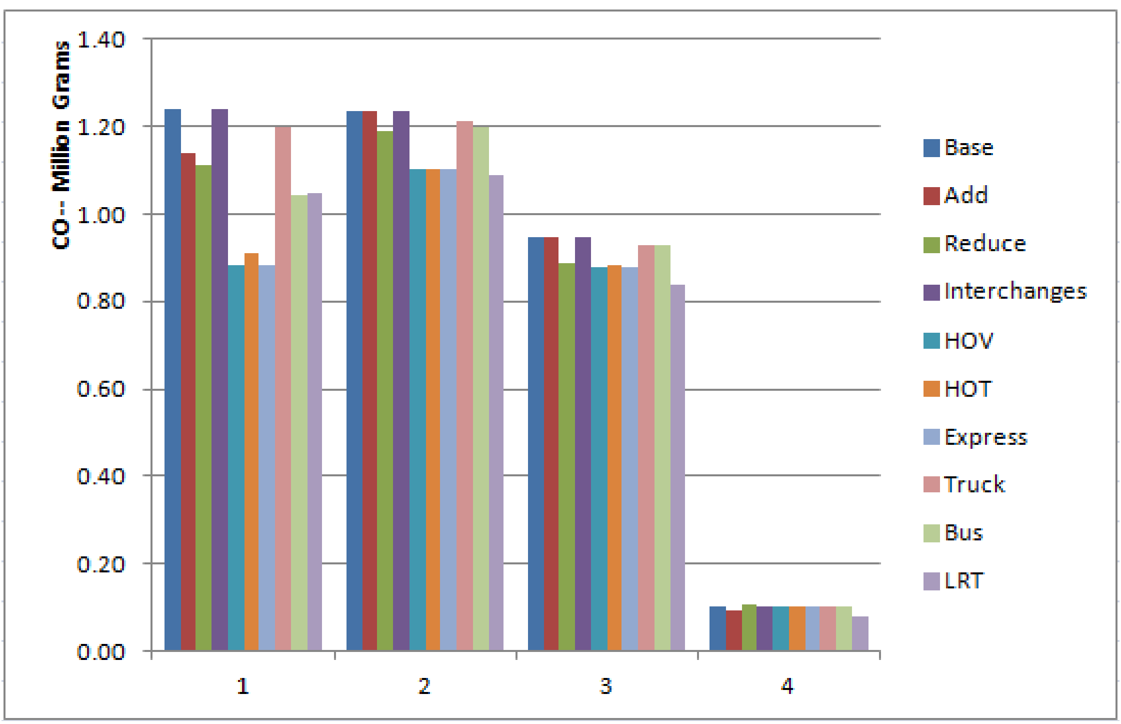
Table 50. NOx Emissions along US 29 corridor (Million Grams)

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	0.39	0.37	0.36	0.39	0.29	0.30	0.29	0.38	0.33	0.35
2	0.41	0.41	0.38	0.41	0.36	0.36	0.36	0.40	0.40	0.38
3	0.29	0.29	0.28	0.29	0.27	0.27	0.27	0.29	0.29	0.28
4	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Total	1.13	1.10	1.05	1.13	0.95	0.96	0.95	1.10	1.05	1.04

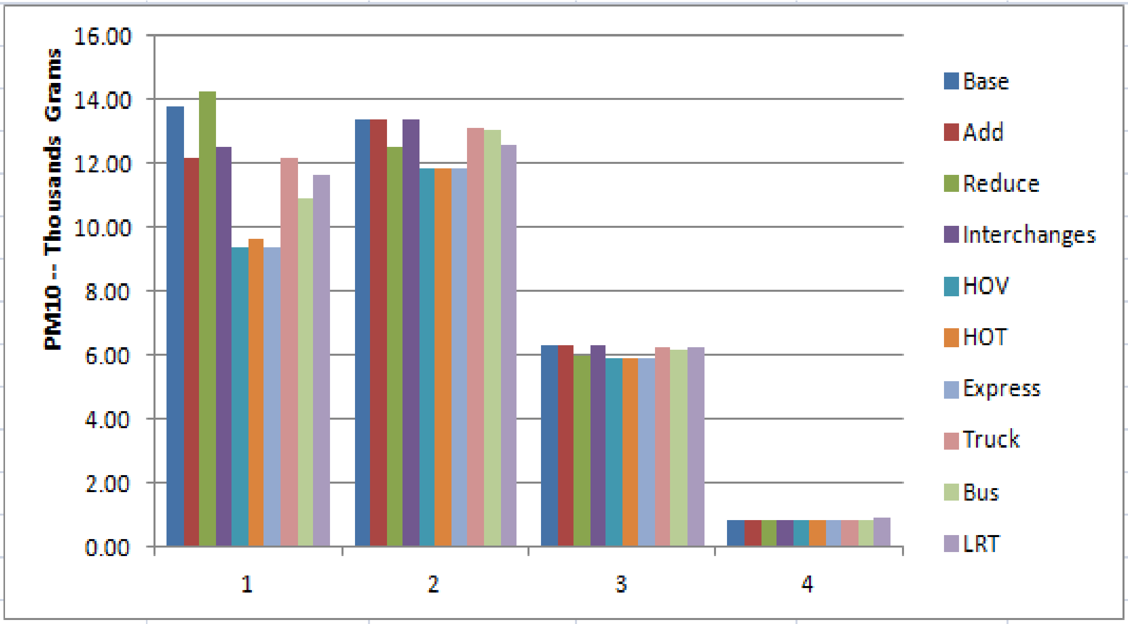
Table 51. PM_{10} Emissions along US 29 corridor (Thousand Grams)

