

ABSTRACT

Title of Document: A MATHEMATICAL OPTIMIZATION
MODEL FOR A BICYCLE NETWORK
DESIGN CONSIDERING BICYCLE LEVEL
OF SERVICE.

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Engineering

Bicycle transportation is an important mode for an integrated transportation system. With more federal funding available and an interest in increasing the bicycle mode share, it is necessary to understand ways to efficiently incorporate the bicycle mode into transportation planning. This thesis formulates and solves a mathematical program that optimizes the location of bike routes and bike lane additions from an existing urban road network. Trip distance and bicycle level of service are considered when creating bike routes that connect origin-destination pairs. A case study uses data from the Baltimore Service Level Evaluation from 2003 to examine an area in Baltimore, which displays the mechanics of the model.

A MATHEMATICAL OPTIMIZATION MODEL FOR A BICYCLE NETWORK
DESIGN CONSIDERING BICYCLE LEVEL OF SERVICE.

By

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Dedication

To my mother, father and sister,
whose love and support mean the world to me.

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Glossary

Bike Facilities: A general term for any improvements or provisions that accommodate or encourage bicycling. These range from parking facilities to on street bike lanes and separate bike trails. Shared roadways not specifically designed for bicycles are also included. (AASHTO)

Bike Lane: A portion of the roadway that is striped with pavement markings showing its exclusive or preferential use for bicycles (AASHTO)

Bikeway: General term for any road or path designed specifically for bicycles, whether the facility is exclusively for bicycles or intended to share with other transportation modes. (AASHTO)

Right-Of-Way: Land or property, usually in a strip, acquired for transportation purposes (AASHTO)

Roadway: The portion of road, including shoulders, intended for automobile use (AASHTO)

Shared Roadway: A roadway that can accommodate automobile and bicycle travel. This may be an existing roadway or a road with a wide curb lane or paved shoulder. (AASHTO)

Shoulder: A portion of the roadway adjacent to through lanes, to accommodate stopped vehicles, emergency use, and lateral support of sub-base, base, and surface courses. (AASHTO)

Wide Curb Lane or Wide Outside Lane: A curbside travel lane, wider than normal to accommodate for bicycles where there is insufficient room for a bike lane.

(Oregon, 1995)

Outside Through Lane: Curbside travel lane, important for bicycle planners because cyclistists travel in this lane if no other facilities are provided

Chapter 1: Introduction

1.1. Research Motivation

1.1.1. Bicycle Transportation

Bicycle transportation is an important mode in an integrated transportation system that offers significant benefits to society. Bicyclists experience health, mobility, and economic rewards while society receives environmental and livability advantages. As concern for congestion and pollution rises, the US Department of Transportation has established a goal to increase bicycle use. Of particular importance is to have bicycle trips replace car trips, so utilitarian trips must be a concern in transportation research.

According to the 2009 National Household Travel Survey, one percent of all trips made by Americans are by bicycle. Realistically, many of these trips are too long to be feasible by bike. Of those trips under three miles, a reasonable distance for a bike, 72 percent are made in vehicles (National Bicycle Study, 2010). For shorter trips, the bicycle competes with cars for travel time, especially when considering congestion. The bicycle is not intended to replace the automobile, but for short trips, it should be a viable option.

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 established eligibility requirements for programs with federal funding so that bicycle transportation projects would qualify. This policy was updated with the

Transportation Equity Act for the 21st Century (TEA-21) of 1998, and the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) of 2005. More programs and policies were added to each act, and the funding for bicycle projects increased.

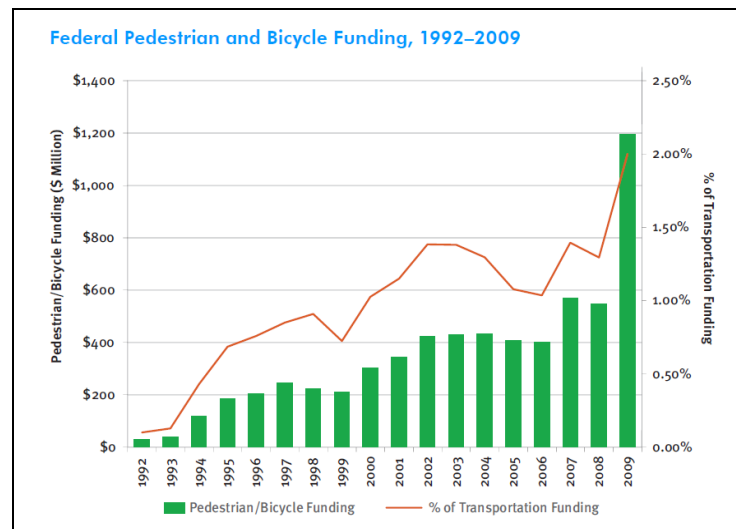


Figure 1.1: 2010 National Bicycle and Walking Study, FHWA

Figure 1.1 illustrates the increased level of federal funding available for bicycle and pedestrian projects, from 1992 to 2009, as a percent of all transportation funding available. The most dramatic increase occurs in 2009, where there is 1.2 billion dollars in funding available, twice the amount from the previous two years. In addition to increases in funding, the United States Department of Transportation now has a policy to incorporate safe and convenient bicycle facilities in transportation projects. Transportation agencies are encouraged to go beyond minimum requirements for incorporating safe bicycle and pedestrian modes (National Bicycle Study, 2010). With interest and funding available for the increase of bicycle transportation, this topic requires further research to make responsible, effective decisions that incorporate bicycles into transportation planning.

1.1.2. Bicycle Lane Improvements

Bike facilities refer to any improvements or provisions that accommodate or encourage bicycling. These range from bicycle parking to on street bike lanes and separate trails. A bike lane, one type of bicycle facility, is a portion of the roadway that is striped with pavement markings showing its exclusive or preferential use for bicycles (AASHTO, 1999). An experienced cyclist may be comfortable biking in automobile traffic with no bike facilities. However, newer cyclists or potential cyclists may not be comfortable unless there is some space for bicycle movements. This thesis focuses on bike lane additions as a means to improve and increase bicycle use within a transportation network. Since there is an interest in increasing the bicycle mode share, facility improvements are necessary to encourage more people to bike rather than rely only on their current means of transportation. Separate bike trails attract more recreational riders because of their typical location outside of a city center. Separate bike trails are also expensive to construct and require space typically unavailable in urban areas where most trips occur. Bike lanes, incorporated into the road network, will offer more direct paths for utilitarian bike trips. Cyclists with utilitarian trip purposes are important to planners because they can replace automobile trips.

There are guidelines, recommendations, and requirements for planning bicycle facilities. However, there is no standard way to design bicycle routes in a network. This thesis formulates a program that can assist bicycle route design by forming connected routes that offer direct paths considering the bicycle level of service.

1.1.3. Bicycle Level of Service

The Bicycle Level of Service is a quantitative measure that has been developed to gauge the perceived level of safety from a cyclist's perspective (Landis, 1997). Many state highway departments and transportation planning agencies across the country are using this measure to evaluate road networks for bicycle use. Current applications for this measure include comparing benefits for proposed improvements, identifying weaknesses in a network to prioritize improvements, creating biking suitability maps and documenting improvements in bicycling conditions over time (Baltimore, 2004). These applications are an important start to network bicycle facility planning. However, the applications do not consider the importance of a link to a network as a whole. Because the entire network should be considered when prioritizing segments for improvements, it is critical that planners have tools that allow them to analyze and evaluate an entire network when they are making decisions intended to increase the bicycle mode share.

1.2. Research Objective and Contribution

1.2.1. Objective

The objective of this thesis is to formulate and solve a mathematical program that can assist in selecting locations for bicycle facility improvements in an urban road network considering a biking level of service, trip distance and connectivity. This tool aims to design an urban bicycle network for utilitarian travel and therefore, is focused on adding bike lanes to existing roadways.

1.2.2. Thesis Contribution

This thesis makes significant additions to the body of literature involving bicycle facility planning. It summarizes previous studies that contribute to bicycle network design. It offers an approach to incorporating bike facilities into urban road networks in a cost effective manner. This thesis provides the development of another tool to help planners analyze and evaluate an entire network to make sound decisions.

1.3. Thesis Organization

In chapter two, a summary of key bicycle studies for mode choice and route choice is presented. The concept of biking level of service measures is introduced. Examples of biking level of service measures applied to bicycle network designs are discussed.

In chapter three, the mathematical formulation is presented as a multi-objective mixed integer program. The parameters and specifications are defined. The Bicycle Level of Service (BLOS) model is described, with an emphasis on the effective width term. In chapter four, the case study parameters and data processing steps are described. Details about the network of study are also summarized.

Chapter five presents a sensitivity analysis to justify parameter values for weights for different components of the multi-objective function. The sensitivity of the model to the budget and service level parameters is also examined. Chapter six presents the results from solving a large sample problem. The budget and service level parameters are adjusted in two sample cases to display the mechanics of the model. Lastly, chapter seven summarizes conclusions and offers areas for further study.

Chapter 2: Literature Review

Efficient bicycle network planning requires a clear understanding of the relationship between facilities and cyclists. Many studies have been conducted, attempting to quantify concepts that may lend to increasing the bicycle mode share in the transportation system. A number of key studies are summarized here.

2.1. Mode Choice Studies

Aggregate mode choice studies determine a significant positive correlation between length of bicycle facilities and number of bicycle commuters. The studies do not prove causation, but offer an argument that facilities are a factor in commute percentage.

Nelson and Allen (1997) used a regression analysis to compile census data from 18 diverse US cities. They found an association between miles of bikeways and number of commuters. Explanatory variables used include temperature, annual rain days, terrain, percent college students, and miles of bikeways. The results show one additional mile of bikeway for every 100,000 residents increases the number of bicycle commuters by 0.069 percent. Dill and Carr (2003) continued with Nelson and Allen's work, using a larger sample size of 43 cities, newer census data, and more variables. Bikeways were divided into two classes: separate bike paths and bike lanes. Results show that for cities with 250,000 residents or more, one mile of bike lanes increases the number of bicycle commuters by 1 percent. Calculated in the

same terms as Nelson's study, adding one mile of any bikeway type per 100,000 residents increases the number of bicycle commuters by 0.023%. This is about a third of the value Nelson found.

Both studies show that there is a significant, positive correlation between miles of bikeways and percent bicycle commuters. It is unclear whether better facilities attract more cyclists, or if facilities are provided as a result of more bikers requesting improvements. Nelson suggests that the location of the bikeways is an important factor not considered in his analysis. If more bikeways exist on residents' commute routes, the routes will be used more in their commutes. Dill's study shows that bike lanes have a stronger correlation to commuting than separated trails. Dill proposes this is because bike lanes are often more direct than separated trails. Bike facility locations are important to encourage cycling for commuting.

2.2. Bicycle Preference Studies

Bicycle route choice studies provide information about individual cyclists' preferences for route choice. A variety of data collection and modeling techniques have been used.

Stinson and Bhat (2003) collected stated preference surveys of bike commuters in the US and used a multinomial logit model to show route choice characteristics. The top four preferred attributes in descending order are shorter travel time, residential roads instead of an arterial road, the presence of bike facilities, and facilities existing on

bridges. Continuous facilities are valued more on arterial streets compared to those on residential streets.

Hunt and Abraham (2007) took stated preference surveys in Edmonton, CA. A logit model was used to show influences on bike use. The value of traveling on different facilities was compared in time units: 1 minute of biking in mixed traffic, 2.8 minutes on a bike path, and 4.1 minutes in a bike lane were all equivalent. This illustrates the trade-off between travel time and level of comfort. Furthermore, the relative attractiveness of bike lanes to a person increases as the level of biking experience increases.

Tilahun, Levison and Krizek (2007) used a computer based adaptive stated preference survey to show the value of different bicycle facilities to users with a travel time trade off. Both a logit model and linear utility model produced similar results: designated bike lanes were valued the most, followed by roadways without car parking on the street and lastly off-road improvements.

Sener, Eluru and Bhat (2009) formulated a stated preference survey of Texan bicyclists into a mixed multinomial logit model. This study looked at both commuters and non-commuters. The most significant variables were travel time, especially for people under 35, and traffic volumes, particularly for commuters. Terrain preferences differed between genders and trip purpose. Women preferred flatter routes than men for utilitarian use. Both men and women preferred more challenging terrain for recreational use, with men preferring steep terrain and women

preferring moderate hills. A dummy variable for continuity was found positive and significant. Finally, routes with less car-parking activity were preferred.

Dill (2009) conducted a study in Portland, Oregon in which participants used a GPS device on their bike to track bike trips over one week. Participants also answered questions about each trip. While 8% of the road network in Portland has bicycle facilities, 52% of bike trips were made on these routes. Factors that influence bike route choice (on a scale of 1 to 5, 5 being the most influential) are the following: minimizing total distance (3.6), avoiding streets with heavy vehicle traffic (3.57), riding in a bike lane (2.95), and riding on a signed bike route (2.62).

The methodologies and results for these disaggregate studies differ, however there are many consistencies among the conclusions. The most valued attributes, in order, are travel time, avoidance of heavy automobile traffic, and the presence of bike lanes. These studies also show that cyclists do value facilities, and make an effort to use them. Continuity, modeled as a dummy variable, was also determined valuable.

The Bureau of Transportation Statistics (2002) conducted a survey to determine the expanse of bicycle and walking activity on a national level, and examine attitudes and behavior in regards to cycling. The findings compliment results from route choice studies. Frequent cyclists are interested in adding bike lanes compared to less frequent cyclists, while less frequent cyclists are interested in more bike paths compared to frequent cyclists. This supports the idea that experienced cyclists are comfortable in bike lanes and want direct access for utilitarian trips. Less

experienced cyclists may not be comfortable in bike lanes yet, and request paths to use recreationally.

2.3. Perceived Bicycle Service Measures

Research has been done by various researchers to quantify cyclists' perception of danger, or alternatively comfort, on a shared roadway. The models most widely used today are the Biking Level of Service (Landis, 1997) and the Bicycle Compatibility Index (Harkey, 1998).

2.3.1. Bicycle Compatibility Index

The Federal Highway Administration sponsored research to determine how compatible roadways are for cyclists and motorists. A Bicycle Compatibility Index (BCI) was developed as a tool for bicycle coordinators, transportation planners, and practitioners to evaluate existing and proposed facilities and assist with planning analyses.

The study used a video-based methodology to acquire data. Bicyclists watched videos clips that displayed roadway segments with a wide range of traffic and roadway conditions. They rated each segment indicating how comfortable they would be bicycling on it. A linear regression model was developed, using roadway characteristics to predict bicyclists' ratings. The model and variable descriptions are displayed below.

$$\text{BCI} = 3.67 - 0.996\text{BL} - 0.410\text{BLW} - 0.498\text{CLW} + 0.002\text{CLV} + 0.0004\text{OLV} + 0.022\text{SPD} + 0.506\text{PKG} - 0.264\text{AREA} + \text{AF}$$

BL = presence of a bicycle lane or paved shoulder

BLW = bicycle lane or paved shoulder width

CLW = curb lane width

CLV = curb lane volume

OLV = other lane(s) volume

SPD = 85th percentile speed of traffic

PKG = presence of a parking lane with more than 30% occupancy

AREA = type of roadside development: residential or other

$AF = f_t + f_p + f_n$

f_t = adjustment factor for truck volumes

f_p = adjustment factor for parking turnover

f_n = adjustment factor for right-turn volumes

The model uses variables which represent road geometry and road characteristics, such as traffic volume and type of roadside development. This is one of two models often used in the field. Another model, the Biking Level of Service, is used more prevalently and is described in the following section.

2.3.2. Biking Level of Service

The Biking Level of Service (BLOS) is derived from people's responses to biking conditions. The perception of hazard, safety or comfort to a cyclist is the performance measure. Landis aimed to quantify this perceived quality of service.

Bicyclists rode on a set course with a variety of roadway conditions and graded each segment for how safe, or comfortable they felt. Using linear regression, Landis

developed a model to express how roadway and traffic conditions influence the quality of service on a road segment. It is intended for the entire population of cyclists on roadways in urban areas in the United States. The model and variable descriptions are

$$\text{BLOS} = a_1 \ln(\text{Vol}_{15}/L) + a_2 \ln[\text{SPDp}(1+\%\text{HV})] + a_3 \ln(\text{COM}_{15} * \text{NCA}) + a_4 (\text{PC5})^{-2} + a_5 (\text{We})^2 + C.$$

Vol_{15} = volume of directional traffic in 15-min time period

L = total number of through lanes

SPDp = posted speed limit (a surrogate for average running speed)

HV = percentage of heavy vehicles (as defined in the Highway Capacity Manual)

COM_{15} = trip generation intensity of the land use adjoining the road segment (stratified to a commercial trip generation of 15, multiplied by the percentage of the segment with adjoining commercial land development)

NCA = effective frequency per mile of non-controlled vehicular access (such as driveways and on-street parking spaces)

PC5 = FHWA's 5-point pavement surface condition rating

We = average effective width of outside through lane ($\text{We} = \text{Wt} + \text{Wl} - \sum \text{Wr}$, where

Wt = total width of outside lane and shoulder pavement, Wl = width of paving between the outside lane stripe and the edge of pavement, and Wr = effective width (reduction) due to encroachments in the outside lane.)

Both studies use bicyclists' perceptions of comfort on a roadway and characteristics of that segment to develop a predictive model, using a linear regression. The

variables used represent conditions of the roadway and environment that would affect a cyclists' comfort level. Some variables are shared by both models, including a bike lane width. Both models also require a large amount of data inputs.

This thesis uses the BLOS model to evaluate road segments because it appears to be used more prevalently in the field. The national cooperative highway research program used the BLOS model in the bicycle section of a multi-modal level of service report (NCHRP, 1999). Many state departments and regional transportation planning agencies have also applied the BLOS model to evaluate road networks (Baltimore, 2004).

2.4. Application in Academia

Klobucar and Fricker (2007) recognized the importance of considering a network as a whole during bicycle facility planning. A Bicycle Network Analysis Tool was developed, taking into account service level and trip length. The 'safe length' is the product of a segment's length and service measure BCI. The shortest 'safe length' path is chosen by a cyclist. This evaluation tool goes beyond current BLOS evaluation practices by considering trip distance with service level, and examining network level improvements.

This thesis will add the development of another bicycle network evaluation tool to the literature. A multi-objective mixed integer program will optimize bicycle network performance, considering service level and distance over a connected network.

Chapter 3: Mathematical Formulation

Bicycle route choice studies highlight key concepts that are important to cyclists: direct bike trips, connectivity and attributes that comprise a reasonable biking level of service. This formulation captures these concepts with a multi-objective mixed integer program. The model creates connected shortest path bicycle routes that meet a minimum level of service requirement, while improving the biking level of service as much as possible with a limited budget.

3.1. Problem Formulation

Labels:

(i, j) or ij arc that starts at node i and ends at node j

(k, l) or kl OD pair (origin k , destination l)

Sets:

N: Nodes

Z: Zones (nodes that are origins or destinations: $\mathbf{Z} \subseteq \mathbf{N}$)

A: Arcs or links ($\mathbf{A} \subseteq \mathbf{N} \times \mathbf{N}$)

B(i): Arcs preceding node i

F(i): Arcs following node i

P: OD pairs ($\mathbf{P} \subseteq \mathbf{Z} \times \mathbf{Z}$)

Parameters:

W_1, W_2 : Weights for terms in objective function

W_{kl} : Weight for demand on OD pair (k,l)

L_{ij} : Length of arc (i,j) in miles

S_{ij} : Bicycle Level of Service on arc (i,j)

S_{ij}^0 : Original Bicycle Level of Service on arc (i,j)

ΔS_{ij} : Change in Bicycle Level of Service with the addition of a bike lane on arc (i,j)

$$S_{ij} = S_{ij}^0 - y_{ij} \cdot \Delta S_{ij}$$

d_{kl} : Demand from origin k to destination l

S_{max} : Minimum level of service requirement

f_{max} : Maximum capacity of bicycle flow allowed on each arc

f_{min} : Minimum flow required on an arc for an improvement to occur

B : Total Budget

C : Cost of restriping bike lane proportional to arc length

Decision Variables:

$$y_{ij} = \begin{cases} 1 & \text{arc } (i,j) \text{ is selected for bike lane striping} \\ 0 & \text{otherwise} \end{cases}$$

$$x_{ij}^{kl} = \begin{cases} 1 & \text{arc } (i,j) \text{ is in the path with flow from origin } k \text{ to destination } l \\ 0 & \text{otherwise} \end{cases}$$

$$f_{ij}^{kl} = \text{Bicycle flow on arc } (i,j) \text{ from origin } k \text{ to destination } l$$

Objective Function:

$$\text{Min } W_1 \sum_{(i,j) \in A} \sum_{(k,l) \in P} L_{ij} \cdot W_{kl} \cdot x_{ij}^{kl} + W_2 \sum_{(i,j) \in A} [S_{ij}^0 - \Delta S_{ij} \cdot y_{ij}] \quad (3.1)$$

Subject to:

$$\sum_{(i,j) \in A} C \cdot L_{ij} \cdot y_{ij} \leq B \quad (3.2)$$

$$S_{ij}^0 \cdot x_{ij}^{kl} - \Delta S_{ij} \cdot y_{ij} \leq S_{max} \quad \forall (i, j) \in \mathbf{A}, \forall (k, l) \in \mathbf{P} \quad (3.3)$$

$$y_{ij} - x_{ij}^{kl} \leq 0 \quad \forall (i, j) \in \mathbf{A}, \forall (k, l) \in \mathbf{P} \quad (3.4)$$

$$-\sum_{j \in F(i)} f_{ij}^{kl} + d_{kl} = 0 \quad \forall (k, l) \in \mathbf{P}, \forall i \in \mathbf{N}: i = k \quad (3.5a)$$

$$\sum_{j \in B(i)} f_{ji}^{kl} - d_{kl} = 0 \quad \forall (k, l) \in \mathbf{P}, \forall i \in \mathbf{N}: i = l \quad (3.5b)$$

$$\sum_{j \in B(i)} f_{ji}^{kl} - \sum_{j \in F(i)} f_{ij}^{kl} = 0 \quad \forall (k, l) \in \mathbf{P}, \forall i \in \mathbf{N}: i \neq l, i \neq k \quad (3.5c)$$

$$f_{ij}^{kl} - x_{ij}^{kl} * f_{max} \leq 0 \quad \forall (i, j) \in \mathbf{A}, \forall (k, l) \in \mathbf{P} \quad (3.6)$$

$$f_{ij}^{kl} - y_{ij} * f_{min} \geq 0 \quad \forall (i, j) \in \mathbf{A}, \forall (k, l) \in \mathbf{P} \quad (3.7)$$

$$y_{ij} = 0,1 \quad \forall (i, j) \in \mathbf{A} \quad (3.8)$$

$$x_{ij}^{kl} = 0,1 \quad \forall (i, j) \in \mathbf{A}, \forall (k, l) \in \mathbf{P} \quad (3.9)$$

$$f_{ij}^{kl} \geq 0 \quad \forall (i, j) \in \mathbf{A}, \forall (k, l) \in \mathbf{P} \quad (3.10)$$

Equation (3.1) is the objective function that includes two objectives. It seeks to optimize the network performance by minimizing the travel distance of bicycle trips and maximizing the biking level of service over the network. The first term minimizes the distance of bicycle trips through the network for each OD pair. The second term maximizes the level of service for links in the network. The lower the level of service score, the better the service quality. The value for the current level of

service, S_{ij}^0 , is reduced by a predetermined amount, ΔS_{ij} , if that link is chosen for improvement. █

The second term in the objective function is important because it takes into account the bicycle service level. It is not enough to provide the shortest distance for bicycle route planning. This term ensures more bike lanes are added to the network. As discussed in the literature review, a better level of service over the network encourages newer cyclists to make bike trips and offers experienced cyclists more routes.

Constraint (3.2) imposes a budgetary restraint for total lane improvements. Constraint (3.3) sets a maximum biking level of service requirement for links in the path system. Constraint (3.4) forces links chosen for improvement to be part of the path system. If a link is not chosen for improvement, it may be part of the path system but is not required. Constraints (3.5a), (3.5b), (3.5c) and (3.6) ensure conservation of flow in the network. Constraint (3.5a) ensures the sum of the flow leaving an origin node equal the demand from that node. Constraint (3.5b) ensures the sum of the flow into a destination node equal the demand for that node. Constraint (3.5c) forces the sum of the flow into a node equal the sum of the flow leaving that node for all intermediate nodes. Constraint (3.6) then connects the flow variable, f_{ij}^{kl} , to the path variable, x_{ij}^{kl} , by setting a capacity constraint on the flow. Constraint (3.7) requires improved road segments have a minimum level of flow. Constraints (3.8) and (3.9) represent the binary integer restrictions on the decision variables. Constraint (3.10) ensures non-negative flow variables.

The formulation is designed for multiple origin-destination pairs. The OD indices (k,l) are necessary to find the shortest path for multiple paths simultaneously. Formulating the problem with a shortest path objective function, minimize $L_{ij} \cdot x_{ij}$, allows one to solve the problem for one OD pair. When multiple OD pairs are introduced to the problem, minimizing $L_{ij} \cdot x_{ij}$ solves the least cost distance for the network. The arc lengths are minimized through the network as whole, which does not ensure shortest paths for each OD pair. The shortest path for each individual bike route is the desired outcome for this problem, while considering the service level for the network. The formulation reflects this by using indices (k,l) for each OD pair's demand. Additionally, the weight parameter, W_{kl} , is the demand weight in the objective function for OD pair (k,l) . This parameter reflects the differences in demand among OD pairs.

The output will display binary answers for decision variables the x_{ij}^{kl} and y_{ij} , and the amount of flow f_{ij}^{kl} for every arc in the network. For each OD pair's demand, the solution will describe the flow, f_{ij}^{kl} , which runs through the path system, x_{ij}^{kl} . Whenever a bike lane is required on a link, y_{ij} is set equal to 1.

3.2. BLOS Parameter

The biking level of service (BLOS) parameter is crucial in this formulation. BLOS is a function of automobile traffic volume, speed limit, percentage heavy vehicles, pavement quality and effective road width. The equation for BLOS was originally derived in 1997 by Landis. Since then it has been recalibrated and adapted as a part of numerous transportation plans throughout the United States (Baltimore, 2004). The Baltimore and Rockville bike plans used the following BLOS equation.

$$BLOS = a1 * \ln (Vol_{15}/Ln) + a2 * SPt(1+10.38HV)^2 + a3 * (1/PR5)^2 + a4 * (We)^2 + C$$

Where:

Vol_{15} = Volume of directional traffic in 15 minute time periods

$$Vol_{15} = (ADT \times D \times Kd) / (4 \times PHF)$$

where:

ADT = Average Daily Traffic on the segment or link

D = Directional Factor (assumed = 0.565)

Kd = Peak to Daily Factor (assumed = 0.1)

PHF = Peak Hour Factor (assumed = 1.0)

Ln = Total number of directional through lanes

SPt = Effective speed limit

$$SPt = 1.1199 \ln(SPp - 20) + 0.8103$$

where:

SPp = Posted speed limit (a surrogate for average running speed)

HV = percentage of heavy vehicles, defined in the 1994 Highway Capacity Manual

PR5 = FHWA's five point pavement surface condition rating

We = Average effective width of outside through lane:

where:

$$We = Wv - (10 \text{ ft} \times \% \text{ OSPA}) \text{ and } Wl = 0$$

$$We = Wv + Wl (1 - 2 \times \% \text{ OSPA}) \text{ and } Wl > 0 \text{ \& } Wps = 0$$

$$We = Wv + Wl - 2 (10 \times \% \text{ OSPA}) \text{ and } Wl > 0 \text{ \& } Wps > 0 \text{ \& a bike lane exists}$$

where:

Wt = total width of outside lane (and shoulder) pavement

OSPA = percentage of segment with occupied on-street parking

Wl = width of paving between the outside lane stripe and the edge of pavement

Wps = width of pavement striped for on-street parking

Wv = Effective width as a function of traffic volume

where:

$W_v = W_t$ if $ADT > 4,000 \text{ veh/day}$

$W_v = W_t (2 - 0.00025 \times ADT)$ if $ADT \leq 4,000 \text{ veh/day}$ & the street or road is undivided and unstriped

a1: 0.507 a2: 0.199 a3: 7.066 a4: - 0.005 C: 0.760

a1- a4 coefficients established by multi-variate regression analysis (Baltimore, 2004)

The BLOS score is part of a letter grade scale that ranges A through F, A being the best and F being the worst. Table 3.1 shows the quantities associated with each letter grade.

Level of Service	Bicycle LOS Score
A	≤ 1.5
B	$> 1.5 \text{ and } \leq 2.5$
C	$> 2.5 \text{ and } \leq 3.5$
D	$> 3.5 \text{ and } \leq 4.5$
E	$> 4.5 \text{ and } \leq 5.5$
F	> 5.5

Table 3.1: Bicycle Level of Service Grading Scale

Samples of each BLOS letter grade are displayed in Figure 3.1.

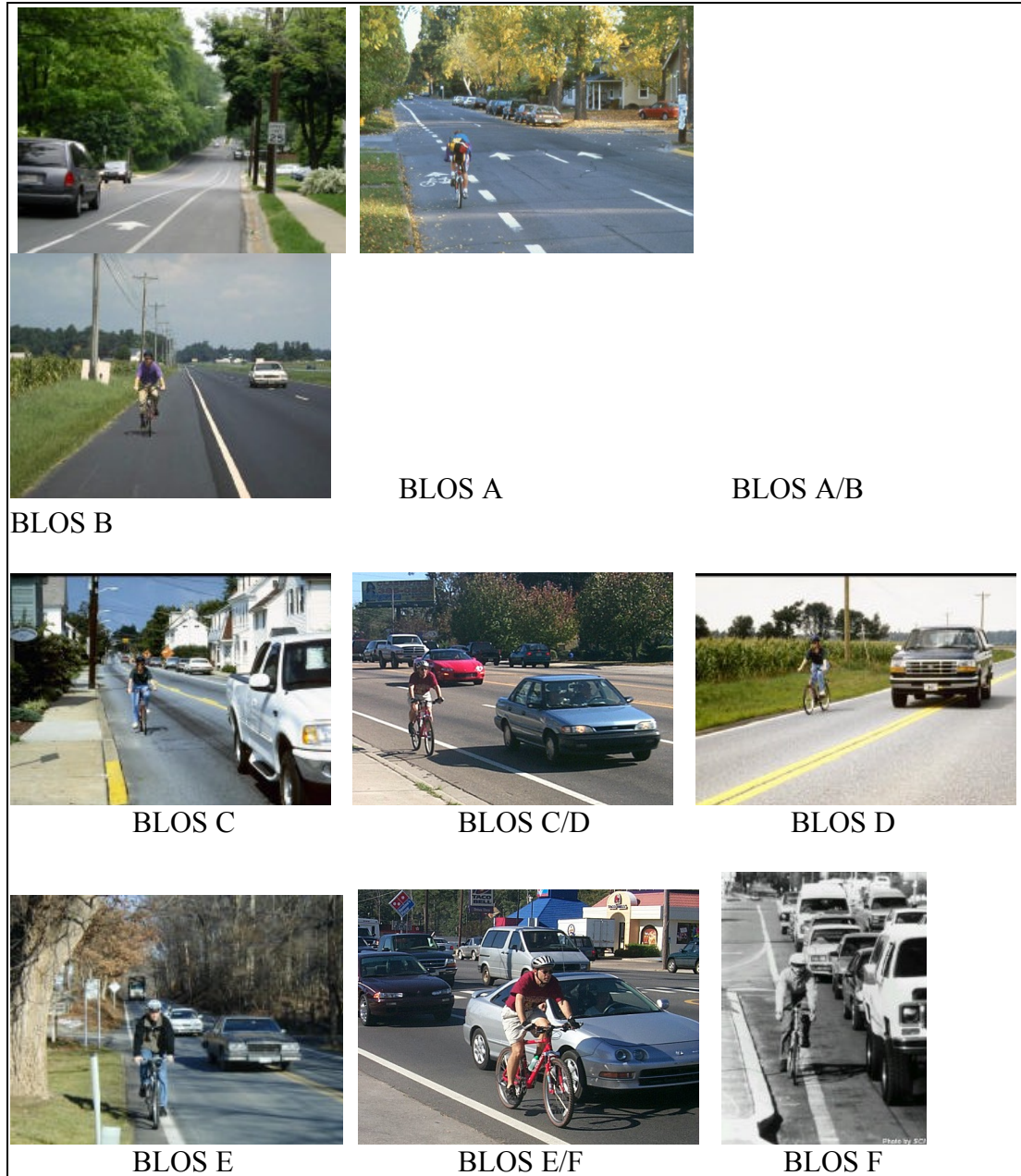


Figure 3.1: Examples of various BLOS letter grades

The pictures with a single letter grade are found in the Anne Arundel County Pedestrian and Bicycle Master Plan from 2003. These photographs were taken in Anne Arundel, Maryland at the time of the study. The pictures with joint letter grades are from the Florida DOT Quality/Level of Service Handbook from 2009.

3.3. Effective Width Term

The effective width term (W_e) is a part of the BLOS parameter described in the previous section. W_e is the average effective width of the outside through lane. This term is of particular importance because it will change with the addition of a bike lane. In this model, the only way to decrease the BLOS value is by improving the effective width.

The W_e term is calculated based on the following conditions: automobile traffic levels, presence of a shoulder or bike lane, percentage of a segment with occupied on-street parking, and width of striping for on-street parking.

W_t is the width of outside through lane plus paved shoulder. W_v is the effective width as a function of traffic volume. If traffic is greater than 4,000 vehicles per day, W_v equals W_t . If traffic volume is less than 4,000 vehicles per day, W_v is

$$W_v = W_t * (2 - (0.00025 \times ADT)) \quad (3.3.1)$$

This rewards segments with low traffic volume by increasing the W_e value.

W_1 is the width of paving between the outside lane stripe and the edge of pavement.

This is essentially the total width of the shoulder and bike lane, if either one exists.

If W_1 is zero then W_e is

$$W_e = W_v - (10\text{ft} * OSPA) \text{ (ft)} \quad (3.3.2)$$

If W_1 is greater than zero and there is no striping for on-street parking, then W_e is

$$W_e = W_v + W_1 * (1 - 2\text{ft} * OSPA) \text{ (ft)} \quad (3.3.3)$$

If W_1 is greater than zero and there is striping for on-street parking, W_e is

$$W_e = W_v + W_l - 2*(10\text{ft} * \text{OSPA}) \text{ (ft)} \quad (3.3.4)$$

Figure 3.2 illustrates the decision process for determining which equation to use to calculate the effective width in different situations.

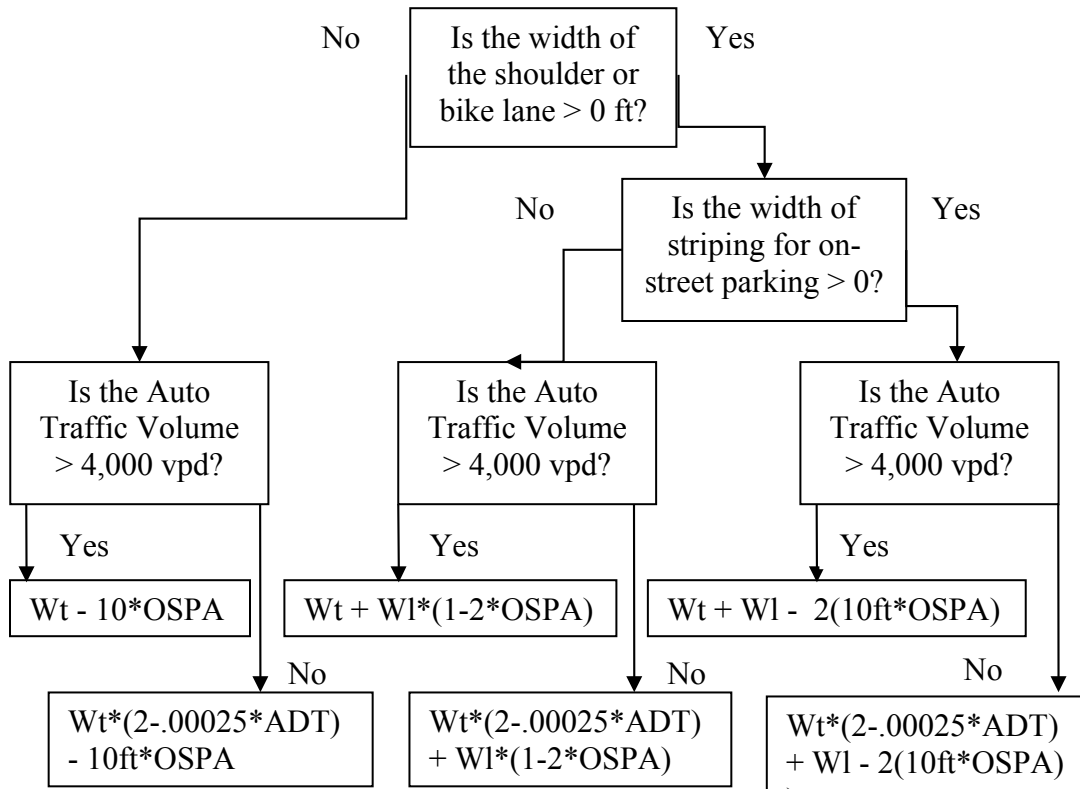


Figure 3.2: Flow chart to determine W_e equation in various scenarios

A road without a bike lane or shoulder can greatly increase its W_e value with the addition of a bike lane, because it will change the W_e equation from (3.3.2) to (3.3.3) or (3.3.4). A road with characteristics for (3.3.3) or (3.3.4) can still increase the value of W_e with the addition of a bike lane because the W_l term will increase. If a wide shoulder is converted into a bike lane and the width of the outside through lane remains the same, the value of W_e remains the same.

There are no segments in the case study network data that have a width of pavement striped for on-street parking (Wps) greater than zero. This simplifies the data processing, described in the next chapter, because the only equations used to calculate the effective width are (3.3.2) and (3.3.3).

3.4. Bicycle Level of Service Model Sensitivity

It is important to understand the BLOS parameter in order to appreciate the affect the addition of a bike lane will have on cyclists' perceived level of safety. A sensitivity analysis is displayed in Figure 3.3.

Bicycle LOS Model Sensitivity Analysis			
Bicycle LOS = $a_1 \ln(\text{Vol}_{15}/\text{Ln}) + a_2 \text{SPt}(1+10.38\text{HV})^2 + a_3(1/\text{PR}_5)^2 + a_4(\text{We})^2 + \text{C}$			
where:	a_1 : 0.507	a_2 : 0.199	a_3 : 7.066 a_4 : -0.005 C: 0.760
T-statistics:	(5.689)	(3.844)	(4.902) (-9.844)
Baseline inputs:			
ADT = 12,000 vpd	% HV = 1	L = 2 lanes	SPp = 40 mph
PR5 = 4 (good pavement)	We = 12 ft		
	<u>BLOS</u>	<u>% Change</u>	
Baseline BLOS Score (Bicycle LOS)	3.98	N/A	
Lane Width and Lane striping changes			
Wt = 10 ft	4.20	6% increase	
Wt = 11 ft	4.09	3% increase	
Wt = 12 ft -- (baseline average) -----	3.98 -----		no
change			
Wt = 13 ft	3.85	3% reduction	
Wt = 14 ft	3.72	7% reduction	
Wt = 15 ft (Wl = 3 ft)	3.57 (3.08)	10% (23%)	
reduction			
Wt = 16 ft (Wl = 4 ft)	3.42 (2.70)	14% (32%)	
reduction			

Wt = 17 ft (Wl = 5 ft) reduction	3.25 (2.28)	18% (43%)
Traffic Volume (ADT) variations		
ADT = 1,000 Very Low	2.75	31% decrease
ADT = 5,000 Low	3.54	11% decrease
ADT = 12,000 Average - (baseline average)	3.98	----- no change
ADT = 15,000 High	4.09	3% increase
ADT = 25,000 Very High	4.35	9% increase
Pavement Surface conditions		
PR ₅ = 2 Poor	5.30	33% increase
PR ₅ = 3 Fair	4.32	9% reduction
PR ₅ = 4 -- Good - (baseline average) -----	3.98	----- no change
PR ₅ = 5 Very Good	3.82	4% reduction
Heavy Vehicles in percentages		
HV = 0 No Volume	3.80	5% decrease
HV = 1 - Very Low - (baseline average) ---	3.98	----- no change
HV = 2 Low	4.18	5% increase
HV = 5 Moderate	4.88	23% increase _a
HV = 10 High	6.42	61% increase _a
HV = 15 Very High	8.39	111% increase _a
_a Outside the variable's range		

Figure 3.3: BLOS Sensitivity Analysis from Baltimore Paper (2004)

It is important to understand the relationship between changes in lane width and changes in lane striping, displayed in Figure 3.3. These values comprise the effective width term, the only adjustable term to improve the biking level of service. The relationship between effective width and BLOS improvement is displayed in the graph shown in Figure 3.4.

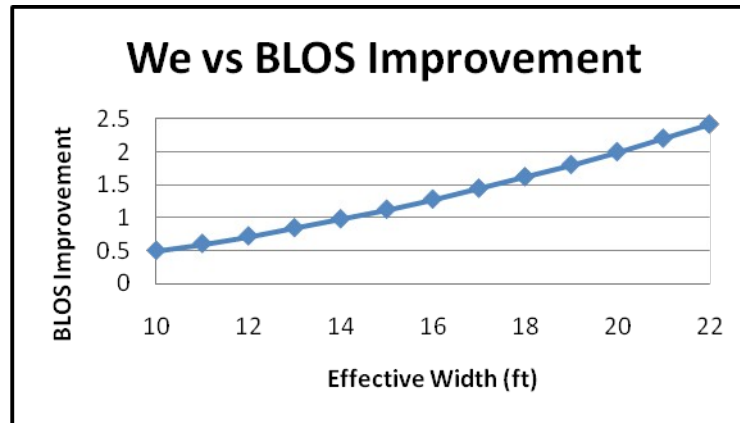


Figure 3.4: Relationship between Effective Width and BLOS Improvement

Figure 5.4 shows that the relationship is positive and concave up, but the coefficient a_4 is so small that it is very close to a linear relationship. As the level of service improves the BLOS value decreases. The coefficient, a_4 , causes a positive relationship between effective width and BLOS.

It is necessary to look at lane width and lane striping changes in terms of effective width. As the width of the outside lane increases (W_t), the effective width increases the same amount ($W_e \equiv W_t$). If the outside lane increases and a bike lane is added the effective width increases by the same amount in addition to the width of the bike lane ($W_e \equiv W_t + W_l$). In other words, the bike lane width is counted twice in the new effective width value.

Notes from the sensitivity analysis for the remaining parameters are listed below.

- **Traffic Volume:** A greater reduction in BLOS occurs when ADT is very low (less than 1,000).
- **Pavement Surface Conditions:** A significant negative affect happens when poor conditions exist.

- **Heavy Vehicles Percentage:** Low values have a slight impact on BLOS. A large increase occurs when HV% is moderate at 5%, and a drastically large increase occurs when HV is high (10%) and very high (15%).

3.5. Bicycle Lane Improvements

There are three basic methods to add bike lanes to an existing urban road network: mark existing shoulders as bike lanes, physically widen the road, and restripe the road (Oregon, 1995). In many urban settings, there are no shoulders present to convert into bike lanes. Widening the roadway is likely infeasible in city centers because of the expense, effort of right-of-way acquisition and the cost of construction. Restriping the road to fit a bike lane or wide curb lane is typically an option that is feasible with the roadway geometry and more economical.

Removing a traffic lane is one solution to allocating enough space for additional bicycle facilities in a roadway. However, the affect one less traffic lane has on the automobile level of service must be considered. The analysis of an automobile level of service is outside the scope of this thesis, so this model will never take away a traffic lane as part of the solution. The Oregon Department of Transportation Bicycle and Pedestrian Plan offers the following approaches to adding bike lanes without removing traffic lanes: reduce travel lane widths, narrow parking lane, remove parking lane from one side of street, and change diagonal parking to parallel parking (1995). If there is not enough space to add a safe bike lane after narrowing traffic lanes, another option suggested by the study is to restripe for wide curb lanes. In

other words, narrow the center through lanes as much as safely possible and give extra space to the outside through lane.

For some road segments the only way to add a bike lane is widening the road. If this is infeasible, it can be captured in the model. The decision variable for a facility improvement for a segment, y_{ij} , should be set to 0, which means there is no improvement. It is no longer in the y_{ij} decision variable choice set. The link may still be included in the path system if all other constraints are met. The path system decision variable, x_{ij}^{kl} , may be 1 or 0 even when y_{ij} is 0.

Chapter 4: Case Study Data

An extensive amount of data is required for a biking level of service evaluation. Fortunately, appropriate data is now being compiled in many cities throughout the United States, thus providing transportation planners with the capacity to evaluate their networks for bicycle compatibility. Furthermore, it indicates an interest in improving bicycle transportation and increasing its use.

4.1. Biking Level of Service Data

4.1.1. Baltimore Service Level Evaluation

“The Bicycle Level of Service Evaluation Update and Pedestrian Level of Service Evaluation” is a study conducted by the Baltimore Metropolitan Council (2004). In

this task report, over 1,400 miles of roadways in the Baltimore region were evaluated. The report offers an update from the 1999 Bicycle Level of Service (BLOS) analysis. It also provides the first Pedestrian Level of Service (PLOS) analysis. The LOS evaluation and updates aim to assess and track changes to bicycle and walking conditions. Another purpose is to provide input for bicycle facility planning. The Baltimore Metropolitan Council used the 1999 BLOS scores as well as the 2004 updated BLOS scores as a factor in prioritizing bicycle projects for long term planning.

4.1.2. BLOS Model Data Needs

The BLOS model is a function of numerous traffic conditions and road geometry. The Baltimore Service Level Evaluation Data includes the following information that is pertinent to calculating the BLOS: Segment ID, Road Name, From, To, Length, Direction of Survey, Number of through lanes, Condition of lanes, Traffic Volume (ADT), Posted Speed Limit, Width of Pavement: Total width of outside lane and shoulder (Wt), Width of shoulder and/or bike lane (Wl), Width of pavement striped for on-street parking (Wps), Width of road grates (Wg), Occupied Parking (OSPA), Width due to volume (Wv), Effective Pavement Width (We), and Pavement Condition. The BLOS score was calculated for each segment and a BLOS letter grade was determined. Tabular results from the BLOS/PLOS evaluation in Baltimore City can be found in the appendix.

4.1.3. Data Sources

Applying the BLOS model to evaluate a network requires a large amount of input data. Some of the necessary data is typically collected by local and regional transportation agencies for traffic analyses. Other data must be collected in the field. The Baltimore Metropolitan Council gathered data from various sources for this study.

Existing Data

The average daily traffic was found in a traffic count database. The percentage of heavy vehicles was taken from a traffic composition database. Lastly, the 85th percentile speed was found in a traffic speed database.

Field Data

Baltimore Metropolitan Council staff collected necessary field data for this study. The direction of travel, number of through lanes of traffic, and estimate of percent occupied on-street parking were collected for all segments. The following pavement width measurements were also taken: outside lane, shoulder, striping for on-street parking, and grate width. The pavement condition was evaluated using FHWA's five point pavement surface condition rating. The scale ranges from 1.0 (very poor) to 5.0 (very good). Finally, the posted speed limit was collected only for segments missing from the traffic speed database. The posted speed limit was then converted to the 85th percentile speed with the BLOS model equation, $S_{pt} = 1.1199 \ln(SP_p - 20) + 0.8103$.

4.1.4. Data Processing

For the optimization model, the following parameters are needed for each link: starting node (i), ending node (j), length in miles, current BLOS score, and change in BLOS score with the addition of a bike lane. The starting and ending node values were determined based on the location and direction of the link. The length and current BLOS score are taken directly from the Baltimore Service Level Evaluation Data. The change in BLOS score was calculated using the inputs from the Baltimore Service Level Evaluation Data, assuming a 4 foot bike lane addition. The change in BLOS is due to the change in the effective width parameter.

$$\Delta \text{BLOS} = 0.005 * [(We')^2 - (We)^2] \quad (4.1)$$

where

$$We' = Wt' + Wl * (1 - 2 * OSPA) \quad \text{if ADT} > 4,000 \text{ vpd} \quad (4.2)$$

$$We' = Wt' * (2 - 0.00025 * ADT) + Wl * (1 - 2 * OSPA) \quad \text{if ADT} < 4,000 \text{ vpd} \quad (4.3)$$

$$Wt' = Wt + Wl \quad (4.4)$$

$$Wl = 4 \text{ feet} \quad (4.5)$$

We, Wt, OSPA and ADT are data inputs found in the Baltimore Service Level Evaluation Data. Furthermore, Wg, the width of grates, affects We negatively. The precise relationship is unclear because Wg is not a part of the model. The Wg term is listed in the Baltimore Service Level Evaluation Data, and when present, the We value is less. To account for this, the value of We' was reduced the same amount the original We value was reduced if grates were present in a segment ($Wg > 0$). This allows grates to have the same negative impact on the new We' and the original We term.

Very few segments in the case study data have an Average Daily Traffic less than 4,000 vehicles per day. This is to be expected, as the study area is the center of Baltimore City. The few segments with low enough traffic volumes had We' values calculated accordingly, with equation (4.3). The low traffic volume is rewarded in the model as equation (4.3) increases the We value, reducing the BLOS score. Recall that Average Daily Traffic is a variable in the first term from the BLOS model, so low volume is rewarded twice.