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	0.39	0.37	0.36	0.39	0.29	0.30	0.29	0.38	0.33	0.35
2	0.41	0.41	0.38	0.41	0.36	0.36	0.36	0.40	0.40	0.38
3	0.29	0.29	0.28	0.29	0.27	0.27	0.27	0.29	0.29	0.28
4	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	1.13	1.10	1.05	1.13	0.95	0.96	0.95	1.10	1.05	1.04

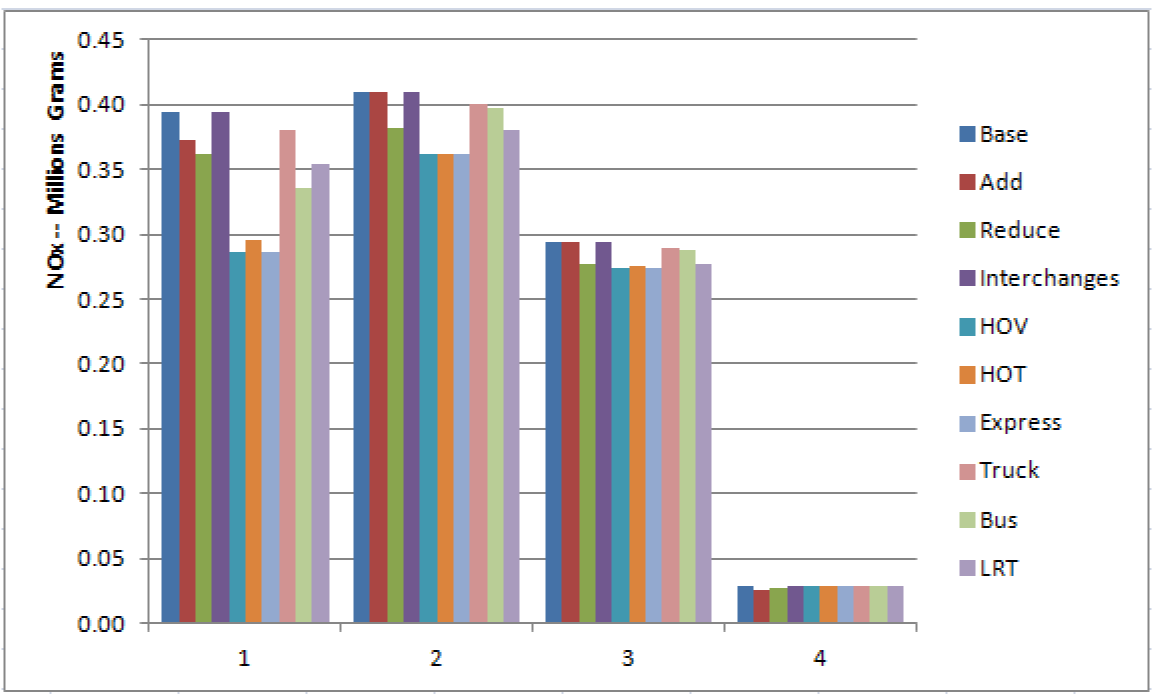
Figure 17. Pollution Emission Results



(1) Total Carbon Monoxide Emission



(2) Total Particulate Matter 10 Emission



(3) Total Nitrogen Oxide Emission

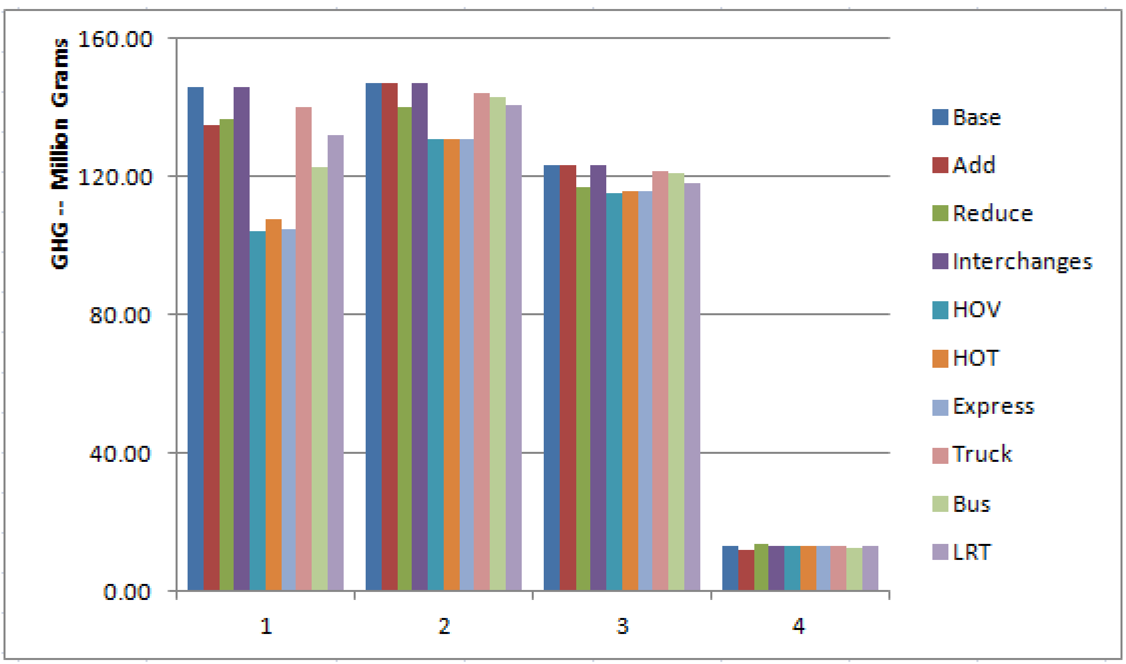
10.6.2. GREEN HOUSE GAS EMISSION ANALYSIS RESULTS

By following the method for the emission estimation models, the Green House Gas (GHG), or Carbon Dioxide (CO_2), emissions along US 29 for each