There are no segments in the network case study data set that have a bike lane or shoulder ($Wl=0$). Furthermore, no links have a width of pavement striped for on-street parking (Wps) greater than zero. These characteristics of the data set simplify calculating the We and We' terms. The original We term is always equation (3.4.2) $We = Wv - (10ft * OSPA)$ and the improved We' term is always equation (3.4.3) $We' = Wv + Wl*(1-2ft * OSPA)$. If an existing road segment has a shoulder, equation (3.4.3) is used to calculate We . After a bike lane is added, equation (3.4.3) is used again to calculate We' . There are various combinations of possible equations needed to calculate We and We' . For this case study data set, there is only one equation for We before improvements and one equation after improvements.

4.1.5. Data Organization

As described in the previous section, the $\Delta BLOS$ value was calculated for each segment using equation (4.1). An excel file was created to capture the data in a format easily transferred into the Xpress solver. Coordinate lists were produced for the three parameters in the problem formulation: Length, BLOS, and $\Delta BLOS$. The

coordinates were in the range N nodes by N nodes. An additional list was created for the precedence parameter. This parameter allows for the conservation of flow constraint (see constraint 3.5 from chapter 3) to be coded in the Xpress solver. A binary cell documents precedence in the network: if a coordinate cell has a value of 1, the y-coordinate node number proceeds the x-coordinate node number. All four parameters require values with the same coordinates. The dataset was populated in excel and transferred to Xpress.

4.2. Additional Parameters

4.2.1. Demand

The origin-destination locations are necessary input in this model. For the case study, the center of Baltimore was analyzed. It is assumed that bike trips are desired throughout this region, so origin and destination locations were chosen in order to see flow sent across the network. The demand was set to 5 for each OD pair. A value larger than 1 was chosen to help differentiate the flow decision variable output from the binary decision variables.

Bicycle count data is one method used to predict demand. This data is often unavailable for planners. Another method used to determine origin and destination data is to make estimates based on location characteristics. Certain locations are known to generate and attract bicycle trips such as school, work, businesses and residential neighborhoods. When a bicycle origin-destination matrix is accurate, the output offered is a more meaningful result.

4.2.2. Flow Parameters

The flow capacity parameter is f_{\max} . In this model, it is set to the total flow from all OD pairs in the network. This parameter exists for the purpose of connecting variables f_{ij}^{kl} and x_{ij}^{kl} , to ensure conservation of flow. Currently, capacity is not a concern for bicycle network planning in the United States because the number of bike trips is low. Ideally, in the future capacity will need to be considered.

The minimum flow parameter is f_{\min} . A minimum amount of flow is required on an arc in order for a link improvement to occur. In this case study, f_{\min} always equals five. This ensures that flow is being sent on a segment if it is used in the network solution.

4.2.3. Weight Values

For this multi-objective problem, weights are necessary for each of the competing terms in the objective function. Weights can be determined by finding a pareto set: weight vectors for which no other solution can improve one term in the objective function without making the other term worse. The pareto front is the objective value for all pareto sets. The preferred solution is then chosen from the pareto set by the decision maker (Ngatchou, 2005).

In this model, term 1 minimizes the distance between OD pairs while term 2 improves the level service as much as possible. If term 1 receives all of the weight ($W1=1$, $W2=0$) the model will find the shortest path for each OD pair. If term 2 receives all of the weight ($W1=0$, $W2=1$) the model will send flow on the longest path with the most opportunity for bike lane improvement, and increase the level of

service across the network. The purpose of the second term is to improve the level of service for network paths as much as the constraints allow. Therefore, the second term should be considered with much less weight. If there is slack from the budget constraint and a segment in the path system already meets the minimum level of service requirement without being improved, the desired solution is for that segment to be improved to offer a better level of service.

The type of solution sought after is known before the problem is solved. The desired solution should be close to the shortest feasible path with a better level of service. This solution type is described in greater detail in the following chapter. The sum of lengths, L_{ij} , in the network is 36.85 miles. The sum of the original level of service, S_{ij}^0 , is 1363.37. The weight term values proportional to the size in the network are $W_1 = 1$ and $W_2 = 0.027$. This problem requires more weight on the first term, so a smaller value for W_2 is to be expected. Precise values for the two weights were determined through a sensitivity analysis.

The weight parameter for demand, W_{kl} , reflects the demand for each OD pair. In this case study, all W_{kl} values are set to 1. It is assumed that demand is equal for every OD pair so all OD pairs are assigned an equal weight.

4.2.4. Budget and Cost

The budget parameter, B , and cost per bike lane mile, C , must be considered in conjunction. They are related in the problem formulation in the budget constraint. It is assumed the cost of adding bike lanes is proportional to the length of improved links. The accuracy of a cost estimate is not crucial for this case study because the

available budget is also unknown. The focus here is to understand the proportion of the budget and the cost per bike lane mile. To simplify interpreting the results, the value of C used was 10 and B was adjusted accordingly. The ratio of budget and cost parameters determines the length of bike lane improvements available in each problem. Real network applications should use an estimated value for the budget and cost per bike lane mile to determine the amount of bike lane improvements that can occur.

4.2.5. Minimum Level of Service

The parameter S_{\max} designates the highest score of BLOS allowed for a link in the network. The letter grade D is the design criteria in this case study, which ranges from 3.5 to 4.5. The lower range, 3.6, is a desirable design level for S_{\max} to ensure a reasonable BLOS in the solution. It is necessary to consider less rigorous design criteria for urban centers in order to find feasible solutions. Furthermore, this model could be applied with more rigorous design criteria for study areas with BLOS values that have the potential to meet them.

4.3. Network Description

4.3.1. Location

The case study network is located in the central business district of Baltimore. The area is just north of the Inner Harbor and covers approximately two square miles. Without demand data, it is assumed that the city center includes many attractions that generate bicycle trips. The region is a dense street network with BLOS data collected for many of its roads. The area is outlined in Figure 4.1.

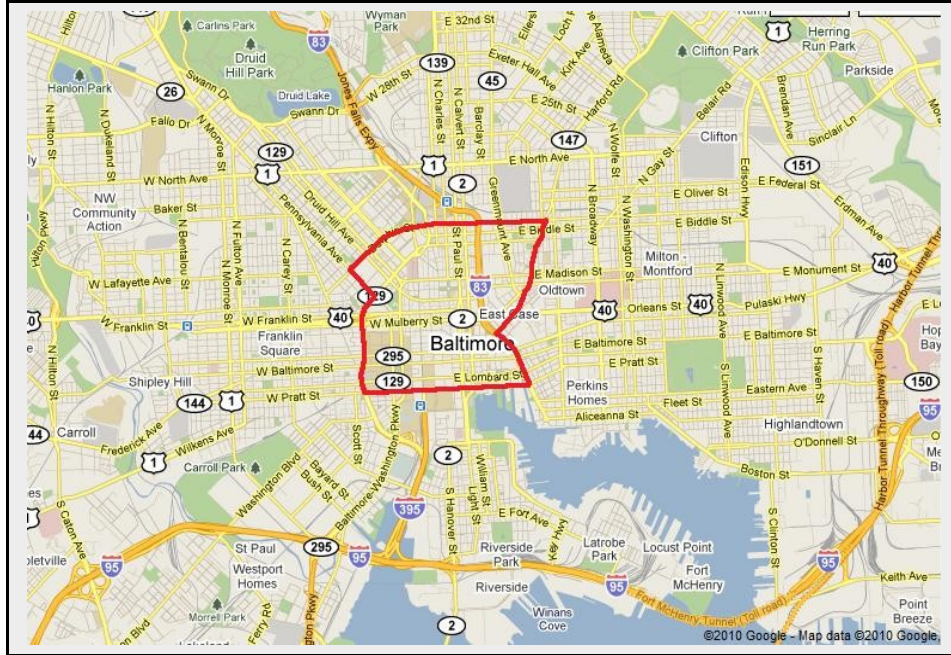


Figure 4.1: Map of Baltimore Region Outlining the Study Area

4.3.2. Segment Data

Segments with data available from the Baltimore Service Level Evaluation Data were configured into a network. The total mileage of data in this network was 20.29 miles. The segments had BLOS scores that ranged from 0.1 to 6.0. The number of miles with each letter grade of BLOS score is illustrated in Figure 4.2.

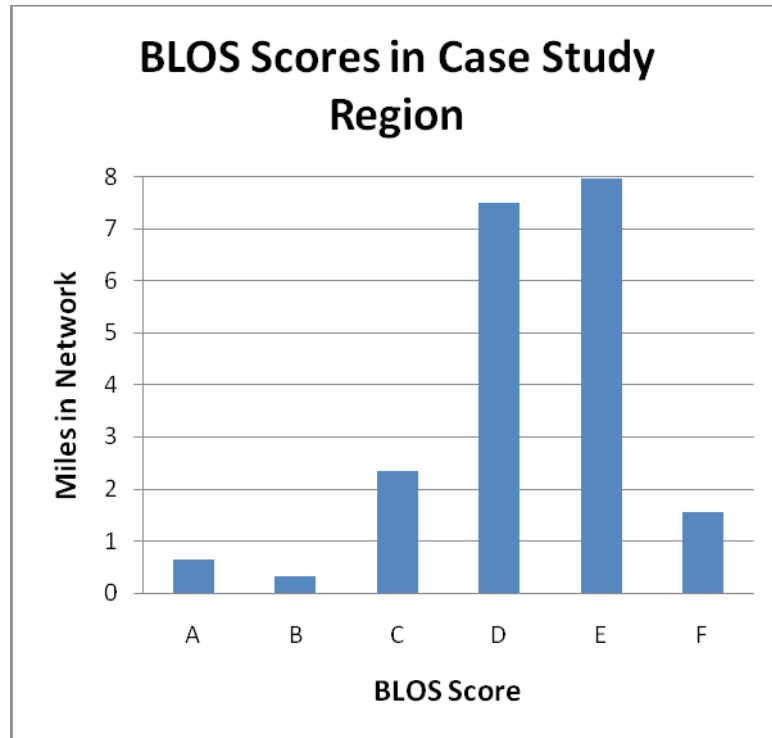


Figure 4.2: BLOS Grades in Case Study Network

Figure 4.2 shows that the network is dominated with BLOS scores of D and E. Basic statistics from the dataset about BLOS scores and the affect a bike lane improvement has on BLOS scores are summarized in Table 4.1.

	BLOS	ΔBLOS
Average per link number	4.268	1.349
Median per link number	4.620	1.256
Average per length	4.229	1.357

Table 4.1: Statistics for BLOS and Δ BLOS

4.3.3. Additional Links

Some roads in the study area were not evaluated in Baltimore's Service Level analysis, and therefore do not have data. As stated previously, it is critical to look at the entire road network to determine where improvements will lead to a fully connected road system. When only looking at known data, some links were difficult

to access or completely inaccessible. For the purpose of this case study, additional segments were added to the network, without data from Baltimore's Service Level Analysis. The following strategies were used to determine missing variables needed to consider the entire road network.

For the streets without data, the length of each segment was measured using a Geographic Information System program, including a map of the city of Baltimore. This provided accurate length data, and segments were measured to the hundredth of a mile.

The assumed value for BLOS and Δ BLOS scores were tailored to the model, and considered network characteristics. As previously stated, the majority of miles are rated D or E, and the average BLOS per length is 4.229. It is better to assume a conservative estimate so the model is more likely to use links with known data when possible, providing a more meaningful result. The BLOS score 4.6 was chosen, with a Δ BLOS of 1.3. This BLOS score is worse than average. If an improvement is made, the new BLOS value is 3.3, which falls in the C grade range.

Many roads were evaluated in one direction of travel. A large portion of the roads in this case study are one way streets, and only one direction of travel was necessary for evaluation. However, some two-way streets were only evaluated in one direction based on the information from the data set. Both travel directions should be included in the network for a full representation of the complete road network. Although BLOS and Δ BLOS values may differ depending on the direction of travel, in this case study it is assumed that they are the same. It is helpful to use available information as

the basis for an estimate because it reflects actual road characteristics. For example, a road with heavy traffic volume in one direction is likely to have heavy traffic in the opposite direction. This method is more accurate than using a network average BLOS score as the basis for an estimated value.

Each additional arc's location is based on the network configuration, and therefore exact. New segments were added into the network. The final case study network is pictured in Figure 4.3.

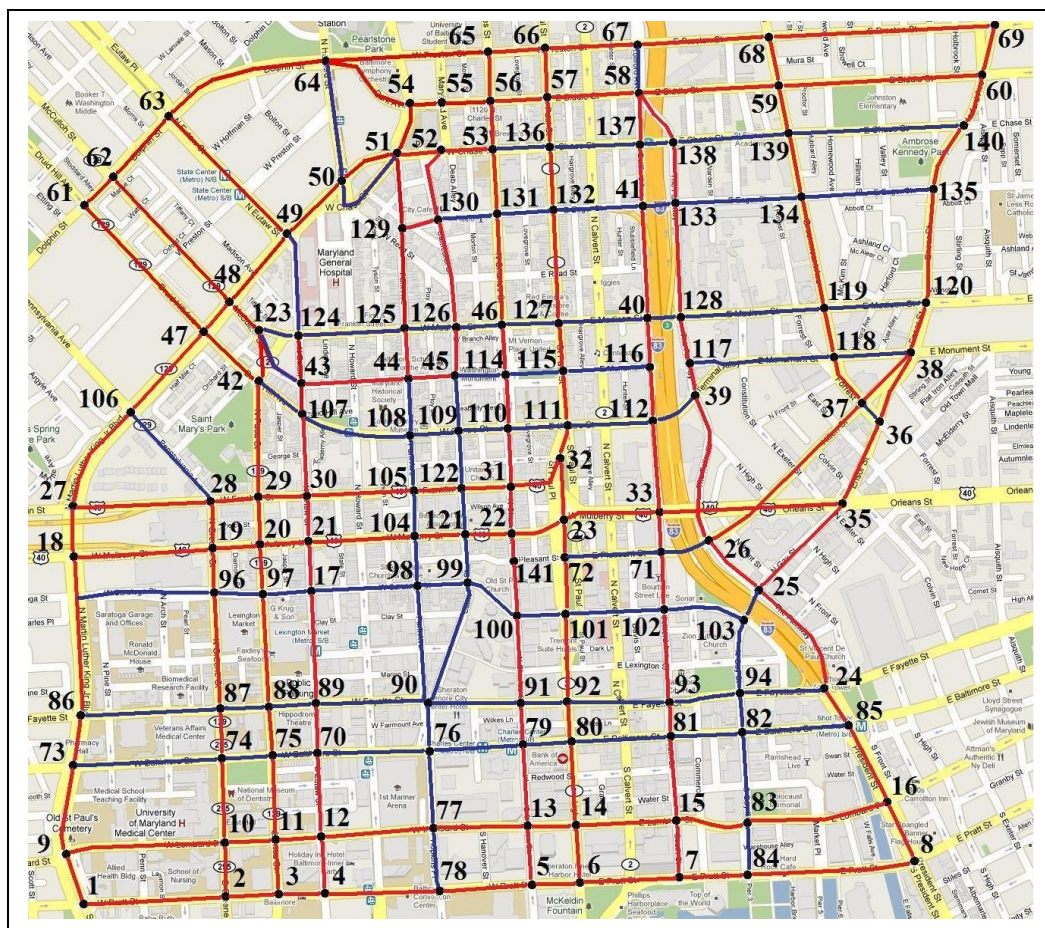


Figure 4.3: Case Study Network

The final network, displayed in Figure 4.3, is made up of 140 nodes and 308 arcs.

The arcs add up to a total of 36.85 miles. Within this network, 204 arcs have known

data, illustrated with red lines, and 104 arcs have estimated BLOS and Δ BLOS values, illustrated with purple lines.

Chapter 5: Sensitivity Analysis

In the previous chapter, necessary data input was computed and prepared for the solver. Parameter values for $W1$, $W2$, B , C , and S_{\max} must be selected before solving a large sample problem. A sensitivity analysis is necessary to determine the two weights in the multi-objective function. The budget and cost per bike lane mile, along with the minimum service level requirement, depend on specifications of each real world project. It is valuable to understand how sensitive a solution is when these parameters change.

5.1. Weight Values for Objective Function

Three samples with different demand locations were analyzed to understand how the weight values in the objective function affect the solutions.

5.1.1. Sample Network 1 with 2 Origin-Destination (OD) Pairs

Two origin-destination (OD) pairs from 4 zones were used in a sample network to analyze the effects of changing the objective function weights' ratio. The weight for the first term, $W1$, is set to a value of 1 while the weight for the second term, $W2$, is adjusted for a number of scenarios. The budget parameter was set large enough so it was not restrictive. The S_{\max} parameter was set to 4.0 to ensure that most links are able to be part of a feasible solution. A summary of results are displayed in Table 5.1.

Scenario Number	1	2	3	4	5
W2	0	0.001	0.005	0.010	0.015
Objective Function	3.44	4.764	10.06	16.68	23.301
Time (seconds)	1276	6456	3600	333	234
Sum of Paths (miles)	3.44	3.44	3.44	3.44	3.44
Bike Lanes (miles)	2.86	3.44	3.44	3.44	3.44
Network BLOS	3.2554	2.9382	2.9382	2.9382	2.9382

Scenario Number	6	7	8	9	10
W2	0.020	0.025	0.030	0.035	0.040
Objective Function	29.936	36.522	43.108	49.688	56.236
Time (seconds)	122	6606	103	257	232
Sum of Paths (miles)	3.59	3.59	3.59	3.78	3.86
Bike Lanes (miles)	3.59	3.59	3.59	3.78	3.86
Network BLOS	2.6764	2.6764	2.6764	2.6030	2.6228

Table 5.1: Network Statistics, OD pairs (63 6) (70 60)

The W2 value, objective function, and program running time are displayed in Table 5.1 for each scenario. The sum of the paths is simply the length of each path added together. Network Length is the length of segments in the network. If paths overlap, the segment length will only be counted once. Bike Lanes shows how many miles of bike lanes are used in each solution. Network BLOS is the average BLOS value per length, over the network. This measurement is a general evaluation of the BLOS for the network. It is an average used to compare solutions, but does not necessarily show which solution has the best BLOS.

The objective function increases as the W2 value increases. Figure 5.1 displays the relationship between the objective function and W2 value.

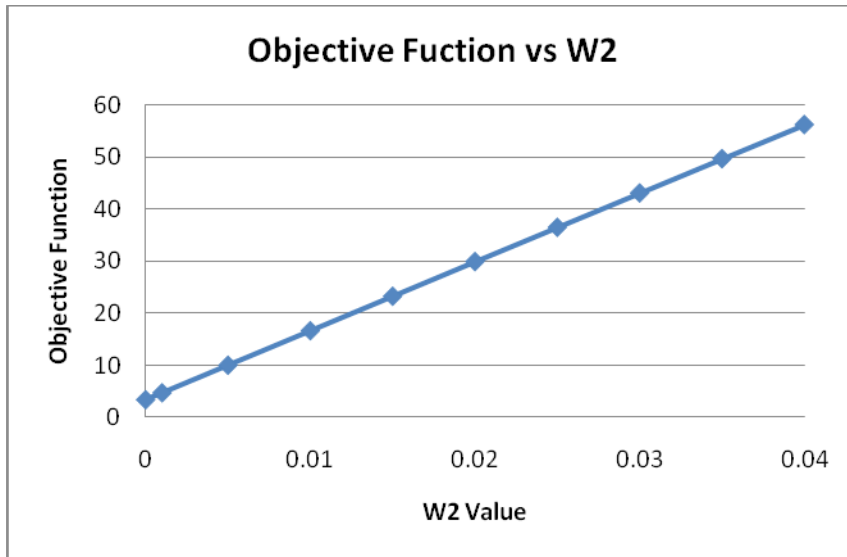


Figure 5.1: Objective Function vs W2, OD pairs (63 6) (70 60)

The positive linear relationship in Figure 5.1 can be described by the following equation: $\text{Objective Function} = 1320.8 * W2 + 3.4672$. As $W2$ increases, the minimum possible value of the objective function also increases.

The Pareto front is the set of Pareto optimal solutions for a multi-objective problem. This solution exists when one objective cannot be improved without negatively affecting the other objective (Ngatchou, 2005). The relationship between the two objective functions is displayed in Figure 5.2.

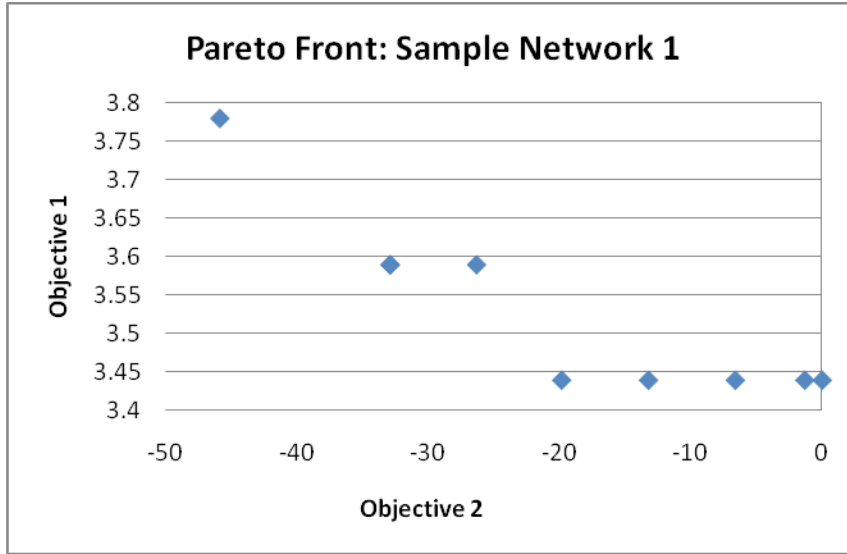


Figure 5.2: Pareto Front, OD pairs (63 6) (70 60)

The shape of the graph in Figure 5.2 is expected because it is a minimization problem. The y-axis represents the first objective function term that minimizes the length. The x-axis is the second objective function term that maximizes improvements. The graph shows that some optimal solutions have the same value in the first objective function, meaning the solutions have the same length.

The network characteristics BLOS and Network Length are also affected by changes in the value of W2. Figure 5.3 shows the relationship between these network characteristics.

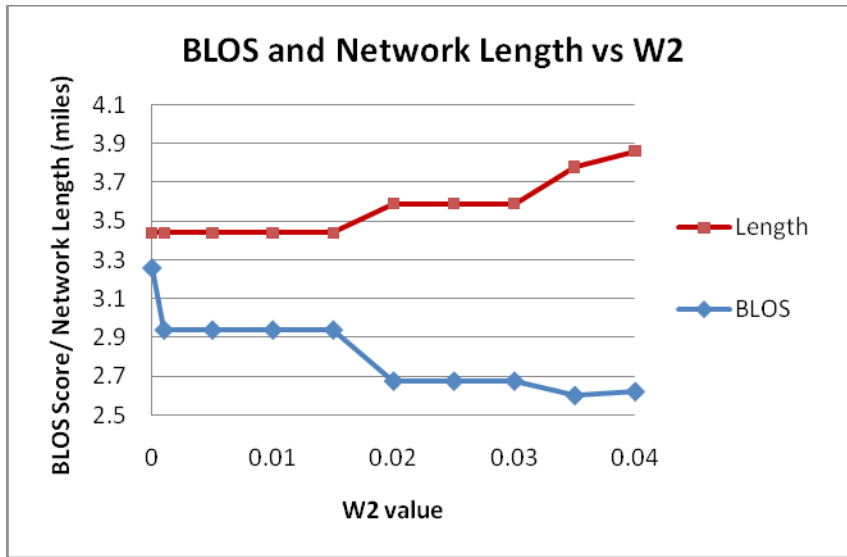


Figure 5.3: BLOS and Length vs W2, OD pairs (63 6) (70 60)

As shown in Figure 5.3, as the W2 value increases the BLOS value decreases, marking an improvement in the BLOS. This is what one would expect, since the second term seeks to maximize improvements to the network. The length of the network increases at the cost of BLOS improvement. Both the network BLOS and network length remain the same for some consecutive scenarios. The solutions for Scenario 2 and Scenario 6 are displayed in a picture of the network solutions in Figure 5.4.

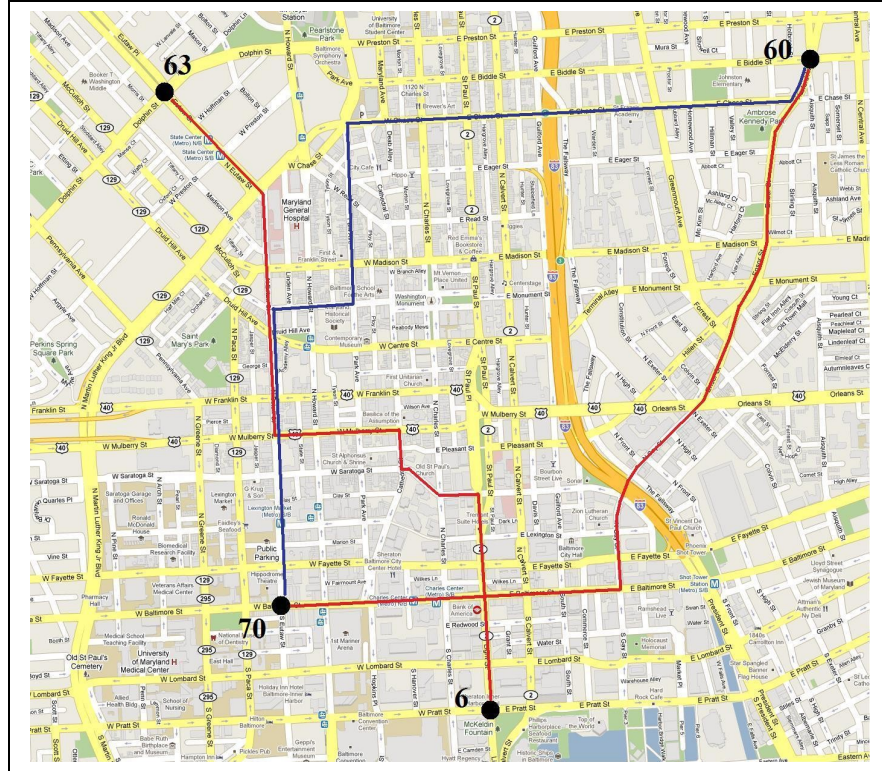


Figure 5.4: Solution for Scenarios 2 and 6, OD pairs (63 6) (70 60)

In Figure 5.4, the red lines show the paths for Scenario 2, while the purple line shows the path for Scenario 6. Path (63 6) remains the same for both scenarios so only one path is drawn.

Details for individual paths from each scenario are displayed in Table 5.2.

Scenario Number	Demand	Length	BLOS	Node Order
1	$d_{63,6}$	1.59	3.189	63-49-124-43-107-30-21-104-121-99-100-101-92-80-14-6
1	$d_{70,60}$	1.85	3.3126	70-76-79-80-81-82-94-103-25-35-36-38-120-135-140-60
2, 3, 4, 5 6, 7, 8	$d_{63,6}$	1.59	2.5027	same as 1, $d_{63,6}$
2, 3, 4, 5 6, 7, 8	$d_{70,60}$	1.85	3.3126	same as 1, $d_{70,60}$
6, 7, 8	$d_{70,60}$	2.0	2.8144	70-89-17-21-30-107-43-44-125-129-51-52-136-137-138-139-140-60
9	$d_{63,6}$	1.71	2.4366	63-49-124-43-107-30-21-104-121-99-100-101-92-80-14-6, 61-62-61
9	$d_{70,60}$	2.07	2.7405	70-89-17-21-30-107-43-44-125-129-51-52-53-136-137-138-139-140-60
10	$d_{63,6}$	1.79	2.4868	63-49-124-43-107-30-21-104-121-99-100-101-92-80-14-6, 36-37-36, 61-62-61
10	$d_{70,60}$	2.07	2.7405	Same as 9, $d_{70,60}$

Table 5.2: Individual Path Statistics, OD pairs (63 6) (70 60)

For Path (70 60), the first five scenarios have the same solution. For Path (63 6) the first eight scenarios have the same path solution, but the first scenario differs from the rest in BLOS. When W2 equals zero in the first scenario, the average BLOS is 3.189. This improves to 2.5027 for Scenarios 2 through 8 because bike lanes were added to every segment in the path. In the first scenario, some segments in the path were not chosen for bike lane improvements. This can happen if the minimum level of service requirement is already met on a segment prior to any improvements.

The first time Path (63 6) changes in length is Scenario 9, when links 61-62 and 62-61 are added to the network. Segment 61-62 functions in two directions and the conservation of flow is maintained in both nodes. In this case, too much weight is placed on the second term and as a result, an unconnected, extra link is added to the network. This occurs because as the second term is issued more weight, the objective function can be reduced if more links are added to the network. This allows for

further improvements to the BLOS on the extra links at the expense of adding distance. This type of solution is not acceptable because it does not make sense to add unconnected links for the sake of adding more bike lanes.

5.1.2. Sample Network 2 with 3 OD Pairs

Three OD pairs from 4 zones were used in the next sample network to further analyze the sensitivity of the objective function weights. This sample is made up of three origins with one destination in common. Similar to the first sample network, the budget parameter was set to an unrestricting value and the S_{\max} parameter was set to 4.0. A summary of the results is displayed in Table 5.3.

Scenario Number	1	2	3	4	5
W2	0	0.001	0.005	0.01	0.015
Objective Function	3.75	5.06765	10.3382	16.9213	23.4903
Time (seconds)	108	2986	288	665	257
Sum of Paths (miles)	3.75	3.75	3.75	3.76	3.8
Network Length (miles)	3.59	3.59	3.59	3.68	3.64
Bike Lanes (miles)	2.9	3.59	3.59	3.68	3.64
Network BLOS	3.3810	3.103104	3.103104	3.1334	2.8745

Scenario Number	6	7	8	9
W2	0.02	0.025	0.03	0.035
Objective Function	30.0502	36.6053	43.1604	49.715
Time (seconds)	1026	475	187	814
Sum of Paths (miles)	3.83	3.83	3.83	3.95
Network Length (miles)	3.6	3.6	3.6	3.87
Bike Lanes (miles)	3.6	3.6	3.6	3.87
Network BLOS	2.8000	2.8000	2.8000	2.7935

Table 5.3: Network Statistics, OD pairs (7 88) (130 88) (139 88)

As seen in Table 5.3, the Network Length and Sum of Paths measurements differ. This occurs because the individual paths have segments in common. The length of Bike Lanes is the same as the Network Length, except for the first scenario when W2

is zero. Fewer bike lanes are needed in this scenario because the minimum level of service requirement is met on some segments without improvements.

In this sample network the objective function also increases as the value of W2 increases. Figure 5.5 shows this relationship.

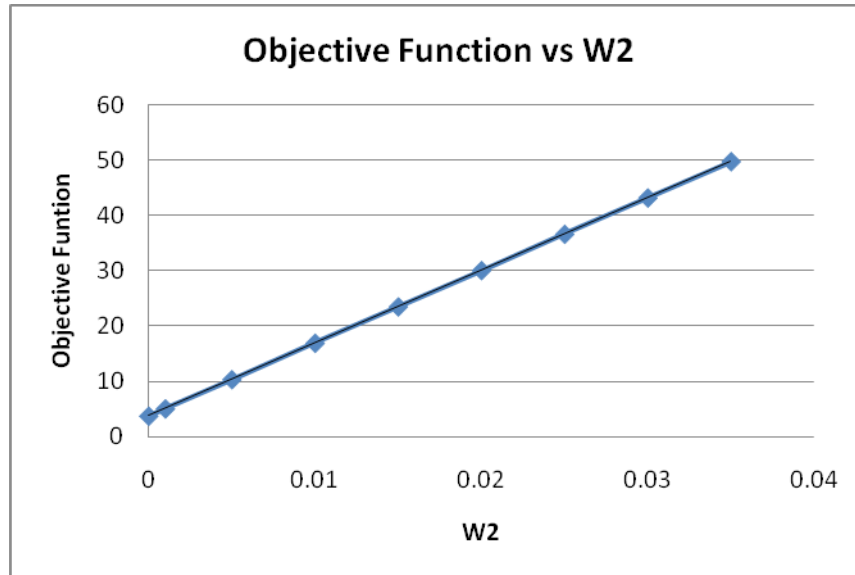


Figure 5.5: Objective Function vs W2, OD pairs (7 88) (130 88) (139 88)

The trend line for the graph displayed in Figure 5.5 reflects the following equation:

Objective Function = 1313.3 * W2 + 3.7695. This is very close to the trend line from Sample 1.

The relationship between the two objective functions is illustrated in Figure 5.6.

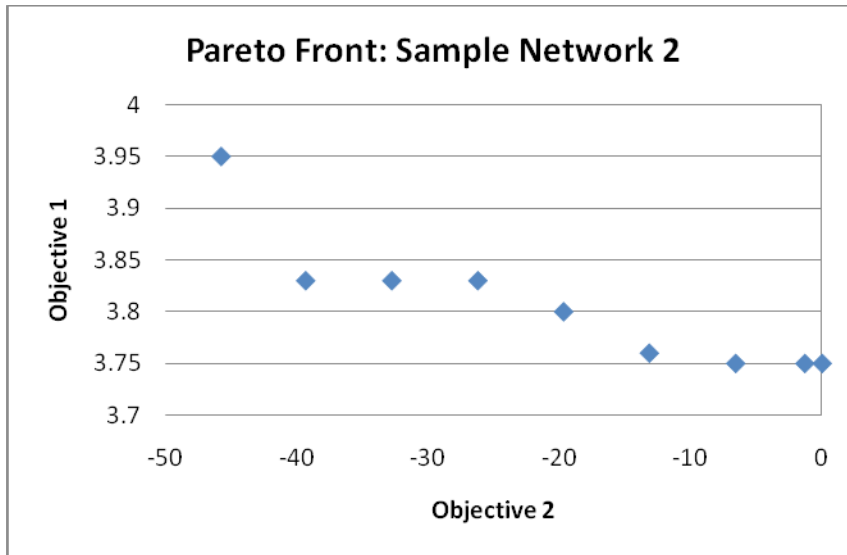


Figure 5.6: Pareto Front, OD pairs (7 88) (130 88) (139 88)

The Pareto front, shown in Figure 5.6, has a smoother line compared to Sample Network 1. The shape is similar, demonstrating the trade-off between reducing the length and improving the service level.

The average BLOS over the network and the total network length change as $W2$ increases. Figure 5.7 displays the relationship between these network characteristics.

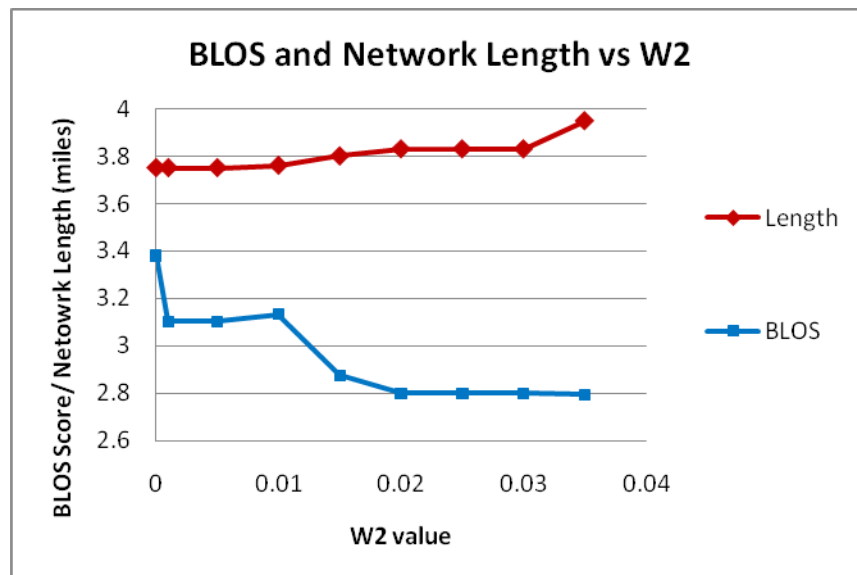


Figure 5.7: BLOS and Length vs W2, OD pairs (7 88) (130 88) (139 88)

As seen in Figure 5.7, the length increases as the W2 value increases. The average BLOS tends to decrease as the W2 value increases, with a slight increase at the 4th scenario. This is possible because the program seeks to minimize the sum of the BLOS scores for links included in the network solution. Figure 5.7 shows the average BLOS per length over the network as a characteristic of the network solution.

The picture in Figure 5.8 displays the solutions to Scenarios 3 and 6, to illustrate the change that occurs when the length increases and BLOS decreases.

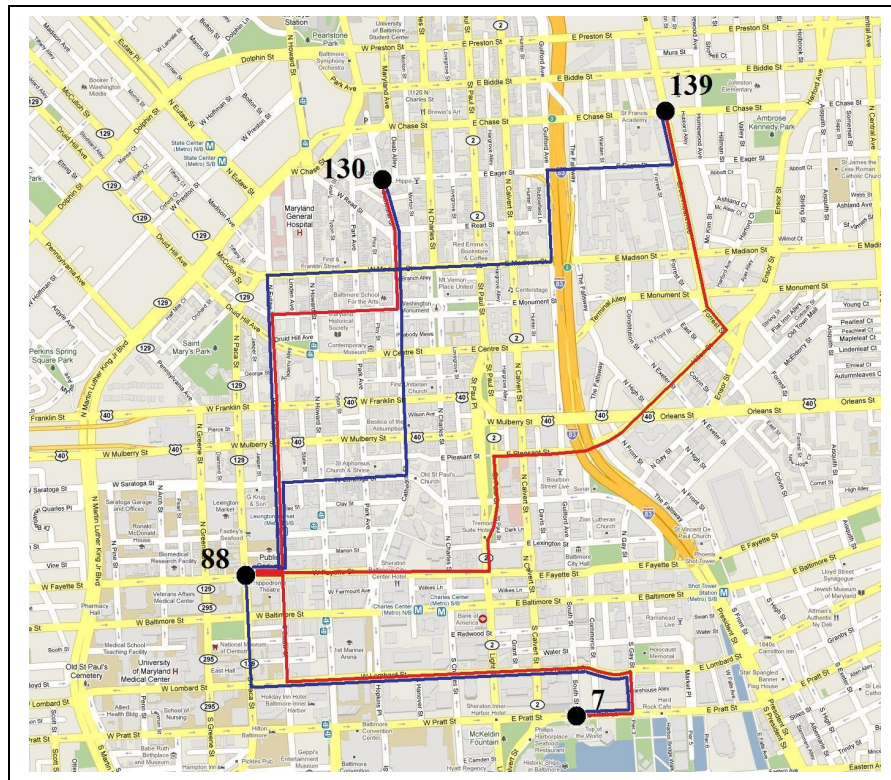


Figure 5.8: Solution for Scenarios 3 and 6, OD pairs (7 88) (130 88) (139 88)

Figure 5.8 displays the solutions for the first three scenarios in red, and the 6th scenario in purple. Path (7 88) only changes slightly while Path (130 88) and Path (139 88) take quite different routes. Path (130 88) can easily join path (139 88) in

Scenario 6, but without a limiting budget constraint the program finds a better solution.

Individual path details are described in Table 5.4.

Scenario Number	Demand	Length	Average BLOS	Node Order
1	$d_{7,88}$	1.05	3.58952	7-84-83-15-14-13-77-12-70-89-88
1	$d_{130,88}$	1	3.10018	130-126-45-44-43-107-30-21-17-89-88
1, 2, 3, 4	$d_{139,88}$	1.7	3.41745	139-134-119-118-37-26-71-72-101-92-91-90-89-88
2, 3	$d_{7,88}$	1.05	3.09333	Same as 1, $d_{7,88}$
2, 3, 4	$d_{130,88}$	1	2.57898	Same as 1, $d_{136,88}$
4, 5, 6, 7, 8, 9	$d_{7,88}$	1.06	3.20075	7-84-83-15-14-13-77-12-11-75-88
5	$d_{130,88}$	1.04	3.16292	130-126-45-109-122-121-99-90-89-88
5	$d_{139,88}$	1.7	2.49453	139-134-133-41-40-127-46-126-45-44-43-107-30-21-17-89-88
6	$d_{130,88}$	1.04	3.04465	130-126-45-109-122-121-99-98-17-89-88
6, 9	$d_{139,88}$	1.73	2.40747	139-134-133-41-40-127-46-126-125-124-43-107-30-21-17-89-88
7, 8	$d_{130,88}$	1.03	2.43029	130-126-125-124-43-107-30-21-17-89-88
7, 8	$d_{139,88}$	1.74	2.7748	139-134-133-41-40-127-46-126-45-109-122-121-99-98-17-89-88
9	$d_{130,88}$	1.15	2.33948	130-126-125-124-43-107-30-21-17-89-88, 62-61-62

Table 5.4: Individual Path Statistics, OD pairs (7 88) (130 88) (139 88)

Table 5.4 shows that Path (7 88) changes its route at Scenario 4, causing a slight increase in length and average BLOS. This occurs because links in the 4th scenario solution have more opportunity for improvement than the previous solution. Typically, when a path is chosen with the greatest amount of improvement opportunity, the average BLOS also improves. In this case, the average BLOS over the length of the path is increased slightly.

The remaining two paths change routes a few times. It is worth noting that as W2 increases, the length of the paths increase by a small amount. Path (139 88) is 1.7 miles long in the first scenario and 1.74 miles long in the 8th scenario. Path (130 88) starts at 1 mile long and is 1.03 miles long in the 8th scenario. Deviating from the shortest path in order to allow for a better service level does not mean drastically increasing the length of path.

5.1.3. Sample Network 3 with 3 OD Pairs, 6 Zones

This sample network analyzes three origin-destination pairs, but this time six zones were used. The value of W2 was adjusted with all other parameters held constant. The budget and cost per bike lane mile, as well as the S_{\max} parameter, were set to the same value as the first two sample networks, unrestricting and 4.0 respectively. The summary of results is displayed in Table 5.5.

Scenario Number	1	2	3	4	5
W2	0	0.001	0.005	0.01	0.015
Objective Function	4.18	5.49133	10.7367	17.2933	23.85
Time (seconds)	6835	124	24956	7112	95
Sum of Paths (miles)	4.18	4.18	4.18	4.18	4.18
Network Length (miles)	4.18	4.18	4.18	4.18	4.18
Bike Lanes (miles)	2.62	4.18	4.18	4.18	4.18
Network BLOS	3.8000	3.297969	3.297969	3.297969	3.297969

Scenario Number	6	7	8	9
W2	0.02	0.025	0.03	0.035
Objective Function	30.3894	36.9067	43.424	49.9412
Time (seconds)	4371	220	300	97
Sum of Paths (miles)	4.32	4.32	4.32	4.38
Network Length (miles)	4.32	4.32	4.32	4.38
Bike Lanes (miles)	4.32	4.32	4.32	4.38
Network BLOS	2.642247	2.642247	2.642247	2.627421

Table 5.5: Network Statistics, OD pairs (1 61) (38 19) (94 68)

Three statistics in Table 5.5; Sum of Paths, Network Length, and Bike Lanes; have the same value for Scenarios 2 through 9. This occurs because all three paths are completely separate and bike lanes are added to every segment in each solution. The first scenario has fewer bike lanes, when $W2 = 0$, because the service level requirement is already met on some segments. Additionally, the objective function increases linearly as the value of $W2$ increases, in a similar fashion as the previous two sample networks.

The Pareto front for this sample is displayed in Figure 5.9.

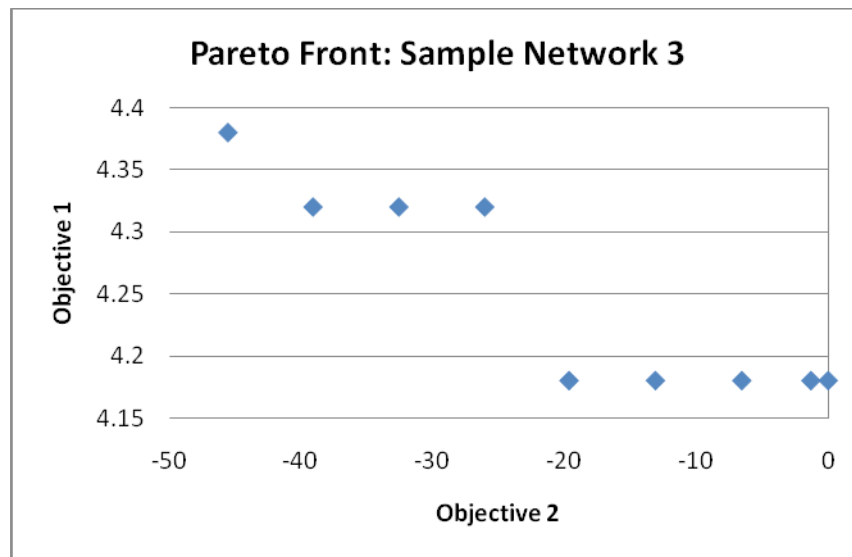


Figure 5.9: Pareto Front, OD pairs (1 61) (38 19) (94 68)

Figure 5.9 shows a similar shape to the previous two samples. The difference is a drastic change between the 4th and 5th points. These two points represent optimal solutions with a larger change in length than previous samples.

The changes in Network BLOS and Network Length for different values of $W2$ are illustrated in the graph in Figure 5.11.

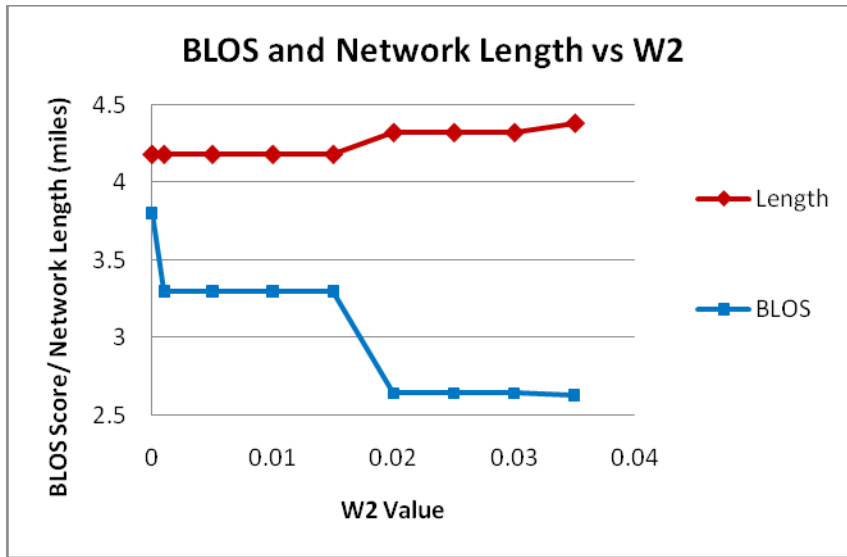


Figure 5.10: BLOS and Length vs W2, OD pairs (1 61) (38 19) (94 68)

Figure 5.10 shows the increasing relationship between Network Length and W2 and the decreasing relationship between average BLOS and W2. The Network Length increases by 0.14 miles when $W2 = 0.02$. In this scenario, the average BLOS decreases by 0.65, a dramatic improvement. This is an example of a tradeoff between distance and level of service where it is worth it to deviate from the shortest path to improve the level of service offered.

The solutions for Scenario 1 and Scenario 6 are displayed in Figure 5.8.

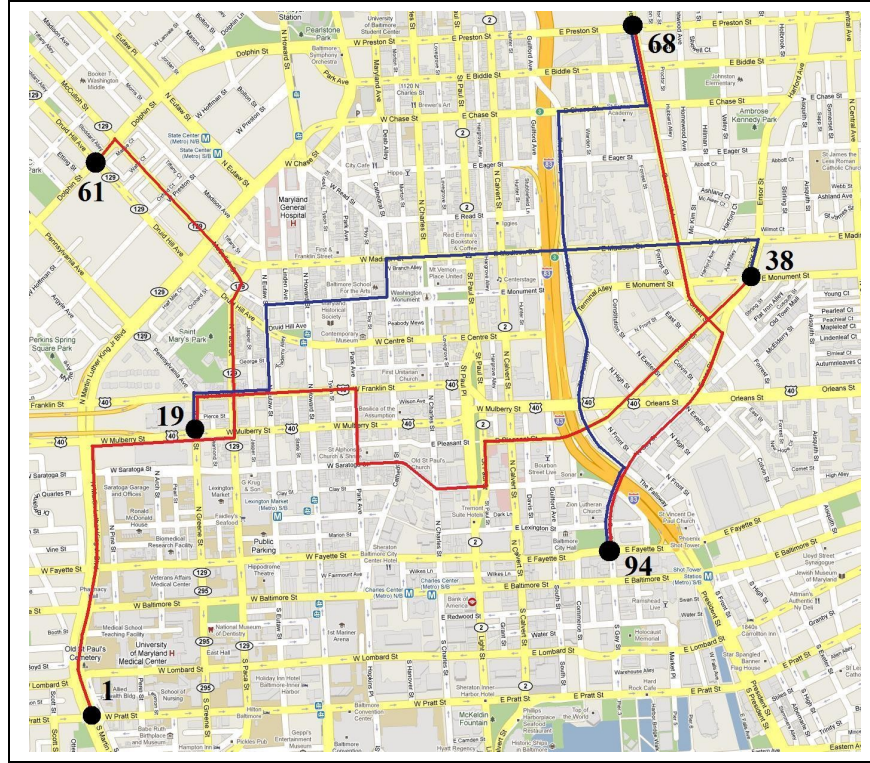


Figure 5.11: Solution for Scenarios 1 and 6, OD pairs (1 61) (38 19) (94 68)

Figure 5.11 shows the path solution for Scenario 1 and Scenario 6. These two paths include all solutions for scenarios 1 through 8. Path (1 61) is the same route in both cases. Path (38 19) and Path (94 68) change drastically. In both cases, the path length increases slightly, while the average path BLOS decreases.

Individual path statistics for each scenario are displayed in Table 5.6.