improvement alternative are computed. The results are listed in Table 52 and presented in Figure 18. They have similar trends to the pollution emission.

Table 52. GHG Emission along US 29 corridor (Million Grams)

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	146.10	135.01	136.52	146.10	104.28	107.75	104.88	140.32	122.78	131.98
2	147.25	147.25	140.05	147.25	130.88	130.90	131.08	144.34	143.00	140.71
3	123.57	123.57	116.95	123.57	115.41	115.82	115.91	121.61	121.12	117.83
4	13.02	11.89	13.59	13.02	12.93	12.90	12.95	12.92	12.79	12.98
Total	429.95	417.72	407.10	429.95	363.49	367.37	364.81	419.19	399.70	403.50

Figure 18. GHG Emissions along US 29



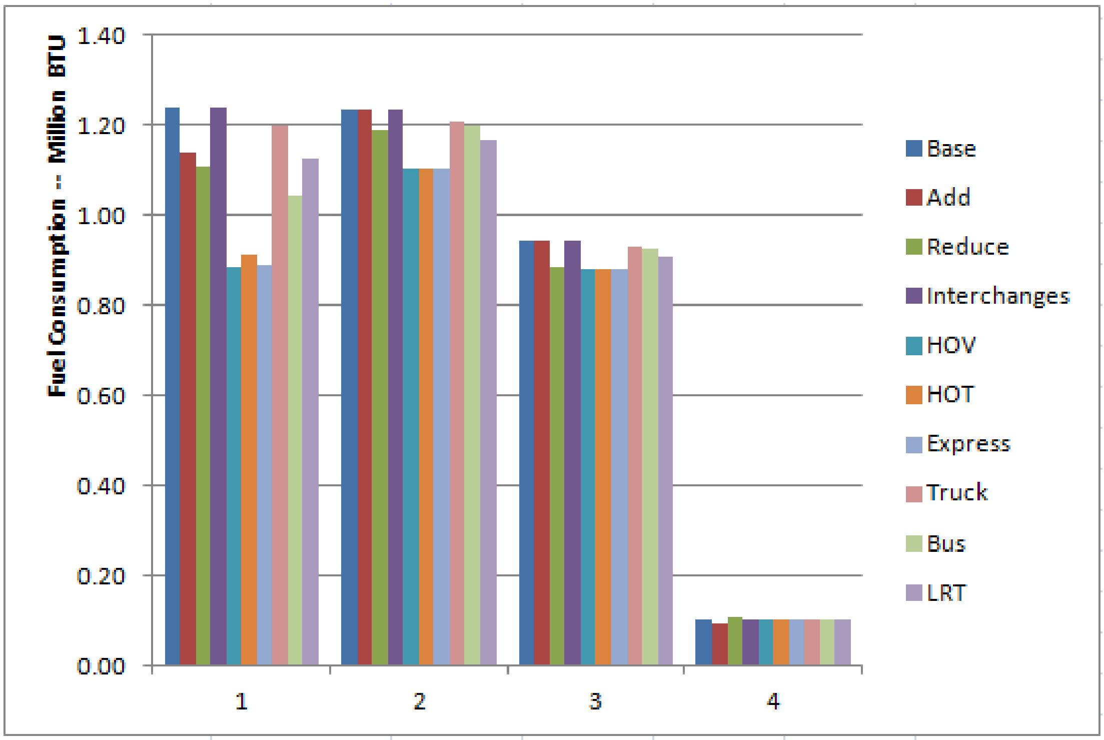
10.6.3. FUEL CONSUMPTION ANALYSIS RESULTS