Scenario Number	Demand	Length	Average BLOS	Node Order
1	(1 61)	1.55	4.06145	1-9-73-86-95-18-19-20-29-42-123-48-62-61
1	(38 19)	1.5	3.65831	38-37-26-71-72-101-100-99-98-104-105-30-29-28-19
1	(94 68)	1.13	3.62956	94-103-25-35-36-37-118-119-134-139-59-68
2,3,4,5,6,7,8	(1 61)	1.55	3.12434	same as 1, $d_{1,61}$
2,3,4,5	(38 19)	1.5	3.29031	same as 1, $d_{38,19}$
2,3,4,5	(94 68)	1.13	3.5463	same as 1, $d_{94,68}$
6,7,8,9	(38 19)	1.55	3.19032	38-120-119-128-40-127-46-126-45-44-43-107-30-29-28-19
6,7,8,9	(94 68)	1.22	1.33343	94-103-25-26-39-117-128-133-138-139-59-68
9	(1 61)	1.61	3.06604	1-9-73-86-95-18-19-20-29-42-123-48-62-61-62

Table 5.6: Individual Path Statistics, OD pairs (1 61) (38 19) (94 68)

As shown in Table 5.6, the first five scenarios have same paths. In the 6th scenario, Path (38 19) and Path (94 68) change, increasing in length while decreasing in BLOS. Path (38 19) increases by 0.05 miles and decreases in BLOS score by 0.10. Path (94 68) increases by 0.09 miles and decreases in average BLOS score by 2.21.

Path (1 61) has the same path for the first eight scenarios, but a different network BLOS in the first scenario due to fewer bike lane improvements. In the 9th scenario, an additional link is added to the path to allow for more improvements. When $W_2=0.035$, more weight is given to improving the level of service to such an extent that a link is added to the network solution for the sake of improving more links rather than improving a path used by an OD pair. This output is an undesirable solution because it includes an unnecessary link.

5.1.4. W2 Value Justification

In Sample Network 1 and Sample Network 3 the desired solutions occurred when W2 was set to 0.02, 0.025, and 0.03. In Sample Network 2, the same three values along with W2 = 0.015 produced the desired outcome. These solutions were close to the shortest path, and had a better average BLOS than solutions with shorter distances. Furthermore, these solutions have no links that are unnecessary.

In all cases, W2 = 0.035 is the point when unnecessary links are added to the network. In the sample networks analyzed, it is obvious when this occurred because the links were often unconnected. In a larger problem, extra links may be connected to the network and difficult to pick out. The conservative acceptable W2 value was chosen for this case study: W2 = 0.02.

The objective function is valuable as a means to compare different solutions. It is important to understand the type of solutions different weight ratios produce. Future analyses should calibrate W1 and W2 to a specific dataset to meet a project's needs.

5.2. Budget and Cost Per Bike Lane Mile Sensitivity

Budget, B, and cost per bike lane mile, C, are two parameters in this model. They are related in Constraint (3.2) displayed in the following equation:

$$\sum_{(i,j) \in A} C \cdot L_{ij} \cdot y_{ij} \leq B$$

The budget divided by cost per bike lane mile is the maximum sum of segment lengths which may receive a bike lane improvement. The sensitivity of the budget and cost per bike lane mile parameters is explored in this section.

5.2.1. Budget Sensitivity Case 1

The sample network used has the same structure as Sample Network 2 in Section 5.1, with OD pairs (7 88), (130 88) and (139 88). The cost per bike lane mile, C , is set to 1 in this sensitivity analysis, while the budget parameter, B , is adjusted over multiple scenarios. The other parameters were set to $W2 = 0.02$ and $S_{\max} = 4.0$. A summary of the output is displayed in Table 5.7.

Scenario Number	1	2	3	4	5	6
Budget	4	3.5	3	2.5	2	1.7
Objective Function	30.0502	30.0537	30.1528	30.2596	30.4215	30.807
Time (seconds)	573	220	622	423	343	604
Sum of Paths	3.83	3.8	3.77	3.75	3.75	4.06
Network Length	3.6	3.49	3.11	2.81	2.81	3.43
Bike Lanes (miles)	3.6	3.49	2.96	2.49	1.99	1.66
Network BLOS	2.8000	2.84208	2.82916	2.87991	3.17211	3.22656

Table 5.7: Network Statistics for Multiple Budget Parameters

As seen in Table 5.7, the budget parameter is 4 in the first scenario. This means there is enough available budget to add 4 miles of bike lanes, yet only 3.6 bike lanes are used. In this case, 3.6 miles is all that is needed for the optimal outcome. When the budget parameter is reduced below 3.6, the solution utilizes almost the entire available budget.

The relationship between the objective function and the budget parameter is displayed in Figure 5.12.

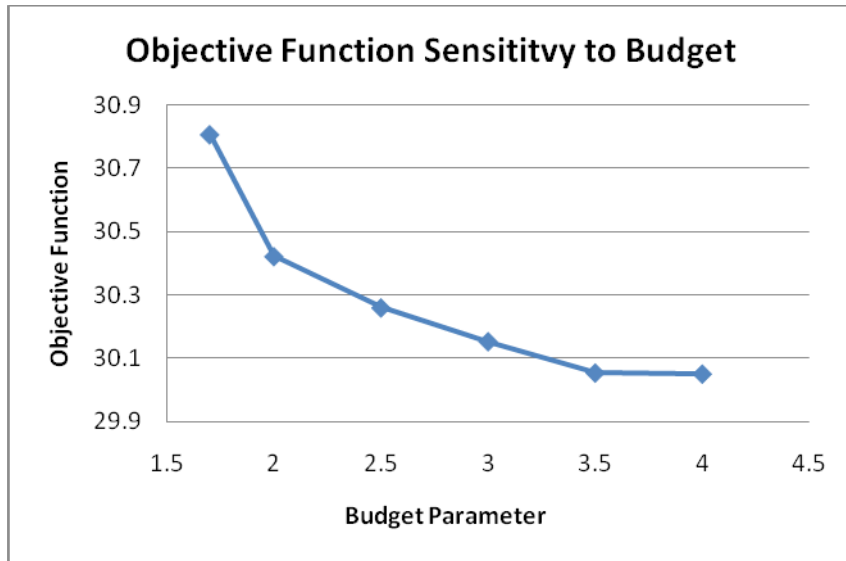


Figure 5.12: Objective Function vs Budget

Figure 5.12 shows the inverse relationship between the objective value and the Budget parameter. When the budget decreases, fewer links are available for improvements, so it is sensible that the objective function cannot be as good.

The network solutions from Scenario 1 and Scenario 4 are illustrated in Figure 5.13.

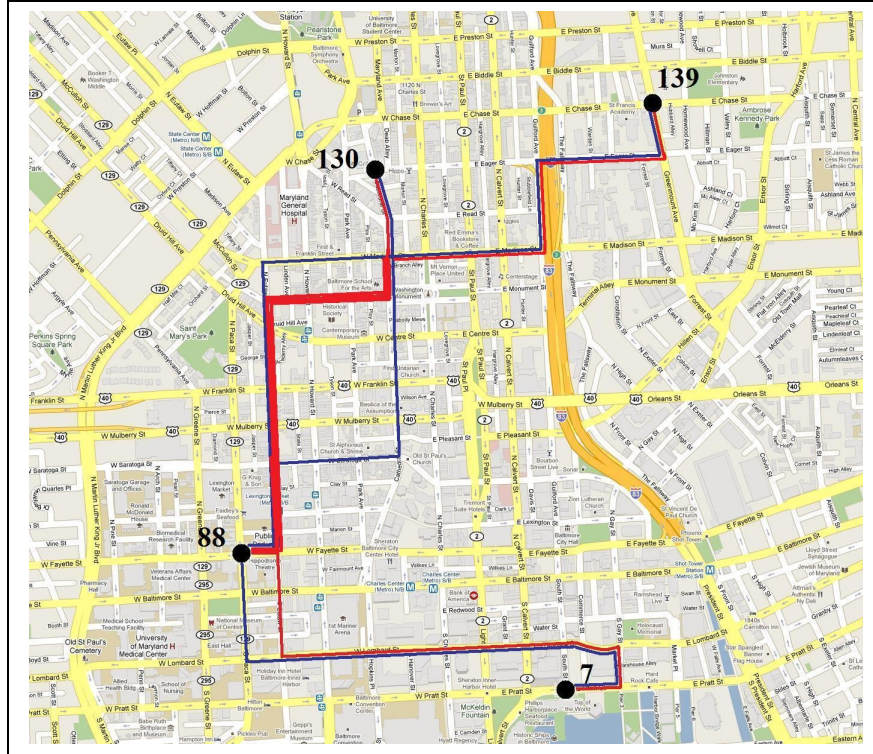


Figure 5.13: Solutions for Scenario 1 and 4, Budget Sensitivity

The purple lines in Figure 5.13 represent the solution from the first scenario. The red lines show the 4th scenario output. The thick red lines represent links where paths combine to share a route. In this sample network, the extra distance necessary to combine paths is minor.

Without a limiting budget, the mathematical program has no reason to combine paths unless a segment is part of the direct path for multiple OD pairs. In fact, the second term in the program seeks to maximize service level improvements, so separate paths for each OD pair produce a better solution.

5.2.2. Budget Sensitivity Case 2

In this case, the budget is analyzed for one sample network with two different values of W_2 . This sample network has the same structure as Sample Network 3 in Section

5.1, with OD pairs (1 61), (38 19) and (94 68). Again, the budget parameter value was adjusted over multiple scenarios, while C was set to 1. S_{\max} was set to 4.5. In the first set, $W_2=0.015$. A summary of the output is shown in Table 5.8.

Scenario Number	1	2	3	4
Budget	4.5	4	3.5	3
Objective Function	23.85	23.8673	23.9029	23.9696
Time (seconds)	1910	856	664	1233
Sum of Paths	4.18	4.18	4.18	4.55
Network Length	4.18	4.18	4.18	3.61
Bike Lanes (miles)	4.18	3.89	3.48	3
Network BLOS	3.29796	3.37816	3.49578	3.70275

Table 5.8: Network Statistics for Multiple Budget Parameters, $W_2=0.015$

In the next set, all parameters remain the same except $W_2=0.02$. The solutions are summarized in Table 5.9.

Scenario Number	1	2	3	4
Budget	4.5	4	3.5	3
Objective Function	30.3894	30.4156	30.4642	30.5585
Time (seconds)	162	1340	14372	129
Sum of Paths	4.32	4.27	4.27	4.27
Network Length	4.32	4.27	4.27	4.27
Bike Lanes (miles)	4.32	3.98	3.48	3
Network BLOS	2.64321	2.74946	2.89173	3.08178

Table 5.9: Network Statistics for Multiple Budget Parameters, $W_2=0.02$

Table 5.8 and Table 5.9 show consistent results. The objective function value increases as the budget tightens. The Sum of Paths and Network BLOS are inversely related in both tables. Furthermore, Table 5.9 has a better network average BLOS and longer path lengths compared to Table 5.8.

The graphs comparing the objective function to budget parameters for the two values of W_2 are displayed in Figure 5.14 and Figure 5.15.

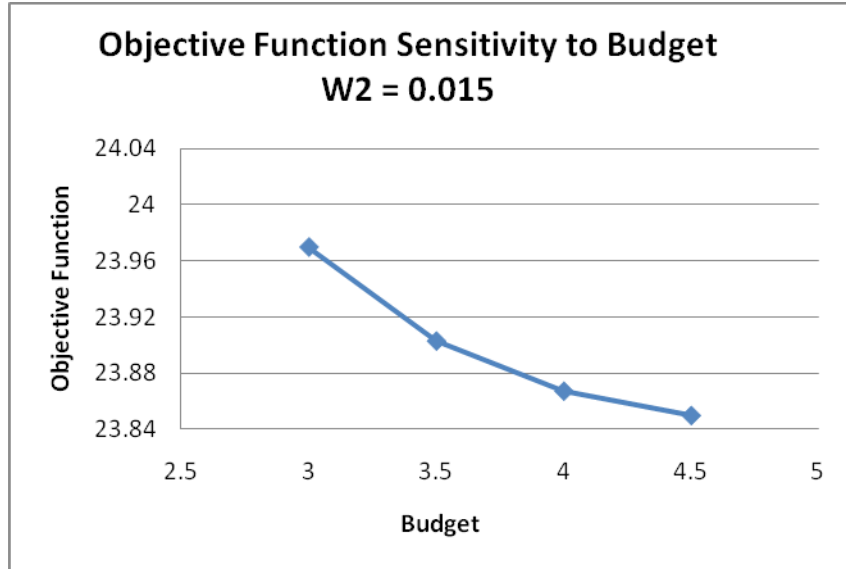


Figure 5.14: Objective Function vs Budget, W2=0.015

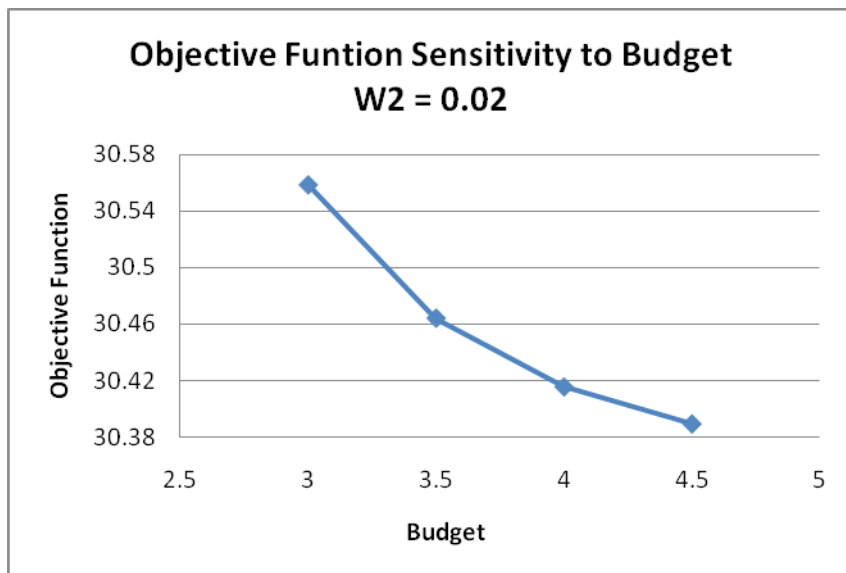


Figure 5.15: Objective Function vs Budget, W2=0.02

The graphs in Figures 5.14 and 5.15 have different objective function values in the y-axis, but the same unit changes to allow for an easy comparison. The graphs have similar shapes, but when $W2=0.02$ the objective function decreases by a greater amount when the budget increases.

5.3. Level of Service Parameter

The service level parameter, S_{\max} , sets an upper limit for the BLOS score on all links in the network solution. This ensures that a minimum level of service is reached on every link in the network solution. This applies to links that receive bike lane improvements and links that remain unchanged.

5.3.1. S_{\max} Sensitivity Case 1

The structure for Sample Network 2 in Section 5.1 is used in this case, with OD pairs (7 88), (130 88) and (139 88). The S_{\max} parameter was adjusted between 3.7 and 4.5. The remaining parameters, B and W2 were set to 3.5 and 0.02 respectively. The results are summarized in Table 5.10.

Scenario Number	1	2	3	4	5
S_{\max}	3.7	3.9	4.1	4.3	4.5
Objective Function	30.4407	30.2596	30.2596	30.2592	30.2526
Time (seconds)	81	383	252	482	13171
Sum of Paths	3.86	3.75	3.75	3.76	3.76
Bike Lanes (miles)	2.44	2.49	2.49	2.47	2.5
Network BLOS	3.10580	2.87991	2.87991	2.92877	2.90439

Table 5.10: Network Statistics for Multiple S_{\max} Values

When the S_{\max} value increases, the service level requirement becomes less rigorous. Links with worse service levels are allowed to be part of the network solution. Even so, the objective function improves. This occurs because the program is less restrictive. Links with worse service levels cannot be included when the S_{\max} constraint is tight, even if one link is needed to connect a path with a better overall BLOS. In Table 5.10, this occurs in the second scenario when the Network BLOS is reduced from 3.1058 to 2.8799 after the S_{\max} value is changed from 3.7 to 3.9.

The graph of the objective function compared with the S_{\max} value is displayed in Figure 5.16.

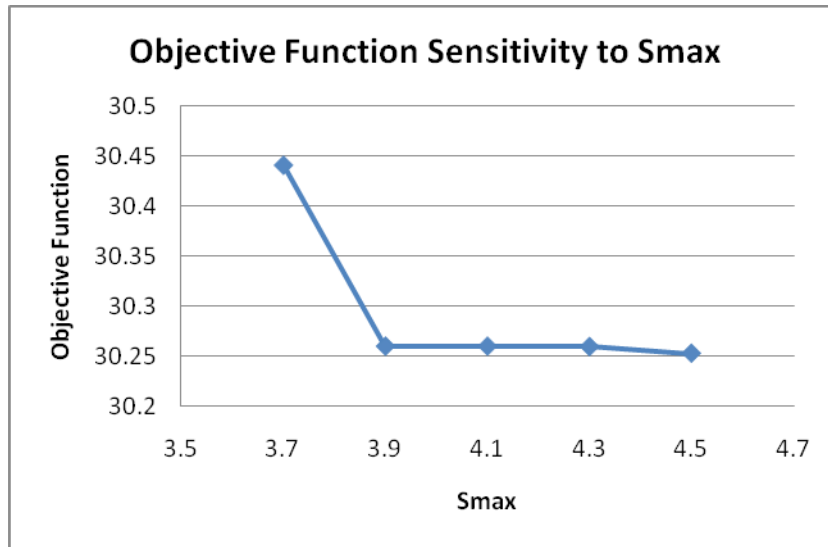


Figure 5.16: Objective Function vs S_{\max} , OD pairs (7 88) (130 88) (139 88)

Figure 5.16 shows a drastic change in the objective function between the first and second scenario, followed by similar objective values. This occurs because the first value for S_{\max} , 3.7, is very restrictive while the remaining S_{\max} values do not impose a tight constraint.

5.3.2. S_{\max} Sensitivity Case 2

This case used the network structure from Sample Network 3 in Section 5.1, with OD pairs (1 61), (38 19) and (94 68). The S_{\max} parameter was adjusted, while the parameters B and W2 were held constant at 3.5 and 0.02 respectively. The results are summarized in Table 5.11.

Scenario Number	1	2	3	4
S_{\max}	3.8	4	4.2	4.4
Objective Function	30.8219	30.6078	30.5737	30.4642
Time (seconds)	58	33	1136	6133
Sum of Paths	4.41	4.38	4.32	4.27
Bike Lanes (miles)	3.47	3.5	3.5	3.48
Network BLOS	2.86951	2.71560	2.81929	2.89173

Table 5.11: Network Statistics for Multiple S_{\max} Values

As seen in Table 5.11, the Sum of Paths decreases as the S_{\max} parameter increases. The mathematical program is able to find shorter paths as the service level constraint relaxes. The Network BLOS changes slightly in the four scenarios. The best average BLOS is in the 2nd scenario, while the worst occurs in the 4th scenario.

The relationship between the objective value and S_{\max} is displayed in Figure 5.17.

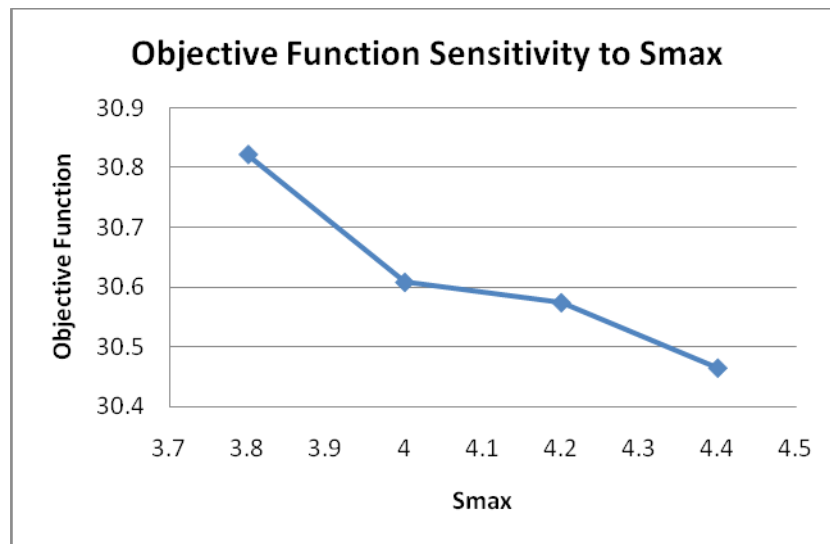


Figure 5.17: Objective Function vs S_{\max} , OD pairs (1 61) (38 19) (94 68)

As seen in Figure 5.17, there is a gradual decrease in the objective value as the S_{\max} value increases. Larger values of S_{\max} still impose a constraint in this case.

In this chapter, the parameter values for W_1 , W_2 , B , C , and S_{\max} have been analyzed.

A large sample problem may now be approached, assigning specific values to the parameters.

Chapter 6: Large Problem Case Study

A problem with a greater number of OD pairs represents a realistic application for the mathematical program. Origin and destination zones are chosen throughout the case study region and parameter values are assigned based on the sensitivity analysis. This chapter examines the type of connected bike route network solution the program produces.

6.1. Problem Setup

The parameters used in the large problem case study are displayed in Table 6.1.

Parameter	Value	
	Case 1	Case 2
f_{\max}	50	50
f_{\min}	5	5
W1	1	1
W2	0.02	0.02
C	10	10
B	60	150
S_{\max}	4.0	3.6

Table 6.1: Input Parameters

As seen in Table 6.1, the parameter values for the budget, B, and the service level, S_{\max} , differ between cases. Case 1 will examine a problem with a tight budget, while Case 2 will meet stricter service level requirements.

There are ten zones included in this sample problem. A zone is a node location that functions as an origin, a destination, or both. The zones chosen are spread across the

network. The ten zones are listed below with their locations depicted in the map in Figure 6.1:

Set of Zones: [10, 25, 48, 51, 63, 68, 81, 97, 99, 135]

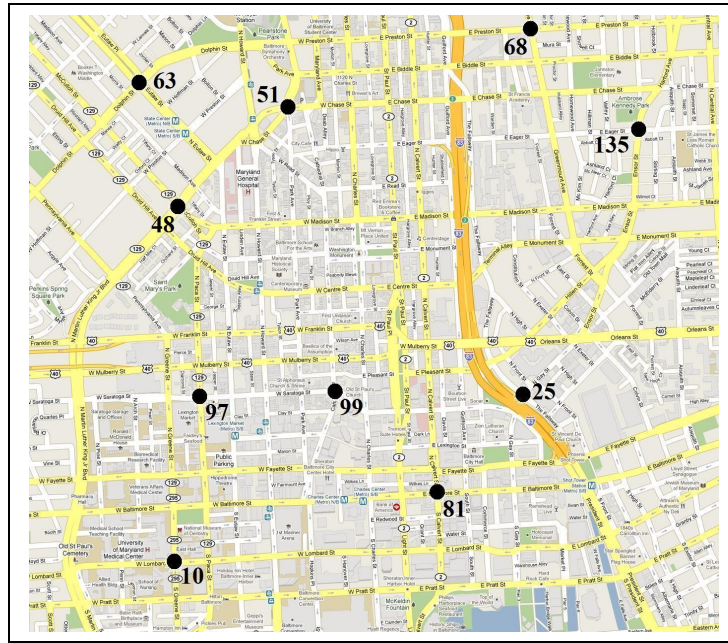


Figure 6.1: Zone Locations for Large Sample Problem

Eight OD pairs were chosen to connect the zones in the case study. The OD pairs are listed below:

(10, 51) (10, 135) (25, 48) (63, 99) (81, 51) (97, 68) (135, 81) (135, 99)

Zones 10, 25, 63, and 97 are origins only. Zones 51, 48, 68 and 99 are destinations.

Zones 81 and 135 are both origins and destinations in different OD pairs.

6.2. Case Study Results

6.2.1. Case 1, Tight Budget

The first case examined assumes a budget limited to 6 miles of bike lane improvements. The level of service must be 4.0 or better. The output results are displayed in Table 6.2.

Network Characteristic	Value
Objective Function	31.3156
Time (seconds)	108,355
Sum of Paths (miles)	12.49
Network Length (miles)	7.58
Bike Lanes (miles)	5.98
Network BLOS	3.1020

Table 6.2: Case 1 Network Statistics

The network characteristics for Case 1 are summarized in Table 6.2. The length of bike lane improvements was limited to 6 miles in this problem, and 5.98 miles of improvements were added in the network solution. The Network Length, 7.58 miles, represents the total length of segments in the solution. The difference between Network Length and Bike Lanes, 1.60 miles, is the length of segments in the network solution that do not receive bike lane improvements. The sum of the length of all OD pairs is 12.49 miles. The minimum service level requirement, S_{\max} , was set to 4 in this problem. The network average BLOS is far less, 3.1021, because the program seeks to make as many improvements as possible.

Individual path details are described in Table 6.3.