Table 53 and Figure 19 indicate that in each improvement scenario, total fuel consumption along US 29 is reduced compared to the base case.

Table 53. Fuel Consumption along the US 29 corridor (Million BTUs)

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
1	1.24	1.14	1.11	1.24	0.88	0.91	0.89	1.20	1.04	1.13
2	1.23	1.23	1.19	1.23	1.10	1.10	1.10	1.21	1.20	1.17
3	0.95	0.95	0.89	0.95	0.88	0.88	0.88	0.93	0.93	0.91
4	0.10	0.09	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Total	3.52	3.41	3.29	3.52	2.97	3.00	2.98	3.44	3.27	3.31

Figure 19. Fuel Consumption along US 29



10.7. COSTS ANALYSIS RESULTS

The total costs for all alternatives were based on per-mile and vehicle costs as mentioned in the earlier cost methodology section.

In the HOV and HOT improvement plans, 8.05 miles of HOV or HOT lanes would have to be built and 18.9 miles of general purpose lanes would have to be converted to HOV or HOT lanes in both directions. The total cost of this construction would be $283 million. As for bus and truck-only lanes, 26.95 miles would be built for either alternative in both directions. By applying the cost rates correspondingly, the final cost would be $808.5 million for the bus-only lanes and $970.2 million for the truck-only lanes. In the LRT scenario, the state would need to both build the necessary infrastructure and provide two vehicles. Thus, the total cost in the LRT scenario would be $3.64 billion. The total cost for each improvement alternative along US 29 is summarized in Table 54 as follows:

Table 54. Total Costs for Each Corridor Improvement Alternative along US 29

Section	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
Total costs ($ million)	104	36	1,160	283	283	283	809	970	3,643

10.8. MOSAIC FINAL SCORES

After obtaining the quantitative results for the case study along US 29, the research team converted the quantitative results into qualitative scores for each major sustainability indicator category. A score of 1 represented the worst condition, and 10 indicated the best improvement (See Table 55 and Figure 20). Table 56 and Figure 21 show the results when the same weight is given to each major category. As an example for the user weighting system contained in MOSAIC, if users were concerned only with mobility and safety indicators, the final trends and scores would appear similar to Figure 22. In contrast, if users were interested solely in natural resource and energy consumption indicators, the trends and scores would appear similar to Figure 23.

Table 55. MOSAIC Final Scores along US 29

Section	Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
Mobility	7.70	10.00	0.00	9.75	5.85	5.82	5.92	8.03	8.45	8.46
Safety	0.00	0.00	0.00	8.95	8.67	7.98	8.34	2.10	5.56	10.00
Socioeconomics	6.54	10.86	0.00	10.00	3.75	5.32	4.55	6.64	5.94	5.24
Natural Resources	10.00	9.63	10.00	3.61	2.94	2.94	2.94	0.00	0.00	4.93
Energy & Fuel	0.00	1.94	3.50	0.39	10.00	9.43	9.92	1.81	4.65	5.14
Costs	10.00	9.71	9.90	6.82	9.22	9.22	9.22	7.78	7.34	0.00
Total	34.25	42.14	23.40	39.52	40.43	40.71	40.90	26.36	31.93	33.76