Demand	Length	Average BLOS	Node Order
(10 51)	1.52	3.46859	10-2-3-11-75-70-89-17-21-104-105-108-44-125-129-51
(10 135)	2.23	3.26144	10-2-3-11-75-70-89-17-21-104-121-22-31-110-111-112-39-117-118-38-120-135
(135 81)	2.07	3.2367	135-120-119-128-40-127-46-126-45-109-122-121-99-90-76-79-80-81
(135 99)	1.35	3.20293	135-120-119-128-40-127-46-126-45-109-122-121-99
(81 51)	1.5	2.95149	81-82-94-93-92-91-100-99-98-104-105-108-44-125-129-51
(25 48)	1.18	2.79643	25-26-39-117-128-40-127-46-126-125-124-123-48
(63 99)	0.99	2.53459	63-49-124-43-107-30-21-104-121-99
(97 68)	1.65	2.99285	97-17-21-104-105-108-44-125-129-51-52-136-137-138-58-59-68

Table 6.3: Individual Path Statistics

Many path solutions have segments in common, as seen in the Node Order column in Table 6.3. This occurs out of necessity, for example, if a location is the origin for multiple OD pairs. This also may occur to allow the program to connect OD pairs with a limited budget. Path (135 81) deviates from a shorter path. It has the same path solution as Path (135 99) and then continues to its destination at Node 81. The program used half as many bike lanes to improve both OD pairs in order to meet all requirements.

The network solution is displayed in Figure 6.2.

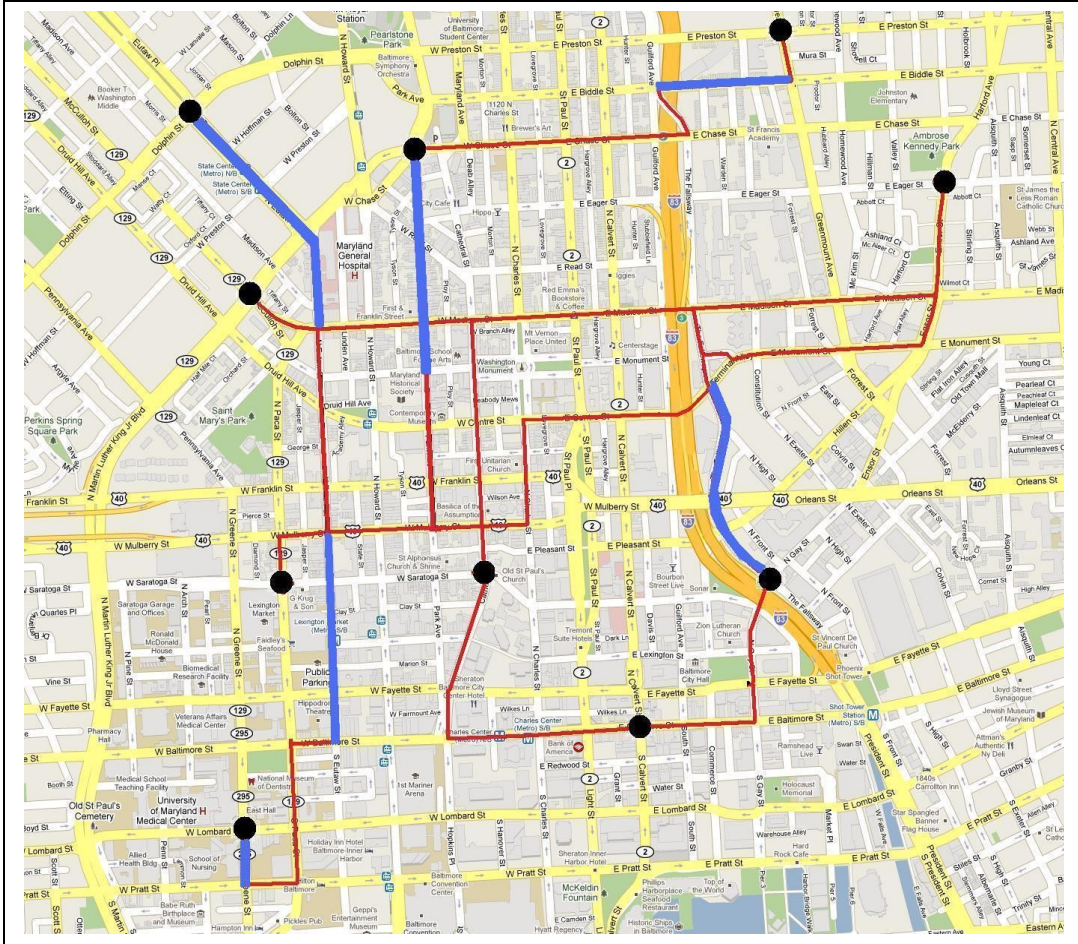


Figure 6.2: Solution for Case 1

The picture in Figure 6.2 illustrates the network solution for this case study. The red and blue lines, together, represent the connected bike network servicing the OD pairs of interest. The red lines show links requiring bicycle lane improvements. The thick blue lines represent links that are part of the network path system, but do not receive bike lane improvements. The blue links must have a current BLOS of 4.0 or better in order to be included in the solution without a bike lane improvement. The solution connects all OD pairs of interest, considering minimizing the distance and improving the service level as much as the constraints allow.

6.2.2. Case 2, Tight Level of Service

In the second case, the budget requirement is relaxed. The service level requirement is more rigorous, with a maximum score set to 3.6. This set-up was chosen to offer an interesting comparison to the first case. The results are displayed in Table 6.4.

Network Characteristic	Value
Objective Function	30.5355
Time (seconds)	101,573
Sum of Paths	12.68
Network Length	10.1
Bike Lanes (miles)	10.1
Network BLOS	2.6598

Table 6.4: Network Statistics for Case 2

The summary of statistics in Table 6.4 displays the same value for Network Length and Bike Lanes. This means that every link in the solution receives a bike lane improvement. The average network BLOS is 2.6598, a score 0.4422 better than Case 1. The tighter level of service requirement forces every link used in the path system to have a BLOS of 3.6 or better. The Sum of Paths, 12.68, is very similar to the Sum of Paths in Case 1, 12.49. The sum for all eight paths is only 0.19 miles longer in Case 1. Even with an unrestricting budget, minimizing the distance is a priority in the program. Finally, the Objective Function, 30.5355, is 0.7801 units less than the Objective Function in Case 1. Although the stand alone value does not mean much, a comparison between objective values can show the preferred solution.

Path statistics for each OD pair are displayed in Table 6.5.

Demand	Length	Average BLOS	Node Order
(10 51)	1.54	2.79445	10-2-3-11-75-70-89-17-21-30-107-43-44-125-129-51
(10 135)	2.25	3.21052	10-2-3-11-75-88-97-20-21-104-121-22-31-110-114-115-116-117-118-38-120-135
(135 81)	2.07	3.2367	135-120-119-128-40-127-46-126-45-109-122-121-99-90-76-79-80-81
(135 99)	1.37	2.70377	135-134-133-41-40-127-46-126-45-109-122-121-99
(81 51)	1.54	1.95438	81-82-94-103-25-26-39-117-128-133-41-132-131-130-129-51
(25 48)	1.18	2.41914	25-26-39-117-128-40-127-46-126-125-124-123-48
(63 99)	1.04	1.63962	63-49-124-43-107-30-21-17-98-99
(97 68)	1.69	2.50065	97-17-98-104-105-108-44-125-129-51-52-136-137-138-58-59-68

Table 6.5: Individual Path Statistics for Case 2

As seen in Table 6.5, some paths increase in length slightly compared to Case 1 due to the more rigorous service level requirement. The average BLOS remains the same or improves on each path. This can be attributed to the 4.12 additional miles of bike lanes.

The network solution for Case 2 is displayed in Figure 6.3.

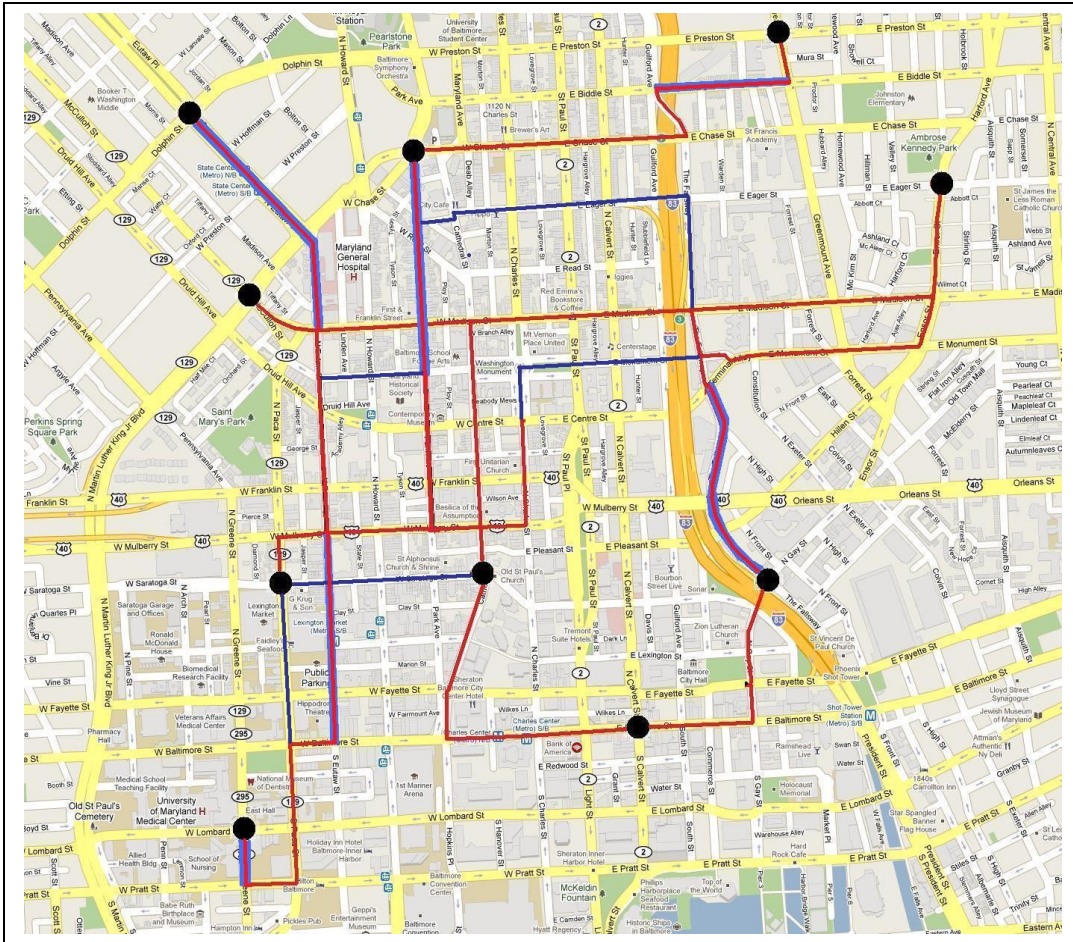


Figure 6.3: Solution for Case 2

Figure 6.3 shows the network solution for this case, with an unlimited budget and a tighter service level requirement. The picture shows Figure 6.2 from the previous sample, with additional links for the sake of comparison. Links in all colors are part of the network solution with bike lane improvements. The red lines show the bike lane improvements from the previous sample. The thick blue lines with red lines in the center represent links in the network solution from the previous sample without bike lane improvements. In this solution all of these links receive improvements. Finally, the purple lines represent links in the solution that are unique to this sample, and not part of the earlier sample problem.

One additional large problem was tested to check the suitability of the W2 value used. Case 2 was re-tested with a W2 value set to 0.03. The solution was deemed undesirable because unnecessary links were added. Path (135, 81) increased to 2.5 miles, 0.43 miles longer. The average BLOS score was reduced by 0.2313. The path is connected, but it is clear that links were added to have more opportunity for improvement. This further justifies the choice of 0.02 for the W2 parameter.

Three sample networks were used in the sensitivity analysis, with various parameter values. Two cases for a larger problem were also analyzed. The number of constraints and variables depends on the network structure: the number of OD pairs, zones, and potential links in the solution. The problem size, along with computational time is summarized in the Table 6.6.

Network Label	OD Pairs	Zones	Decision Variables		Constraints	Time (seconds)
			Integer	Continuous		
Sample 1	2	4	921	614	2121	103 - 6,606
Sample 2	3	4	1228	921	2874	81 - 13,171
Sample 3	3	6	1228	921	2874	58 - 24,956
Case 1	8	10	2178	1944	5461	108,355
Case 2	8	10	2763	2456	6639	101,573

Table 6.6: Problem Size and Running Time

The computational time varies greatly among problems. The solver, Xpress, uses the branch-and-bound method to find an integer solution. Typically, when a problem runs for a longer time, the solver finds the integer solution within the first 100 seconds but spends most of the time closing the bounds to ensure optimality.

6.3. Further Considerations

This problem provides insight to applying a mathematical program to determine the locations for bike lanes in an urban setting. Reflections are discussed for others to fully explore.

Realistic Dataset: Some links have an initial BLOS so high, they would never be considered in the network even with a bike lane improvement. There is no need for these links to be included in the network. The initial dataset could be more concise, and produce the same results, if links were excluded based on high BLOS scores and low improvement levels.

Applicability to City Planning: In this formulation, the amount of flow on a link does not influence the solution. Flow is used in the problem to ensure a connected network solution is produced. The demand has a large impact on the solution through origin and destination locations, which shape the paths the model optimizes. In this case study example, the origin and destination nodes were chosen to illustrate the mechanics of the model. With real origin-destination data, the results could become recommendations for city planners in Baltimore.

Running Time for Solving Problems: The problem is solved as an integer program using Xpress and the optimal solution is found. One drawback of the formulation is the amount of time it takes to find optimal solutions for some large problems. In the future, a heuristic should be developed to find a solution faster. This problem is similar in structure to a minimum cost multi-commodity flow problem, with the addition of the second term in the objective function and additional constraints which

address the level of service. One approach to developing a heuristic would be to exploit the similarities the problem has to a minimum cost multi-commodity flow problem. For example, the minimum cost, or shortest path, can be solved first for all OD pairs. Using this as the base solution, the level of service term can be incorporated. This thesis developed and solved a mixed integer program to determine bike lane locations in an existing urban road network. A heuristic is likely necessary to use this model for real world applications.

Chapter 7: Conclusions and Direction for Further Study

7.1. Conclusions

Bicycle travel is a healthy, inexpensive, environmentally friendly way to make short trips. It makes good sense for transportation planners to design road facilities that accommodate cyclists. Federal and state policy changes prove that there is an interest to increase bicycle use on a national scale, and transportation funding is available for that purpose. Research and pilot studies are taking place to determine best practices for planning in the future. Bicycle route choice and mode choice studies, described in the literature review, found cyclists do value bike facilities and make an effort to use them but for utilitarian trips, distance is the most important factor.

A biking level of service measure, developed by Landis and adapted by agencies around the United States, quantifies the perceived level of comfort a cyclist experiences while riding on a road segment. The measure is a function of traffic volume, speed, heavy vehicle percentage, pavement conditions, and effective width. The effective width is a measure of space a biker can use on a roadway considering the width of the outside lane, street parking occupancy, and the presence of a bike lane or shoulder. A bike lane increases the effective width and thus improves the biking level of service for that segment.

This thesis formulated a mathematical program to determine the optimum locations of bike lanes within an urban street network considering the travel distance and biking level of service. With bicycle demand for origins and destination pairs, bicycle routes

are created with a network wide perspective. The multi-objective function simultaneously considers the travel distance for each path and the service quality of the entire network.

A dataset for BLOS values was found in the Baltimore Level of Service Evaluation conducted by the Baltimore Metropolitan Council. A study area in the center of Baltimore was used in a case study to test the formulation. A sensitivity analysis was conducted by testing various sample networks, to examine how solutions changed when parameter values changed. The model's output listed links that formed a bicycle route for each OD pair, and whether each link in the route required a bike lane improvement. The network solutions were evaluated by measuring each routes length and level of service. Network solutions for different problems were compared to gain a full understanding of the model.

The model succeeded in finding bicycle routes considering travel distance while improving the level of service as much as possible. The weight values chosen for the terms in the objective function put a higher relative weight on the distance minimization term. This model offers a tool that locates bicycle routes in an urban street network for bicycle use, considering the network's layout and demand.

6.2. Further Study

6.2.1. Considerations for Applicability

The formulation presented offers a bike route network planning tool that considers trip distance, biking level of service, and connectivity. However, preparing the data in a way for the Xpress solver to read was time consuming. It is unrealistic to expect

planners and engineers to spend as much time processing data, especially for larger networks. A code is necessary to pre-process the data, so that the code's output can be the input for the Xpress solver. A user-friendly interface can be designed so data can easily be entered in the system in large quantities at one time. The development of an interface that would prepare the data for the Xpress solver is necessary before the routine use of this formulation is practical for transportation planners.

A post-results processing code that would generate the solution and key decision making statistics would also be useful for the industry. Ideally the code would have the capacity to generate a picture of the network with path link and bike improvement locations highlighted. This tool would be advantageous because it would allow a wider range of professionals to use the model.

6.2.2. Further Optimization

In many cases, politics play a role for transportation planners during the decision making process. A geographic constraint could be added to a future formulation to address such issues. This constraint would attempt to ensure improvements are equitable across the network, taking the location of individual neighborhood into account.

This optimization model allows for BLOS improvements to occur by adding a bike lane. Additional factors in the BLOS model, such as pavement condition, could be considered in the future. A bike lane improvement option could be resurfacing, which would change the pavement condition score from its current value to 5.0, the

score assigned to new pavement. Restriping and resurfacing could have different costs assigned separately, and a reduced cost for both improvements on one segment. It is worth noting from BLOS Model Sensitivity section 3.4; the pavement condition term is not as sensitive as the effective width term to reduce the BLOS, unless resurfacing a pavement with poor quality.

The affect bicycle facility improvements have on demand is an area of further study. The elasticity of bicycle demand in response to adding more bicycle facilities is useful information for this thesis topic. Further research is necessary to quantify demand before and after bicycle facilities are added. Once the relationship between demand and improvements is understood, a formulation could reflect it by adding a feedback loop to consider induced demand.

The remaining terms in the BLOS model, traffic volume, number of lanes, speed limit, and heavy vehicle percentage, are connected to an automobile level of service. A future optimization could consider the biking level of service and the automobile level of service. Increasing in complexity, a model could incorporate level of service measures for automobiles, transit, bicycles and pedestrians. Further research in multimodal level of service is an interest in the United States, made evident as the National Cooperative Highway Research Program drew experts from each mode's field to produce "Multimodal Level of Service Analysis for Urban Streets (2008)." Such a model would contribute to transportation planning as an integrated system. Converting a traffic lane into a bike lane and sidewalk increases the biking and pedestrian level of service but decreases the automobile and bus transit level of service. Pedestrian right-of-way space often competes with space for cyclists. The

interrelationships among all modes compose an interesting problem. Modeling this type of problem is a possible direction for future research.

Appendix

Baltimore Bicycle and Pedestrian Level of Service Evaluation

Seg ID	Route No.	Road Name	From	To	Length (Ls) (Mi)	Jurisdiction	Dir. of Sur.	Lanes (L) Th Tu Con. u/d/s	Traffic Volume (ADT) (vpd)	Post. Spd. (SPs) (mph)	Width of Pavement (ft) (ft) (ft) (ft)				Occupied Parking (OSPA) (N/E S/W)	# of Grts (N)	Width Due to Vol. (Wv) (ft)	Pvmt. Width (Ww) (ft)	Enfr. (Pct) (1.5)	Pavement (Pct) (1.5)	Bike Lane? (Y/N)	BLOS Score (A, F)	Grade		
312e		MD 173 Patasco Avenue	MD 2 Potee Street	Hanover Street	0.08	Balt. City	e	4	u	20,200	40	21.2	0.0	0.0	2.5	0	50	2	21.2	17.8	4.0	0.0	n	3.80	D
313	139	MD 139 Charles Street	Baltimore City Line	Northern Parkway	0.70	Balt. City	n	4	u	19,675	35	10.1			1.0	0	0	17	10.1	9.7	4.0		n	4.54	E
314	139	MD 139 Charles Street	Northern Parkway	Cold Spring Lane	1.14	Balt. City	s	4	u	21,375	35	10.1			1.0	0	0	26	10.1	9.8	4.0		n	4.80	E
315	139	MD 139 Charles Street	Cold Spring Lane	MD 139 Saint Paul Street	0.36	Balt. City	s	4	u	25,400	25	9.5			1.0	0	0	4	9.5	9.3	4.0		n	4.44	D
316	139	MD 139 Charles Street	MD 139 Saint Paul Street	MD 139 Charles St / Ch	0.12	Balt. City	s	2	ow	6,500	25	16.5			1.0	0	0	1	16.5	16.4	3.5		n	3.01	C
320	139	MD 139 Charles Street / Charlotte R	Charles St / Charlotte R	University Parkway	0.50	Balt. City	n	4	u	12,900	25	9.8				0	0		9.8	9.8	3.0		n	4.23	D
326a	150	MD 150 Eastern Avenue	Dundalk Avenue	Bonsal Street	0.10	Balt. City	w	6	d	25,750	35	18.8			1.5	50	6	18.8	14.9	3.0		n	4.38	D	
326b	150	MD 150 Eastern Avenue	Bonsal Street	Ponca Street	0.47	Balt. City	w	6	d	27,100	35	9.6			1.5		3	9.6	9.5	3.0		n	5.07	E	
327a		MD 150 Eastern Avenue	Haven Street	Chester Street	1.33	Balt. City	w	2	u	29,505	25	20.4			1.5	70	80	11	20.4	12.7	3.0		n	4.82	E
327b		MD 150 Eastern Avenue	Haven Street	Ponca Street	0.45	Balt. City	w	4	d	32,600	25	12.0				0	0		12.0	12.0	3.0		n	4.61	E
330	40	US 40 Edmondson Avenue	Baltimore County Line	Hilton Parkway	2.10	Balt. City	e	6	d	46,900	30	10.9			1.8	0	0	11	10.9	10.8	3.0		n	5.24	E
333a	151	MD 151 Erdman Avenue	MD 151 North Point Boulevard	US 40 Pulaski Highway	0.81	Balt. City	n	6	d	28,150	35	11.7			1.5		17	11.7	11.2	3.0		n	4.91	E	
333b		MD 151 North Point Boulevard	MD 151 Erdman Avenue	Baltimore County Line	0.46	Balt. City	n	4	d	29,375	35	11.7						11.7	11.7	3.0		n	5.08	E	
342a	40	US 40 WEST Franklin Street	US 1 SOUTH Monroe St	Martin Luther King Junior Boulevard	1.06	Balt. City	w	2	ow	13,850	30	23.7	0.0		1.8	20	20	14	23.7	21.3	3.0		n	3.02	C
342b	40	US 40 WEST Franklin Street	Martin Luther King Junior Boulevard	MD 295 SOUTH Green	0.20	Balt. City	w	2	ow	21,400	30	23.7	0.0		1.8	20	20	14	23.7	19.8	3.0		n	3.76	D
354	45	MD 45 Greenmount Avenue	US 1 North Avenue	Preston Street	0.48	Balt. City	s	2	u	15,600	25	12.8			1.5	0	0		12.8	12.8	3.0		n	4.34	D
355	45	MD 45 Greenmount Avenue	Preston Street	Biddle Street	0.08	Balt. City	s	2	u	12,100	25	12.8			1.5	0	0		12.8	12.8	3.0		n	4.21	D
356	45	MD 45 Greenmount Avenue	Biddle Street	Ensor Street	0.57	Balt. City	s	2	u	16,300	25	10.0			1.5	0	0		10.0	10.0	3.0		n	4.68	E
357	45	MD 45 Greenmount Avenue	33rd Street E	29th Street E	0.35	Balt. City	s	2	u	16,800	25	9.8			1.5	0	0		9.8	9.8	3.0		n	4.72	E
358	45	MD 45 Greenmount Avenue	29th Street E	28th Street E	0.09	Balt. City	s	2	u	20,900	25	10.0				0	0		10.0	10.0	4.0		n	4.63	E
359	45	MD 45 Greenmount Avenue	28th Street E	24th Street E	0.38	Balt. City	s	2	u	19,600	25	10.0			1.5	0	0	1	10.0	9.9	4.0		n	4.45	D
363a	2	MD 2 Hanover Street	MD 2 Potee Street	Wells Street W	0.95	Balt. City	n	4	u	39,300	25	11.3			2.5	0	0		11.3	11.3	1.0		n	11.08	F
363b	2	MD 2 Hanover Street	Wells Street W	MD 2 NORTH Montgo	0.79	Balt. City	2	u	11,118	25	18.8			2.5	80	80		18.8	10.8	2.0		n	5.40	E	
365am	147	MD 147 Harford Road	Old Harford Road	Moravia Road	1.72	Balt. City	s	3	u	21,750	30	11.7			1.5	0	0	5	11.7	11.6	3.5		n	4.68	E
365pm	147	MD 147 Harford Road	Old Harford Road	Moravia Road	1.72	Balt. City	n	2	u	24,300	30	20.0			1.5	50	50	5	20.0	19.9	3.5		n	3.68	D
368a	147	MD 147 Harford Road	32nd Street E	25th Street E	0.93	Balt. City	s	6	d	27,750	30	10.1			1.5	0	0	5	10.1	10.0	4.0		n	4.53	E
368bam	147	MD 147 Harford Road	25th Street E	Broadway	0.22	Balt. City	s	2	u	28,800	30	12.0			1.5	0	0	2	12.0	11.8	4.0		n	4.90	E
368bpm	147	MD 147 Harford Road	25th Street E	Broadway	0.22	Balt. City	s	3	u	28,800	30	12.0			1.5	0	0	2	12.0	11.8	4.0		n	4.55	E
369am	147	MD 147 Harford Road	Broadway	US 1 North Avenue	0.17	Balt. City	s	2	u	20,100	30	9.8				0	0		9.8	9.8	4.0		n	4.94	E
369pm	147	MD 147 Harford Road	Broadway	US 1 North Avenue	0.17	Balt. City	s	3	u	20,100	30	9.8				0	0		9.8	9.8	4.0		n	4.59	E
371	41	MD 41 Hillen Road	Cold Spring Lane	33rd Street E	1.29	Balt. City	s	3	d	26,975	35	10.6			1.5	0	0	16	10.6	10.3	4.0		n	4.86	E
372	41	MD 41 Hillen Road	33rd Street E	32nd Street E	0.10	Balt. City	s	2	u	22,900	30	16.8			1.5	0	0	3	16.8	16.1	4.0		n	4.18	D
373	41	MD 41 Hillen Road	32nd Street E	MD 147 Harford Road	0.38	Balt. City	s	2	u	22,900	30	16.8			1.5	0	0	3	16.8	16.6	4.0		n	4.10	D
374a	26	MD 26 Liberty Heights Avenue	Northern Parkway	Ferndale Avenue	0.47	Balt. City	w	2	u	29,300	30	10.0				0	0		10.0	10.0	3.5		n	5.26	E
374b	26	MD 26 Liberty Heights Avenue	Ferndale Avenue	Berwyn Avenue	1.03	Balt. City	w	2	u	26,700	30	14.5				0	0		14.5	14.5	3.5		n	4.70	E
374c	26	MD 26 Liberty Heights Avenue	Berwyn Avenue	Callaway Avenue	0.29	Balt. City	w	2	u	28,300	30	17.6				0	0		17.6	12.6	3.5		n	4.95	E
374d	26	MD 26 Liberty Heights Avenue	Callaway Avenue	Hilton Street	0.43	Balt. City	w	3	d	28,000	30	16.8				0	0		16.8	16.8	3.5		n	3.62	D
375	26	MD 26 Liberty Heights Avenue	Hilton Street	MD 140 Reisterstown R	1.11	Balt. City	w	3	d	28,800	35	12.0							12.0	12.0	3.5		n	4.86	E
376	26	MD 26 Liberty Heights Avenue	Baltimore County Line	Northern Parkway	0.08	Balt. City	w	2	u	36,400	30	13.0				0	0		13.0	13.0	3.5		n	5.02	E
378	542	MD 542 Loch Raven Boulevard	Baltimore County Line	Northern Parkway	0.46	Balt. City	s	2	d	22,900	35	12.0				0	0		12.0	12.0	3.5		n	5.10	E
379	542	MD 542 Loch Raven Boulevard	Northern Parkway	Cold Spring Lane / Mor	1.44	Balt. City	s	2	d	21,975	35	12.0				0	0		12.0	12.0	3.5		n	5.07	E
380	542	MD 542 Loch Raven Boulevard	Cold Spring Lane	MD 542 The Alameda	0.40	Balt. City	s	2	d	23,000	30	11.0			1.5	0	0	5	11.0	10.7	4.0		n	4.91	E
383a	129	MD 129 NORTH McCulloh Street	US 1 North Avenue	MD 129 Swann Drive	0.65	Balt. City	n	2	u	8,100	25	17.0				60	60		17.0	11.0	3.0		n	4.09	D
383b	129	MD 129 NORTH McCulloh Street	Dolphin Street	US 1 North Avenue	1.83	Balt. City	n	2	u	7,562	25	18.0				40	50		18.0	13.5	3.0		n	3.74	D
393a	40	US 40 EAST Mulberry Street	US 1 NORTH Fulton Av	Martin Luther King Junior Boulevard	0.92	Balt. City	e	2	ow	13,034	30	24.2			2.0	40	40	4	24.2	20.1	3.5		n	3.08	C
393b	40	US 40 EAST Mulberry Street	Martin Luther King Junior Boulevard	MD 295 SOUTH Green	0.20	Balt. City	e	3	ow	20,100	30	24.2			2.0	40	40	4	24.2	19.6	3.5		n	3.38	C
403	US1	US 1 North Avenue	MD 139 NORTH Charles	MD 2 SOUTH Saint Pa	0.09	Balt. City	w	6	d	33,700	30	10.0				0	0		10.0	10.0	3.0		n	4.95	E
404	US1	US 1 North Avenue	MD 2 SOUTH Saint Pa	Gulford Avenue	0.13	Balt. City	e	6	d	38,800	30	12.3				0	0		12.3	12.3	2.5		n	5.13	E
405	US1	US 1 North Avenue	Gulford Avenue	MD 45 Greenmount Av	0.16	Balt. City	e	6	d	33,800	30	11.5				0	0		11.5	11.5	2.5		n	5.15	E
406	US1	US 1 North Avenue	MD 45 Greenmount Av	MD 147 Harford Road	0.56	Balt. City	e	4	u	28,800	30	10.0				0	0		10.0	10.0	4.0		n	4.75	E
407	US1	US 1 North Avenue	MD 147 Harford Road	Broadway	0.23	Balt. City	e	4	u	19,025	30	10.0			1.0	0	0	1	10.0	9.9	4.0		n	4.36	D
411	648	MD 295 NORTH Paca Street	MD 295 Greene St / Pa	Pratt Street	0.14	Balt. City	n	4	ow	23,000	30	9.7							9.7	9.7	3.0		n	4.93	E
416a	129	MD 129 Park Heights Avenue	Northern Parkway	Garrison Avenue	0.68	Balt. City	n	4	d	18,575	30	19.5				40	40		19.5	15.5	3.5		n	3.79	D
416b	129	MD 129 Park Heights Avenue	Garrison Avenue	Cold Spring Lane	0.66	Balt. City	n	4	u	16,800	30	16.6				80	80		16.6	8.6	3.5		n	4.62	E
443	648	MD 295 Russell Street	MD 648 Annapolis Road	MD 295 Greene St / Pa	1.08	Balt. City	s	6	d	63,158	35	11.2							11.2	11.2	3.5		n	5.62	F
452	45	MD 45 York Road	Baltimore County Line	Northern Parkway	0.49	Balt. City	s	2	u	21,900	30	10.8			1.5	0	0	4	10.8	10.6	3.5		n	5.05	E
453	45	MD 45 York Road	Northern Parkway	Cold Spring Lane	1.32	Balt. City	s	2	u	23,675	30	10.5			1.5	0	0	11	10.5	10.3	3.5		n	5.12	E
454	45	MD 45 York Rd / Greenmount Ave	Cold Spring Lane	33rd Street E	1.23	Balt. City	s	2	u	20,575	25	9.8			1.5	0	0	8	9.8	9.7	3.5		n	4.80	E

Seg ID	Route No.	Road Name	From	To	Length (Ls) (Mi)	Jurisdiction	Dir. of Sur.	Lanes (L) Th #	Con. #	Traffic Volume (ADT) (vpd)	Spd. (SPS) (mph)	Width of Pavement (ft) (ft)	Width of (Wp) (ft)	Width of (Wg) (ft)	Occupied Parking (OSPA) (N/E S/W)	# of Grts (N)	Width Due to (Wv) (Wv)	Eff. Width (We) (We)	Pavement Condition (PCT) (PCT)	Bike Lane? (Y/N)	BLOS Score (A, F)	Grade		
187		Biddle Street	Harford Avenue	Greenmount Avenue	0.32	Balt. City	w	3	ow	8,000	25	10.0			0	0		10.0	10.0	3.0	n	3.92	D	
188		Biddle Street	Greenmount Avenue	Guilford Avenue	0.24	Balt. City	w	3	ow	7,985	25	10.0			0	0		10.0	10.0	3.0	n	3.92	D	
189		Biddle Street	Guilford Avenue	Saint Paul Street	0.11	Balt. City	w	2	ow	8,000	25	19.0			90	90		19.0	10.0	3.0	n	4.12	D	
190		Biddle Street	Saint Paul Street	Charles Street	0.08	Balt. City	w	3	ow	8,000	25	10.0		1.0	0	0	2	10.0	9.6	3.0	n	3.95	D	
191		Biddle Street	Charles Street	Preston Street	0.23	Balt. City	w	3	ow	8,000	25	10.0		2.0	0	0	3	10.0	9.6	4.0	n	3.63	D	
192		MD 173 NORTH Birch Street	MD 173 Pennington Ave	MD 173 NORTH Curtis	0.09	Balt. City	e	2	ow	13,600	15	23.5	0.0	0.0	1.5	0	0	1	23.5	23.2	3.0	n	1.43	A
195		Broadway	US 1 North Avenue	US 40 Orleans Street	1.17	Balt. City	s	4	d	8,374	30	23.4		2.0	70	70	3	23.4	16.3	3.0	n	3.25	C	
196		Broadway	US 40 Orleans Street	Fayette Street	0.09	Balt. City	s	4	d	8,400	30	18.0			100	100		18.0	8.0	3.0	n	4.27	D	
197		Broadway	Fayette Street	Eastern Avenue	0.58	Balt. City	s	4	d	8,400	30	18.5			100	100		18.5	8.5	3.0	n	4.22	D	
198		Charles Street	US 1 North Avenue	Preston Street	0.45	Balt. City	n	3	ow	9,894	30	10.0			0	0	2	10.0	10.0	3.0	n	4.25	D	
199		Charles Street	Preston Street	Biddle Street	0.09	Balt. City	n	3	ow	22,000	30	10.0			0	0		10.0	10.0	4.0	n	4.69	E	
200		Charles Street	Biddle Street	Madison Street	0.34	Balt. City	n	3	ow	22,000	30	10.0			0	0		10.0	10.0	3.0	n	5.02	E	
201		Charles Street	Madison Street	US 40 EAST Mulberry	0.33	Balt. City	n	2	ow	10,675	30	18.0			95	95		18.0	8.5	3.0	n	4.81	E	
202		Charles Street	US 40 EAST Mulberry	Lombard Street	0.44	Balt. City	n	3	ow	15,000	30	10.0			0	0		10.0	10.0	3.0	n	4.54	E	
203		Charles Street	Lombard Street	Pratt Street	0.09	Balt. City	n	4	ow	4,300	30	22.8			0	0		22.8	22.8	3.0	n	1.59	B	
204		Charles Street	Boston Street	Eastern Avenue	0.08	Balt. City	n	2	u	1,000	30	19.0			90	90		33.3	24.3	3.0	n	0.90	A	
227	144	MD 144 Frederick Avenue	Lombard Street	Pratt Street	0.17	Balt. City	s/w	4	u	9,000	30	19.7	0.0	0.0	1.5	0	100	3	19.7	14.3	3.0	n	3.60	D
229		MD 295 SOUTH Greene Street	US 40 EAST Mulberry	Lombard Street	0.41	Balt. City	s	4	ow	11,675	30	9.6			0	0		9.6	9.0	2.5	n	4.76	E	
230		MD 295 SOUTH Greene Street	Lombard Street	Pratt Street	0.09	Balt. City	s	3	ow	11,675	30	12.0			0	0		12.0	12.0	4.0	n	3.96	D	
231		MD 295 SOUTH Greene Street	Pratt Street	MD 295 Greene St / Pa	0.09	Balt. City	s	3	ow	11,675	30	12.0			0	0		12.0	12.0	4.0	n	3.96	D	
234		Green Spring Avenue	Northern Pkwy	Cold Spring Lane	1.03	Balt. City	n	2	u	11,000	30	22.0		2.0	15	15	4	22.0	20.4	1.0	n	9.46	F	
236		Guilford Avenue	Pratt Street	Lombard Street	0.07	Balt. City	s	4	u	7,160	25	11.0			0	0		11.0	11.0	2.0	n	4.67	E	
237		Guilford Avenue / South Street	Lombard Street	US 40 Orleans Street	0.48	Balt. City	s	2	ow	13,200	30	19.0			85	80		19.0	10.8	2.0	n	5.70	F	
239		Guilford Avenue	Biddle Street	Mount Royal Avenue	0.13	Balt. City	s	4	d	3,700	30	22.0			40	30		22.0	18.5	3.0	n	2.45	B	
240		Guilford Avenue	Mount Royal Avenue	US 1 North Avenue	0.40	Balt. City	s	2	u	3,724	25	21.0			60	60		22.4	16.4	3.5	n	2.78	C	
255		MD 144 WEST Lombard Street	US 1 NORTH Fulton Ave	US 1 SOUTH Monroe S	0.09	Balt. City	w	2	ow	11,900	30	19.2			70	70		19.2	12.2	3.0	n	4.48	D	
256		MD 144 WEST Lombard Street	US 1 SOUTH Monroe S	MD 144 Frederick Ave	0.31	Balt. City	w	4	ow	11,900	30	10.5			0	0		10.5	10.5	2.8	n	4.47	D	
257		Lombard Street	US 1 NORTH Fulton Ave	MD 295 SOUTH Greene	1.21	Balt. City	w	2	ow	9,928	30	18.4			80	80		18.4	10.4	3.0	n	4.42	D	
258		Lombard Street	MD 295 SOUTH Greene	MD 295 NORTH Packer	0.07	Balt. City	w	4	ow	15,900	30	10.0	0.0		0	0		10.0	10.0	2.8	n	4.67	E	
259		Lombard Street	MD 295 NORTH Packer	Charles Street S	0.38	Balt. City	w	4	ow	16,200	30	10.5			0	0		10.5	10.5	2.8	n	4.69	E	
260		Lombard Street	Charles Street S	MD 2 SOUTH Light Str	0.07	Balt. City	w	4	ow	24,000	30	10.0			0	0		10.0	10.0	3.0	n	4.92	E	
261		Lombard Street	MD 2 SOUTH Light Str	Guilford Avenue	0.14	Balt. City	w	5	ow	27,000	30	19.0			0	0		19.0	19.0	3.0	n	3.57	D	
262		Lombard Street	Guilford Avenue	President Street	0.33	Balt. City	w	5	ow	25,112	30	10.0			0	0		10.0	10.0	3.5	n	4.66	E	
277		MD 140 Pennsylvania Avenue	MD 140 Fulton Avenue	MD 29 Liberty Heights	0.51	Balt. City	n	4	d/u	11,500	30	20.8			70	70		20.8	13.8	4.0	n	3.64	D	
278		MD 140 Pennsylvania Avenue	MD 140 Fulton Avenue	US 1 North Avenue	0.30	Balt. City	n	2	u	11,500	30	19.6			50	80		19.6	13.1	3.0	n	4.41	D	
279		President Street	Fallsview	Pratt Street	0.30	Balt. City	s	6	d	42,350	35	11.0			0	0		11.0	11.0	4.0	n	5.04	E	
281		Preston Street	Harford Avenue	Greenmount Avenue	0.35	Balt. City	w	3	ow	9,200	30	11.6		1.5	0	0	1	11.6	11.5	4.0	n	3.72	D	
282		Preston Street	Greenmount Avenue	Guilford Avenue	0.24	Balt. City	w	3	ow	9,200	25	10.0			0	0		10.0	10.0	3.5	n	3.81	D	
283		Preston Street	Guilford Ave	MD 2 SOUTH Saint Paul	0.11	Balt. City	w	2	ow	6,918	25	18.0			90	90		18.0	9.0	3.5	n	3.97	D	
284		Preston Street	MD 2 SOUTH Saint Paul	Charles Street N	0.08	Balt. City	w	2	ow	8,500	25	18.0			80	80		18.0	10.0	3.5	n	3.98	D	
285		Preston Street	Charles Street N	Biddle Street	0.18	Balt. City	w	2	ow	8,500	25	18.0			100	75	8	18.0	9.3	3.0	n	4.23	D	
288		Roland Avenue	Northern Parkway	Lake Avenue	0.50	Balt. City	n	4	d	10,175	35	22.9	12.0		0	0		22.9	34.9	3.0	3.0	n	0.00	A
289		Roland Avenue	Northern Parkway	Cold Spring Lane	1.27	Balt. City	s	4	d	12,875	35	24.7	13.8		50	50		24.7	24.7	3.0	3.0	n	2.08	B
290		Roland Avenue	Cold Spring Lane	University Parkway	0.16	Balt. City	s	4	d	13,800	35	23.9	12.1		75	75		23.9	17.9	3.5	3.5	n	3.40	C
291		MD 2 SOUTH Light Street	Pratt Street	Lombard Street	0.08	Balt. City	s	5	ow	20,800	30	10.0						10.0	10.0	3.0	n	4.73	E	
292		MD 2 SOUTH Saint Paul St / Light S	Lombard Street	US 40 Orleans Street	0.48	Balt. City	s	4	ow	20,700	30	10.0						10.0	10.0	2.8	n	5.00	E	
293		MD 2 SOUTH Saint Paul Street	US 40 Orleans Street	Biddle Street	0.63	Balt. City	s	3	ow	17,126	30	10.0						10.0	10.0	3.0	n	4.70	E	
294		MD 2 SOUTH Saint Paul Street	Biddle Street	Preston Street	0.07	Balt. City	s	3	ow	21,400	30	10.0			0	90		10.0	5.5	3.5	n	5.18	E	
295		MD 2 SOUTH Saint Paul Street	Preston Street	US 1 North Avenue	0.45	Balt. City	s	2	ow	20,201	30	21.2		2.0	80	80	4	21.2	12.9	3.0	n	4.85	E	
296		MD 139 SOUTH Saint Paul Street	US 1 North Avenue	28th Street E	0.76	Balt. City	s	3	ow	11,975	30	10.0			0	0		10.0	10.0	3.0	n	4.53	E	
297		MD 139 SOUTH Saint Paul Street	28th Street E	31st Street E	0.27	Balt. City	s	3	ow	17,700	30	9.8			0	0		9.8	9.8	3.0	n	4.74	E	
298		MD 139 SOUTH Saint Paul Street	31st Street E	University Parkway	0.40	Balt. City	s	3	ow	14,200	35	9.8			0	0		9.8	9.8	3.5	n	4.61	E	
299		MD 139 SOUTH Saint Paul Street	University Parkway	MD 139 Charles Street	0.97	Balt. City	s	4	d	11,300	35	17.0			30	30		17.0	14.0	3.5	n	3.91	D	
323	129	MD 129 SOUTH Druid Hill Avenue	US 1 North Avenue	MD 295 NORTH Packer	1.22	Balt. City	s	2	ow	8,450	25	18.0			30	30		18.0	15.0	4.0	n	3.20	C	
324	129	MD 129 SOUTH Druid Hill Avenue	MD 129 Swann Drive	US 1 North Avenue	0.50	Balt. City	s	2	ow	11,800	25	18.0			30	30		18.0	15.0	4.0	n	3.51	D	
325	150	MD 150 Eastern Avenue	Baltimore County Line	Dundalk Avenue	0.76	Balt. City	w	6	d	27,125	35	19.9		1.5	15	14		19.9	18.7	3.0	n	3.76	D	
328		Eastern Avenue	Chester Street	Broadway	0.33	Balt. City	w	2	u	14,500	25	19.5		1.5	90	90	2	19.5	10.4	3.0	n	4.58	E	
329		Eastern Avenue	Broadway	President Street	0.47	Balt. City	w	2	u	5,600	25	19.1		1.5	90	90	4	19.1	9.9	3.0	n	4.01	D	
331	40	US 40 Edmondson Avenue	Hilton Parkway	US 40 Franklin Street	0.37	Balt. City	w	6	d	51,300	30	10.5						10.5	10.5	3.0	n	5.32	E	
332	151	MD 151 Erdman Avenue	US 40 Pulaski Highway	US 1 Belair Road	1.95	Balt. City	n	6	d	28,575	35	12.3		2.5		15		12.3	12.0	3.0	n	4.83	E	
337	25	MD 25 Falls Road	36th Street W	I-83 Ramp	0.26	Balt. City	s	4	d	13,175	25	20.4			80	80	2	20.4	12.4	3.5	n	3.78	D	
338	25	MD 25 Falls Road	I-83 Ramp	29th Street W	0.68	Balt. City	s	3	u	4,000	25	10.0			0	0		10.0	10.0	3.0	n	3.50	C	
339	25	MD 25 Falls Road	29th Street W	Charles Street N	1.02	Balt. City	s	3	u	2,875	25	10.0			0	0		12.8	12.8	3.0	n	3.01	C	
340	40	US 40 Franklin Street	US 40 Edmondson Ave	US 40 Franklin St / Mul	0.40	Balt. City	w	6	d	29,200	40	11.3			0	0		11.3	11.3	3.0	n	5.05	E	
341	40	US 40 Franklin Street	US 40 Franklin St / Mul	US 1 SOUTH Monroe S	1.01	Balt. City	w	3	ow	13,850	30	12.0			0	0		12.0	12.0	3.0	n	4.37	D	
343	40	US 40 WEST Franklin Street	MD 295 SOUTH Greene	MD 295 NORTH Packer	0.07	Balt. City	w	3	ow	21,400	30	9.8			0	0		9.8	9.8	3.5	n	4.85	E	
344	40	US 40 WEST Franklin Street	MD 295 NORTH Packer	Charles Street N	0.38	Balt. City	w	3	ow	21,161	30	11.9			0	0		11.9	11.9	3.5	n	4.62	E	
345	40	US 40 WEST Franklin Street	Charles Street	MD 2 SOUTH Saint Paul	0.13	Balt. City	w	3	ow	21,400	30	11.9			0	0		11.9	11.9	3.0	n	4.80	E	