Figure 20. MOSAIC Final Scores along US 29

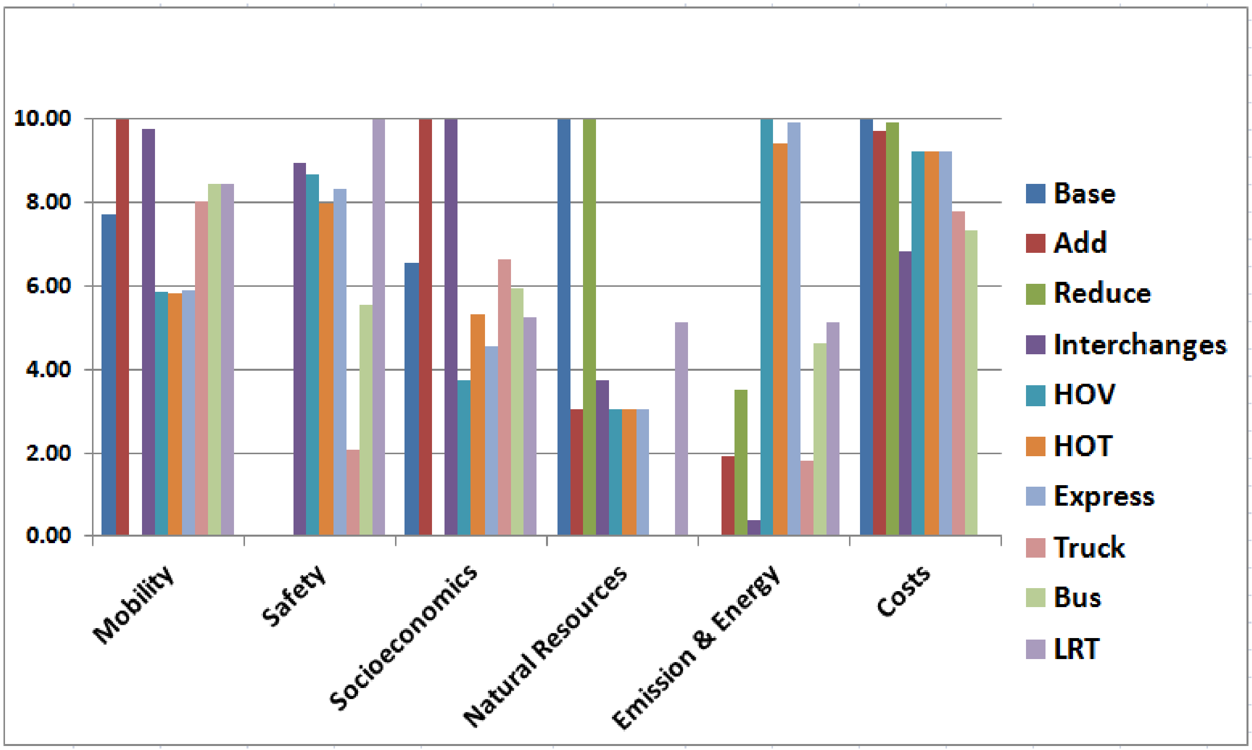
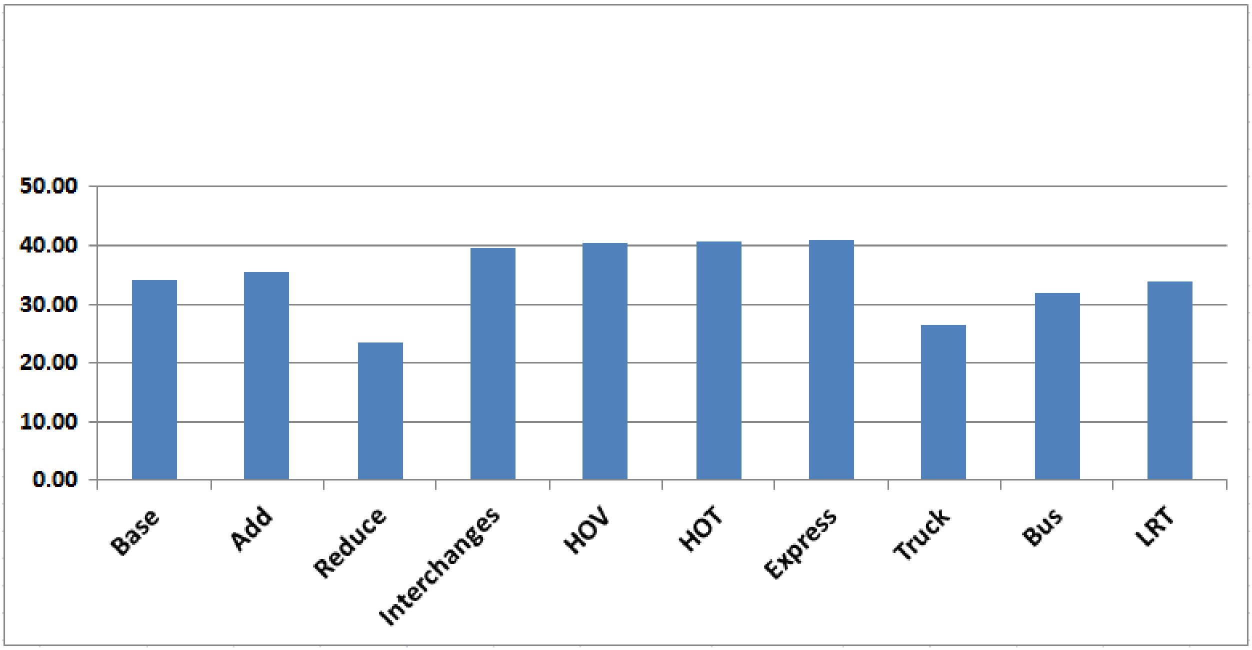