Seg ID	Route No.	Road Name	From	To	Length (Ls) (Mi)	Jurisdiction	Dir. of Sur.	Lanes (L) Th Tu Con.	Traffic Volume (ADT) (vpd)	Post. Spd. (85th P) (mph)	Width of Pavement (ft) (ft) (ft) (ft) (ft)	Occupied Parking (OSPA) (ft) (ft) (ft) (ft) (ft)	# of Grts (N) (N) (N) (N) (N)	Width Due to (Wt) (Wt) (Wt) (Wt) (Wt)	Eff. Pmnt (Wt) (Wt) (Wt) (Wt) (Wt)	Condition (PCT) (PCT) (PCT) (PCT) (PCT)	Bike Lane? (Y/N)	BLOS Score (A, F)	Grade				
360	2	Hanover Street	Baltimore City Line	MD 173 Patapsco Avenue	0.34	Balt. City	n	2	u	17,900	25	21.2		70	70	21.2	14.2	3.0	n	4.22	D		
361	2	Hanover Street	MD 173 Patapsco Avenue	Frankfurt Avenue	0.30	Balt. City	n	2	u	27,500	25	20.0		20	30	20.0	17.5	4.0	n	3.73	D		
362	2	MD 2 NORTH Hanover Street	Frankfurt Avenue	MD 2 SOUTH Potee Street	0.79	Balt. City	n	4	ow	37,100	40	12.0		0	0	12.0	12.0	3.0	n	6.23	E		
364	147	MD 147 Harford Road	Baltimore County Line	Old Harford Road	0.72	Balt. City	s	4	u	24,600	30	20.0		1.5	60	60	19.7	3.5	n	3.37	C		
366	147	MD 147 Harford Road	Moravia Road	MD 151 Erdman Avenue	1.32	Balt. City	s	4	u	20,850	30	18.0		1.5	70	70	18.9	10.9	3.5	n	4.64	E	
367	147	MD 147 Harford Road	MD 151 Erdman Avenue	32nd Street E	0.08	Balt. City	s	6	d	20,850	30	12.7		1.5	0	0	12.7	12.7	4.0	n	4.07	D	
370	150	MD 150 SOUTH Haven Street	Monument Street	Lombard Street	0.57	Balt. City	s	3	u	10,500	30	19.6		1.5	70	70	19.6	12.3	4.0	n	3.80	D	
377	2	MD 2 SOUTH Light Street	Pratt Street	Key Highway	0.36	Balt. City	s	4	d	37,100	30	21.6		2.5		2	21.6	21.4	4.0	n	3.09	C	
381	144	Lombard Street	MD 150 SOUTH Haven Street	MD 150 NORTH Kress Street	0.14	Balt. City	e	4	u	10,500	25	10.1		1.5		1	10.1	9.9	3.0	n	4.11	D	
382	144	Lombard Street	MD 150 NORTH Kress Street	Ponca Street	0.26	Balt. City	e	2	u	10,500	25	10.6					10.6	10.6	3.0	n	4.40	D	
384	129	MD 129 NORTH McCulloh Street	MD 295 NORTH Paces	Dolphin Street	0.86	Balt. City	n	2	u	8,100	25	16.5		90	90	16.5	7.5	3.5	n	4.23	D		
386	US1	US 1 SOUTH Monroe Street	US 1 North Avenue	US 40 WEST Franklin Street	1.12	Balt. City	s	2	ow	5,648	30	19.6		1.0	70	70	19.6	12.6	3.0	n	3.88	D	
387	US1	US 1 SOUTH Monroe Street	US 40 WEST Franklin Street	US 40 EAST Mulberry Street	0.06	Balt. City	s	2	ow	12,900	30	15.9					15.9	15.9	3.0	n	4.01	D	
388	US1	US 1 SOUTH Monroe Street	US 40 EAST Mulberry Street	Lombard Street	0.46	Balt. City	s	2	ow	12,600	30	18.8		1.5	85	85	18.8	10.3	3.0	n	4.73	E	
389	US1	US 1 SOUTH Monroe Street	Lombard Street	Pratt Street	0.07	Balt. City	s	2	ow	12,600	30	18.8		2.0	80	80	18.8	10.8	3.0	n	4.67	E	
390	US1	US 1 SOUTH Monroe Street	Pratt Street	US 1 Wilkens Avenue	0.22	Balt. City	s	2	ow	15,400	30	18.8		2.0	75	75	18.8	11.3	3.0	n	4.72	E	
391	40	US 40 EAST Mulberry Street	US 40 Franklin St / Muller	US 1 SOUTH Monroe Street	1.01	Balt. City	e	2	ow	18,500	30	10.0		2.0		5	10.0	9.8	3.5	n	4.79	E	
392	40	US 40 EAST Mulberry Street	US 1 SOUTH Monroe Street	US 1 NORTH Fulton Avenue	0.14	Balt. City	e	3	ow	14,400	30	24.2		70	70	24.2	17.2	3.5	n	3.46	C		
394	40	US 40 EAST Mulberry Street	MD 295 SOUTH Green Street	MD 295 NORTH Paces	0.07	Balt. City	e	3	ow	13,034	30	11.1		2.0	0	3	11.1	9.8	3.5	n	4.41	D	
395	40	US 40 EAST Mulberry Street	MD 295 NORTH Paces	Charles Street	0.38	Balt. City	e	3	ow	20,300	30	11.1		2.0	0	1	11.1	11.0	3.5	n	4.70	E	
396	40	US 40 EAST Mulberry Street	Charles Street	MD 2 SOUTH Saint Paul	0.13	Balt. City	e	3	ow	20,600	30	11.1			0		11.1	11.1	3.5	n	4.70	E	
397	US1	US 1 North Avenue	US 1 SOUTH Monroe Street	US 1 NORTH Fulton Avenue	0.11	Balt. City	w	4	d	24,100	30	18.0		50	50	18.0	13.0	3.5	n	4.47	D		
398	US1	US 1 North Avenue	US 1 NORTH / MD 140	Pennsylvania Avenue	0.21	Balt. City	w	4	u	21,000	30	20.0		50	50	20.0	15.0	3.5	n	4.12	D		
399	US1	US 1 North Avenue	Pennsylvania Avenue	MD 129 SOUTH Druid	0.27	Balt. City	w	4	u	18,000	30	20.0		90	90	20.0	11.0	3.5	n	4.36	D		
400	US1	US 1 North Avenue	MD 129 SOUTH Druid	MD 129 NORTH McCulloh	0.08	Balt. City	w	4	u	22,400	30	20.0				20	20.0	4.0	n	3.12	C		
401	US1	US 1 North Avenue	MD 129 NORTH McCulloh	Howard-where I-83N	0.76	Balt. City	w	6	d	27,299	30	10.0				10	10.0	4.0	n	4.52	E		
402	US1	US 1 North Avenue	Howard Street	Charles Street	0.35	Balt. City	w	n	d	28,600	30	10.0				10	10.0	3.0	n	4.87	E		
408	US1	US 1 North Avenue	Broadway	Gay Street / US 1 Belair	0.59	Balt. City	e	4	u	24,000	30	10.0		1.0	0	0	7	10.0	9.8	4.0	n	4.68	E
409	40	US 40 Orleans Street	MD 2 SOUTH Saint Paul	Broadway	1.03	Balt. City	e	6	u/d	36,000	30	10.7		2.0	0	21	10.7	10.1	4.0	n	4.65	E	
410	40	US 40 Orleans Street	Broadway	US 40 Pulaski Highway	1.11	Balt. City	e	4	u	26,425	30	10.7		1.5		22	10.7	10.2	3.0	n	5.01	E	
412	648	MD 295 NORTH Paces	Pratt Street	Lombard Street	0.09	Balt. City	n	4	ow	12,200	30	9.7					9.7	9.7	3.0	n	4.41	D	
413	648	MD 295 NORTH Paces	Lombard Street	US 40 EAST Mulberry Street	0.42	Balt. City	n	3	ow	12,175	30	19.5			90	90	19.5	10.5	3.0	n	4.48	D	
414	648	MD 295 NORTH Paces	US 40 EAST Mulberry Street	US 40 WEST Franklin Street	0.08	Balt. City	n	3	ow	12,175	30	19.5		1.8	85	85	19.5	10.7	3.5	n	4.29	D	
415	129	MD 129 Park Heights Avenue	Baltimore County Line	Northern Parkway	2.00	Balt. City	n	4	u	22,004	30	20.0					20.0	20.0	3.5	n	3.27	C	
417	129	MD 129 Park Heights Avenue	Cold Spring Lane	MD 140 Reisterstown Road	1.36	Balt. City	n	4	d	23,100	30	22.1		25	25	22.1	19.6	3.5	n	3.37	C		
418	173	MD 173 SOUTH Pennington Ave	MD 173 Pennington Ave	MD 171 Church Street	0.63	Balt. City	s	2	ow	10,700	30	21.2		40	30	21.2	17.7	3.5	n	3.43	C		
419	173	MD 173 SOUTH Pennington Ave	MD 171 Church Street	MD 173 NORTH Birch	0.28	Balt. City	s	2	ow	10,700	30	21.2		40	50	21.2	16.7	3.5	n	3.60	D		
420	173	MD 173 Pennington Ave / Hawkins Pkwy	MD 173 NORTH Birch	Anne Arundel County Line	2.57	Balt. City	s	4	u	12,150	30	12.0					12.0	12.0	3.5	n	4.05	D	
421	41	MD 41 Perring Parkway	Baltimore County Line	Northern Parkway	0.30	Balt. City	s	n	d	31,300	45	9.6		2.5		2	9.6	9.3	4.0	n	5.06	E	
422	41	MD 41 Perring Pkwy / Hillen Rd	Northern Parkway	Cold Spring Lane	1.86	Balt. City	s	6	d	25,075	35	10.5		2.5	0	90	10.5	10.1	4.0	n	4.64	E	
423	150	Ponca Street	Lombard Street	MD 150 Eastern Avenue	0.36	Balt. City	s	2	d/u	7,000	30	11.5					11.5	11.5	5.0	n	3.70	D	
424	173	MD 173 Patapsco Avenue	Hanover Street	MD 173 Pennington Ave	1.18	Balt. City	e	4	u	4,500	30	20.5		1.8	40	40	10	20.5	16.3	3.0	n	2.95	C
425	2	MD 2 SOUTH Potee Street	MD 2 NORTH Hanover Street	Waterview Avenue	1.60	Balt. City	n	2	u	30,400	25	12.0		2.5			12.0	12.0	3.0	n	4.92	E	
426	144	MD 144 EAST Pratt Street	Frederick Avenue	US 1 SOUTH Monroe Street	0.26	Balt. City	e	2	ow	10,300	30	20.0			70	70	20.0	13.0	3.0	n	4.31	D	
427	144	MD 144 EAST Pratt Street	US 1 SOUTH Monroe Street	US 1 NORTH Fulton Avenue	0.11	Balt. City	e	2	ow	10,300	30	20.0		20	80	20	15.0	15.0	3.0	n	4.03	D	
428	144	Pratt Street	US 1 NORTH Fulton Avenue	MD 295 SOUTH Green Street	1.14	Balt. City	e	2	ow	9,731	30	20.0		20	80	20	15.0	15.0	3.0	n	3.82	D	
429	144	Pratt Street	MD 295 SOUTH Green Street	MD 295 NORTH Paces	0.09	Balt. City	e	4	ow	15,025	30	11.0		0	0		11.0	11.0	3.0	n	4.39	D	
430	144	Pratt Street	MD 295 NORTH Paces	Charles Street	0.37	Balt. City	e	4	ow	32,600	30	10.8		0	0		10.8	10.8	3.5	n	4.82	E	
431	144	Pratt Street	Charles Street	MD 2 SOUTH Light Street	0.07	Balt. City	e	4	ow	30,700	30	10.8		0	0		10.8	10.8	3.5	n	4.79	E	
432	144	Pratt Street	MD 2 SOUTH Light Street	Gulford Avenue	0.08	Balt. City	e	4	ow	29,000	30	10.8		0	0		10.8	10.8	3.5	n	4.76	E	
433	144	Pratt Street	Gulford Avenue	President Street	0.35	Balt. City	e	4	ow	37,055	30	19.2		90	90		19.2	10.2	3.0	n	5.12	E	
434	40	US 40 Pulaski Highway	US 40 Orleans Street	MD 150 SOUTH Haven Street	0.57	Balt. City	e	4	u	44,025	30	11.5		1.5		4	11.5	11.3	3.5	n	5.18	E	
435	40	US 40 Pulaski Highway	MD 150 SOUTH Haven Street	MD 151 Erdman Avenue	0.73	Balt. City	e	4	u	47,600	30	11.5		1.5		3	11.5	11.4	3.5	n	5.21	E	
436	40	US 40 Pulaski Highway	MD 151 Erdman Avenue	Moravia Road	0.99	Balt. City	e	6	d	49,600	30	13.5		1.5		9	13.5	13.3	3.5	n	4.80	E	
437	40	US 40 Pulaski Highway	Moravia Road	Baltimore County Line	0.17	Balt. City	e	6	d	47,700	30	14.2		1.5		5	14.2	13.5	3.5	n	4.74	E	
438	140	MD 140 Reisterstown Road	MD 26 Liberty Heights Avenue	MD 129 Swann Drive	0.28	Balt. City	n	4	u	21,000	30	10.0					10.0	10.0	3.5	n	4.74	E	
439	140	MD 140 Reisterstown Road	Baltimore County Line	Northern Parkway	1.44	Balt. City	s	4	u	31,500	30	10.0		0	0		10.0	10.0	3.5	n	4.95	E	
440	140	MD 140 Reisterstown Road	Northern Pkwy	Cold Spring Lane	1.53	Balt. City	s	4	u	21,500	30	10.0		0	0		10.0	10.0	2.5	n	5.29	E	
441	140	MD 140 Reisterstown Road	Cold Spring Lane	MD 129 Park Heights Avenue	1.14	Balt. City	s	4	u	24,300	30	10.0		0	0		10.0	10.0	3.0	n	4.99	E	
442	140	MD 140 / MD 129 Reisterstown Road	MD 129 Park Heights Avenue	MD 129 Swann Drive	0.28	Balt. City	n	8	d	22,900	30	10.0					10.0	10.0	4.0	n	4.28	D	
444	129	MD 129 Swann Drive	Reisterstown Rd	Green Spring Avenue	0.27	Balt. City	n	6	d	21,500	30	17.6		0	0		17.6	17.6	4.5	n	3.25	C	
445	129	MD 129 Swann Drive	Green Spring Avenue	Gwynns Falls Parkway	0.18	Balt. City	n	6	d	32,900	30	17.9		2.0	75	0	2	17.9	13.8	4.5	n	4.05	D
446	129	MD 129 Swann Drive	Gwynns Falls Parkway	MD 129 Druid Hill Avenue	0.31	Balt. City	n	6	d	32,850	30	17.9		2.0	75	0	2	17.9	14.0	4.5	n	4.03	D
447	542	MD 542 The Alameda	MD 542 Loch Raven Boulevard	MD 147 Harford Road	0.97	Balt. City	s	2	d	16,450	30	16.1		1.5		10	16.1	15.9	3.5	n	4.62	D	
448	372	MD 372 Wilkens Avenue	Baltimore City Line	US 1 Southwestern Boulevard	0.33	Balt. City	w	4	u	25,000	30	9.4		1.8		3	9.4	9.2	3.5	n	4.91	E	
449	US1	US 1 Wilkens Avenue	US 1 Southwestern Boulevard	US 1 ALT Caton Avenue	0.59	Balt. City	w	6	s/u	20,575	30	17.4					17.4	17.4	3.0	n	3.68	D	
450	US1	US 1 Wilkens Avenue	US 1 ALT Caton Avenue	US 1 SOUTH Monroe Street	1.80	Balt. City	e	4	u	11,925	25	16.0		45	20		16.0	12.8	3.0	n	3.86	D	
451	US1	US 1 Wilkens Avenue																					

Seg. ID	Route No.	Road Name	From	To	Length (Ls) (Mi)	Jurisdiction	Dir. of Sur.	Lanes (L)			Volume (ADT) (vpd)	Post. Spd. (85th) (mph)	Width of Pavement				Occupied Parking (OSPA)		# of Grts (N)	Width Due to Vol. (Wv)	Eff. Pmnt. Width (We)	Pavement Condition (PCT) (1.5)		Bike Lane? (Y/N)	BLOS Score Grade (A, F)	
								Th	Tu	Con. #			(Wt)	(Wl)	(Wps)	(Wg)	N/E	S/W				(Pct)	(Pct)			
1064a		Martin Luther King Junior Boulevard	US 40 WEST	Franklin Street	MD 129 SOUTH	Druid	Balt. City	n	6	d	64,000	35	12.6	0.0	0.0	1.5	0	0	11	12.6	11.9	3.5	0.0	n	5.66	F
1064b		Martin Luther King Junior Boulevard	MD 129 SOUTH	Druid	MD 129 NORTH	Druid	Balt. City	n	6	d	61,000	35	12.6	0.0	0.0	1.5	0	0	1	12.6	12.2	3.5	0.0	n	5.49	E
1064c		Martin Luther King Junior Boulevard	MD 129 NORTH	McCulloh Street	Howard Street		Balt. City	n	4	d	58,000	35	12.6	0.0	0.0	1.5	0	0	6	12.6	12.1	3.5	0.0	n	5.44	E
1064d		Chase Street	Howard Street	Charles Street		Balt. City	e	4	u	2,400	30	18.2	0.0	0.0	1.5	100	100	2	25.5	15.3	3.5	0.0	n	2.60	C	
1064e		Martin Luther King Junior Boulevard	Washington Boulevard	Lombard Street		Balt. City	n	6	d	49,325	35	12.6	0.0	0.0	1.5	0	0	10	12.6	11.8	3.5	0.0	n	5.19	E	
1064f		Martin Luther King Junior Boulevard	Lombard Street	US 40 EAST	Mulberry		Balt. City	n	6	d	61,000	35	12.6	0.0	0.0	1.5	0	0	6	12.6	12.3	3.5	0.0	n	5.48	E
1064g		Martin Luther King Junior Boulevard	US 40 EAST	Mulberry	US 40 WEST	Franklin	Balt. City	n	6	d	62,400	35	12.6	0.0	0.0	1.5	0	0	22	12.6	7.0	3.5	0.0	n	6.00	F
194		Broadway	Chester Street	US 1 North Avenue		Balt. City	n	6	d	8,875	30	9.6				2.0		3	9.6	9.2	3.0		n	3.99	D	
2000		Fort Avenue	MD 2	Hanover Street	Jackson Street		Balt. City	e	2	u	6,000	25	19.0				80	80		19.0	11.0	3.5	n	3.76	D	
2001		Fort Avenue	Jackson Street	Lawrence Street		Balt. City	e	2	u	6,000	25	24.0				80	80		24.0	16.0	3.5	n	0.00	A		
2002		Ostend Street	Lawrence Street	MD 2	Hanover Street		Balt. City	e	2	u	8,800	25	16.0			2.0	10	10	2	16.0	14.9	4.0	n	3.29	C	
2003		Ostend Street	Washington Boulevard	Scott Street		Balt. City	e	2	u	8,800	25	20.0				50	50		20.0	15.0	3.5	n	3.43	C		
2004		Fallsay	President Street	Centre Street		Balt. City	n	4	u	3,900	30	18.0				80	80		18.5	10.5	3.5	n	3.47	C		
2005		Fallsay	Centre Street	Guilford Avenue		Balt. City	n	2	ow	3,900	30	22.5				2.0	30	30	3	22.5	19.3	2.5	n	0.00	A	
2006		Monument Street	Eutaw Street	Cathedral Street		Balt. City	w	2	u	24,300	25	18.0				90	90		18.0	9.0	4.0	n	4.80	E		
2007		Cathedral Street	Biddle Street	Monument Street		Balt. City	s	3	ow	13,400	25	20.0				90	90		20.0	11.0	3.0	n	4.21	D		
2008		Park Avenue	Monument Street	Park Avenue / Chase Street		Balt. City	n	2	ow	7,200	25	20.0				80	80		20.0	12.0	4.0	n	3.52	D		
2009		Martin Luther King Junior Boulevard	Park Avenue / Chase Street	Biddle Street		Balt. City	n	2	ow	22,000	25	11.0				0	0		11.0	11.0	4.0	n	4.49	D		
2010		Lawrence Street	Key Highway	Fort Avenue		Balt. City	s	2	u	17,900	25	23.0				5	60		23.0	19.8	4.0	n	2.95	C		
2011		Eutaw Street	Saratoga Street	Baltimore Street		Balt. City	s	2	ow	2,400	25	9.5				0	0		9.5	9.5	3.0	n	3.56	D		
2012		Eutaw Street	Baltimore Street	Saratoga Street		Balt. City	n	1	ow	2,400	25	19.0				90	90		19.0	10.0	3.0	n	3.86	D		
2013		Eutaw Street	Martin Luther King Junior	Saratoga Street		Balt. City	s	2	u	4,800	25	19.0				2.0	10	10	3	19.0	17.8	3.5	n	2.66	C	
2014		Eutaw Street	Martin Luther King Junior	Dolphin Street		Balt. City	s	4	d	4,800	25	24.0				2.0	70	70	3	24.0	16.6	4.0	n	2.37	B	
2015		Eutaw Street	Dolphin Street	US 1 North Avenue		Balt. City	n	4	d	10,162	25	17.0				2.0	40	40	1	17.0	13.0	4.0	n	3.43	C	
2016		Eutaw Street	Whitecliff Street	Druid Park Lake Drive		Balt. City	n	2	ow	2,400	25	23.0				90	90		23.0	14.0	4.0	n	2.70	C		
2017		Eutaw Street	US 1 North Avenue	Whitecliff Street		Balt. City	n	1	ow	2,400	25	22.0							22.0	22.0	4.0	n	1.61	B		
2018		Madison Avenue	Druid Park Lake Drive	US 1 North Avenue		Balt. City	s	1	ow	7,600	25	22.0				90	90		22.0	13.0	3.0	n	4.10	D		
2019		Washington Boulevard	Monroe Street	Hollins Ferry Road		Balt. City	n	4	u	16,300	35	10.0				0	0		10.0	10.0	3.5	n	4.57	E		
2020		Washington Boulevard	Monroe Street	Bayard Street		Balt. City	n	1	ow	8,200	35	9.0				0	0		9.0	9.0	3.0	n	4.94	E		
2021		Washington Boulevard	Bayard Street	Monroe Street		Balt. City	s	2	ow	8,200	35	17.0				20	20		17.0	15.0	3.0	n	3.87	D		
2033		Denison Street	North Avenue	Clifton Avenue		Balt. City	n	2	u	2,200	25	17.0				2.0	25	25	1	24.7	22.0	4.0	n	1.28	A	
2034		Denison Street	Clifton Avenue	Gwynns Falls Parkway		Balt. City	n	2	u	2,200	25	14.0				2.0	10	10	2	20.3	19.0	4.0	n	1.89	B	
2035		Lafayette Avenue	Franklin Avenue	Claymont Street		Balt. City	e	2	u	4,500	25	12.0				2.0	80	80	1	12.0	3.9	3.0	n	4.32	D	
2036		Lafayette Avenue	Claymont Street	Eutaw Street		Balt. City	e	2	u	4,500	25	18.0				2.0	40	40	2	18.0	14.0	3.5	n	3.25	C	
2037		Charles Street (S-bound only)	University Parkway	29th Street E / W		Balt. City	S	1	OW	2,000	25	14.0				1.8	0	0		14.0	14.0	2.0	n	4.29	D	
2038		Walther Avenue	MD 147	Harford Road	Northern Parkway		Balt. City	s	4	D	11,340	30	21.6				0	0		21.6	21.6	3.0	n	2.68	C	
2039		Fallstaff Road	Cross Country Boulevard	MD 129	Park Heights Avenue		Balt. City	n	2	u	4,000	25	19.0				2.0	20	20	1	19.0	16.7	3.5	n	2.76	C
2040		Cross Country Boulevard	Fallstaff Road	Green Spring Avenue		Balt. City	e	2	u	7,700	30	15.0							15.0	15.0	3.0	n	3.77	D		
2041		Cross Country Boulevard	Green Spring Avenue	Kelly Avenue		Balt. City	e	2	u	7,700	30	17.0				2.0		1	17.0		4.5	n	0.00	A		
2042		Kelly Avenue	Cross Country Boulevard	Sulgrave Avenue		Balt. City	e	2	u	5,900	30	15.0							15.0	15.0	4.0	n	3.30	C		
2043		Kelly Avenue	Sulgrave Avenue	MD 25	Falls Road		Balt. City	e	4	u	16,803	30	11.0			2.0		3	11.0	10.7	4.0	n	4.21	D		
2044		Gay Street / Ensor Street	Fallsay	Monument Street		Balt. City	n	3	ow	10,100	30	12.0				80	80		12.0	4.0	3.5	n	4.68	E		
2045		Hilton Street	Monument Street	Fallsay		Balt. City	s	3	ow	10,100	30	12.0				25	30		12.0	9.3	3.5	n	4.33	D		
2046		Washington Boulevard	Bayard Street	Martin Luther King Junior Boulevard		Balt. City	s	2	u	9,383	25	18.0				80	80		18.0	10.0	3.5	n	4.09	D		
2047		Monroe Street	US 1	Wilkins Avenue	Washington Boulevard		Balt. City	n	4	u	21,600	30	11.0				0	0		11.0	11.0	3.5	n	4.65	E	
2048		Eutaw Street	Baltimore Street	Pratt Street		Balt. City	n	4	u	10,200	25	11.0				0	0		11.0	11.0	3.5	n	3.81	D		
218a		Druid Park Lake Drive	Madison Avenue	McCulloh Street		Balt. City	e	4	d	41,300	35	10.0				0	0	2	10.0	10.0	3.0	n	5.67	F		
218b		Druid Park Lake Drive	I-83 Jones Falls Expressway	Madison Avenue		Balt. City	e	6	d	41,300	35	10.0				0	0		10.0	10.0	3.0	n	5.46	E		
219a		Dundalk Avenue	Boston Street	Holabird Avenue		Balt. City	n	4	d	23,450	35	23.6				1.0	0	70	2	23.6	20.1	4.0	n	3.31	C	
219b		Dundalk Avenue	Holabird Avenue	Baltimore County Line		Balt. City	n	4	d	20,100	35	23.4				1.0	0	75	1	23.4	19.6	3.5	n	3.48	C	
232		MD 45	Greenmount Avenue	US 1 North Avenue	24th Street E		Balt. City	s	2	u	16,300	25	10.0				0	0		10.0	10.0	3.0	n	4.74	E	
233a		Green Spring Avenue	Baltimore County Line	Cross Country Boulevard		Balt. City	n	2	u	9,500	30	22.0				0	0		22.0	22.0	3.5	n	2.40	B		
233b		Green Spring Avenue	Cross Country Boulevard	Sulgrave Avenue		Balt. City	n	2	u	10,100	30	12.0				0	0		12.0	12.0	4.0	n	4.16	D		
233c		Green Spring Avenue	Sulgrave Avenue	Northern Parkway		Balt. City	n	4	u	10,800	30	10.0				2.0	0	0	26	10.0	8.2	4.0	n	4.23	D	
235a		Green Spring Avenue	Cold Spring Lane	Druid Park Drive		Balt. City	n	2	u	11,400	30	21.4				70	70		21.4	14.4	3.5	n	4.05	D		
235b		Green Spring Avenue	Druid Park Drive	MD 129	Swann Drive		Balt. City	n	2	u	7,000	20	10.6				0	0		10.6	10.6	2.0	n	4.30	D	
238a		Guilford Avenue	Biddle Street	Eager Street		Balt. City	s	2	ow	3,800	30	17.6				100	100		17.6	7.6	3.0	n	4.19	D		
238b		Guilford Avenue	Eager Street	Madison Street		Balt. City	s	3	ow	10,000	30	26.0				0	0		26.0	26.0	3.5	n	1.20	A		
238c		Guilford Avenue	Madison Street	US 40	Orleans Street		Balt. City	s	3	ow	10,000	30	11.9			2.0	0	0	2	11.9	11.7	3.5	n	3.89	D	
242a		Gwynns Falls Parkway	Hilton Parkway	Longwood Street		B																				

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