Table 56. MOSAIC Final Scores for Each Alternative

Base	Add	Reduce	Grade-separated	HOV	HOT	Express	Truck	Bus	LRT
34.25	35.56	23.40	39.66	40.55	40.82	41.01	26.36	31.93	33.96

Figure 21. MOSAIC Final Scores for Each Alternative (Same weight)



The results show that several improvement options will provide improved sustainability along the US 29 corridor: adding a general purpose lane, upgrading intersections to grade-separated interchanges, constructing a high-occupancy vehicle lane, constructing a high-occupancy toll lane, or constructing an express toll lane. Based on the default-weighted scores, the express toll lane scenario is able to improve the corridor's sustainability to the largest extent, and reducing one general-purpose lane is the worst alternative. However, the research team gave the same weight for each major sustainability category for the case study. Users can change the weights according to their particular focus by moving the weighting bar mentioned in Chapter 9. The final scores may change along with the change of weights. In this way, certain improvement alternatives may prove better-suited for the US 29 corridor based on prevailing policies and interests.

Figure 22. MOSAIC Final Scores for Each Alternative (Focusing on Mobility and Safety)

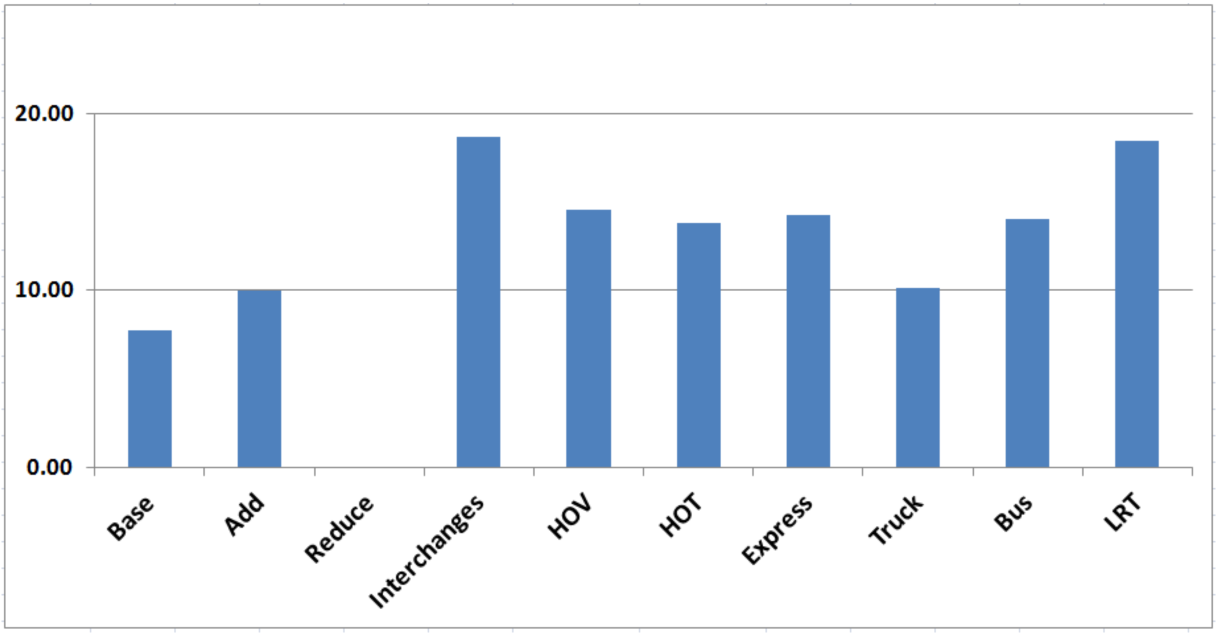
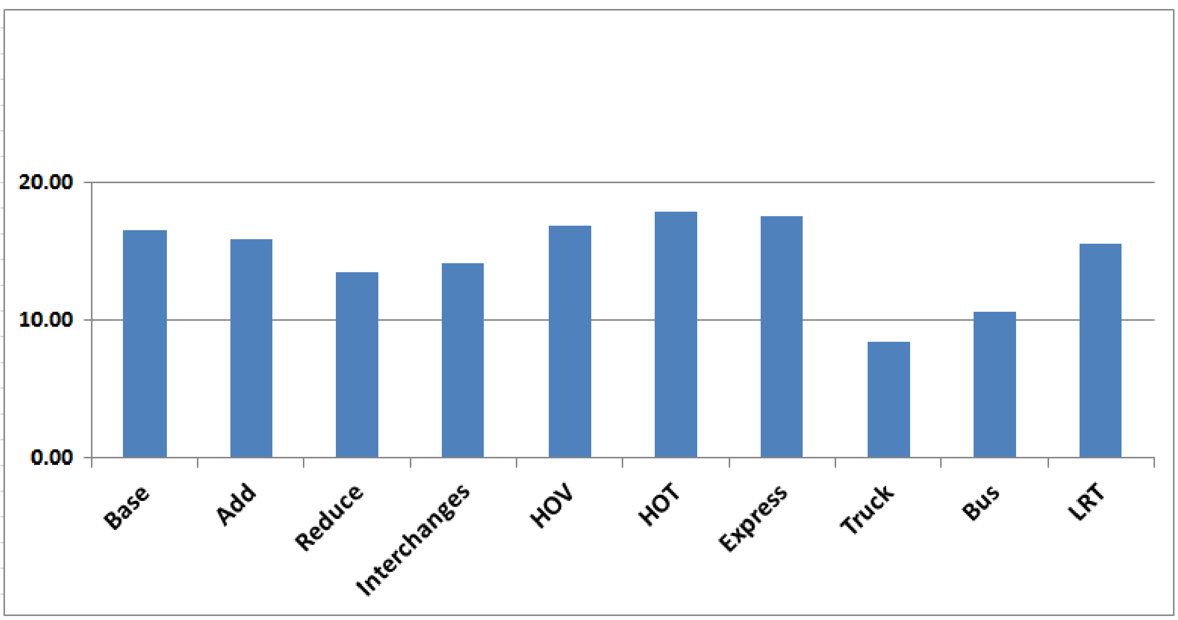


Figure 23. MOSAIC Final Scores for Each Alternative (Focusing on Green Solutions)

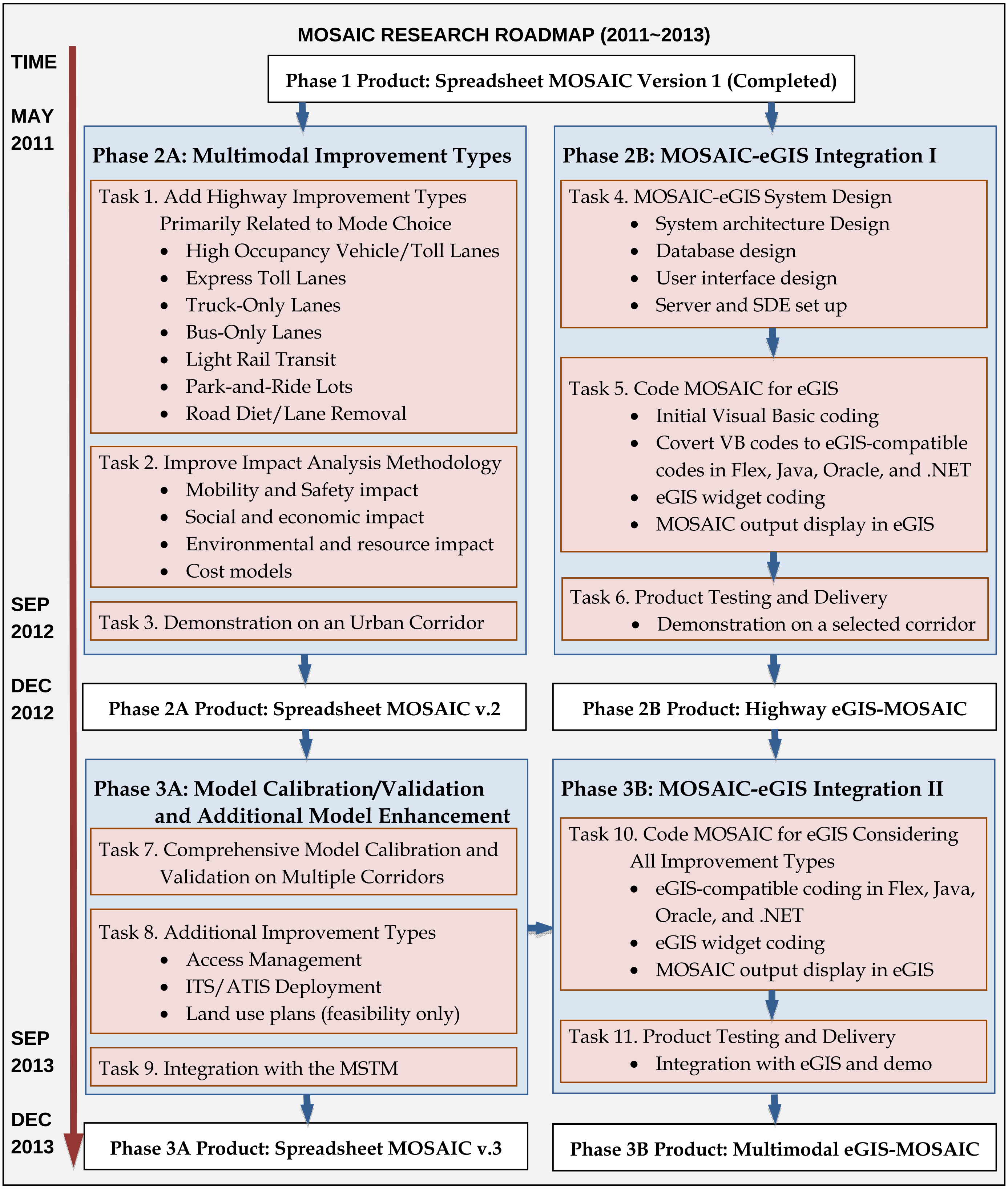


CHAPTER 11: MOSAIC RESEARCH ROADMAP

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 Enterprise Geographical Information System (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. 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. Also, the roadmap will 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 can become a flagship application of the SHA CHC program and sustainability initiatives. By doing so, it would not only assist SHA in multimodal highway corridor improvement decision-making but also demonstrate SHA’s commitment to incorporating social, economic, environmental, and sustainability considerations in its transportation planning process.

Figure 24. MOSAIC Research Roadmap



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APPENDIX I: AESTHETICS AND LAND USE SURVEY

Model Of Sustainability and Integrated Corridors (MOSAIC) Survey

Introduction

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. Our Comprehensive Highway Corridor Planning with Sustainability Indicators project as well as the Model Of Sustainability and Integrated Corridors (MOSAIC) will assist SHA in selecting the most sustainable corridor improvement option for its Highway Needs Inventory to balance its mobility, safety and environmental stewardship objectives based on pre-defined policy goals.

In phase two, MOSAIC takes into account the no-build case and six highway improvement options, including adding one HOV or HOT lane, converting one general purpose lane to HOV or HOT lane, adding one bus or truck-only lane, adding new LRT, and applying the road diet.

Aesthetics

Aesthetics is a branch of philosophy dealing with the nature of beauty, art, and taste, and with the creation and appreciation of beauty, and it is sometimes called judgments of sentiment and taste. More broadly, scholars in the field define aesthetics as "critical reflection on art, culture and nature." MOSAIC incorporates four aesthetic factors into its socioeconomic models: facility compatibility, land use attraction, visual appeal, and historical roads' and sites' protection. Please rate and weight the factors below which would potentially affect the roadway aesthetics in the base case and six improvement options:

1. Facilities' Compatibility

How would you rate the facilities compatibility condition along US-29 in base case and six improvement alternatives? The facilities include traffic control devices, lighting, Splitter Island, roundabouts' design, etc.

2. Land Use Attraction

How would you rate the land use attraction condition along US-29 in base case and six improvement alternatives? The Land Use Attraction includes the transportation network's land use issue and landscape.

3. Visual Appeal

How would you rate the visual appeal condition along US-29 in base case and six improvement alternatives? Visual Appeal includes visual friction (various interesting views or boring too smooth views along the corridor), views conservation (with or without visual intrusive), sight distance and clear areas.

4. Historical Roads' and Sites' Protection

How would you rate the historical roads' and sites' protection condition along US-29 in base case and six improvement alternatives?

5. Please also weight each factor reflecting their importance in determining the performance of aesthetics. (1=not important at all; 7= most important)

6. Comments

If there are other factors that you think are important in affecting the performance of aesthetics, please list them below and give your weight with the scores from 1 to 7.

Land-use Mix Scores

Land use mix refers to locating different types of land uses close together. Increased land use mix tends to reduce the distances that residents must travel for errands and allows more use of walking and cycling for such trips.

MOSAIC regards the land-use mix condition as one of the main factors that affect the livability within a quarter mile buffer on either side of the highway corridors. Land-use types considered in MOSAIC include industrial, commercial, recreational, agricultural, and low and high-density residential areas. The land-use mix score along US-29 is 0.66 in base case, where 0 represents the worst land-use mix condition, while 1 represents the best condition. Please give your land-use scores below for six improvement alternatives along US-29: