Appendix G

Additional Performance Measures
ADDITIONAL PERFORMANCE MEASURES

This Appendix compiles additional performance measurement details that were developed and referenced throughout the establishment of existing conditions and the review and assessment of proposed improvement scenarios. Specific content includes:

- Attachment G1: System-wide Delay Comparison
- Attachment G2: Level of Traffic Stress Research
- Attachment G3: Level of Service Comparison
ATTACHMENT G1

SYSTEM-WIDE DELAY COMPARISON
Delay – AM Low Growth – No Build

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 40%
- 5-10: 30%
- 10-15: 16%
- >15: 9%
Delay – AM Low Growth – Fill in the Gaps

Vehicle Miles Traveled by Delay (minutes):

- 0-5: 42%
- 5-10: 31%
- 10-15: 14%
- >15: 11%
Delay – AM Low Growth – Moderate Investment

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 42%
- 5-10: 17%
- 10-15: 9%
- >15: 32%
Delay – AM Low Growth – Heavy Investment

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 48%
- 5-10: 26%
- 10-15: 9%
- >15: 17%
Delay – AM Medium Growth – No Build

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 35%
- 5-10: 16%
- 10-15: 10%
- >15: 39%
Delay – AM Medium Growth – Fill in the Gaps

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 40%
- 5-10: 32%
- 10-15: 11%
- >15: 16%
Delay – AM Medium Growth – Moderate Investment

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 32%
- 5-10: 8%
- 10-15: 18%
- >15: 42%
Delay – AM Medium Growth – Heavy Investment

Vehicle Miles Traveled by Delay (minutes)

- 47%
- 27%
- 10%
- 16%

0-5, 5-10, 10-15, >15
Delay – AM High Growth – No Build

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 44%
- 5-10: 16%
- 10-15: 7%
- >15: 33%
Delay – AM High Growth – Fill in the Gaps

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 40%
- 5-10: 35%
- 10-15: 14%
- >15: 6%
Delay – AM High Growth – Moderate Infrastructure

Vehicle Miles Traveled by Delay (minutes)
Delay – AM High Growth – Heavy Investment

Vehicle Miles Traveled by Delay (minutes)
Delay – PM Low Growth – No Build

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 39%
- 5-10: 41%
- 10-15: 10%
- >15: 18%
Delay – PM Low Growth – Fill in the Gaps

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 39%
- 5-10: 20%
- 10-15: 10%
- >15: 11%
Delay – PM Low Growth – Moderate Investment

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 51%
- 5-10: 16%
- 10-15: 11%
- >15: 42%
Delay – PM Low Growth – Heavy Investment

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 28%
- 5-10: 12%
- 10-15: 13%
- >15: 46%
Delay – PM Medium Growth – No Build

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 36%
- 5-10: 30%
- 10-15: 12%
- >15: 17%
Delay – PM Medium Growth – Fill in the Gaps

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 37%
- 5-10: 20%
- 10-15: 12%
- >15: 32%
Delay – PM Medium Growth – Moderate Investment

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 38%
- 5-10: 17%
- 10-15: 17%
- >15: 13%
Delay – PM Medium Growth – Heavy Investment

Vehicle Miles Traveled by Delay (minutes)
Delay – PM High Growth – No Build

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 47%
- 5-10: 27%
- 10-15: 16%
- >15: 10%

Legend:
- Green: 0-5
- Yellow: 5-10
- Orange: 10-15
- Red: >15
Delay – PM High Growth – Fill in the Gaps

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 44%
- 5-10: 27%
- 10-15: 19%
- >15: 10%

Legend:
- 0-5
- 5-10
- 10-15
- >15
Delay – PM High Growth – Moderate Investment

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 42%
- 5-10: 29%
- 10-15: 11%
- >15: 18%
Delay – PM High Growth – Heavy Investment

Vehicle Miles Traveled by Delay (minutes)

- 0-5: 59%
- 5-10: 10%
- 10-15: 19%
- >15: 11%
ATTACHMENT G2

LEVEL OF TRAFFIC STRESS RESEARCH
Visualizing and Measuring Low-Stress Bicycle Network Connectivity in Delaware

Final Report

Peter G. Furth, PhD and Theja V.V.K. Putta
Northeastern University

August 10, 2016
1. Introduction

The Delaware Department of Transportation (DelDOT) has made and will continue to make substantial investments in bicycle route facilities in recognition of the benefits that increased cycling offers in the realms of public health, sustainability, livability, and economic competitiveness. While many supply-side factors such as cost and feasibility are used for choosing which investments to make, the most important criterion on the demand side should be *low-stress connectivity* — that is, the degree to which a proposed investment will create low traffic stress connections for bicycling between homes and destinations. DelDOT recognizes that a large fraction of its population is willing to ride a bike only on routes with low traffic stress, and that the utility of a link is greater if it creates or completes low stress routes that connect many origins (homes) to many destinations (jobs, other homes, recreational attractors, etc.). The concept of low-stress connectivity was introduced by Mekuria, Furth, and Nixon (2012) in a case study of San Jose, California, and it is rapidly becoming recognized nationwide as an important objective for bicycle route planning.

Because there are no generally available tools for visualizing or measuring low-stress connectivity, DelDOT engaged Northeastern University in 2014 to develop them for application in Delaware. This report documents that study, whose major components were:

- Refining and expanding Level of Traffic Stress (LTS) criteria for application in Delaware
- Developing methodology for translating low-stress connectivity into a predicted number of bicycle user based on a target bike share and a propensity model in which bicycling demand is sensitive to distance and detour.
- Developing software for implementing these methodologies
- Resolving data issues so that existing data sources can be exploited to calculate LTS and network connectivity
- Creating baseline LTS maps
- Performing an alternatives analysis based on low-stress connectivity for alternative alignments of a Wilmington – Newark trail.
- Refining alternative alignments for a Wilmington – Newark trail with a connectivity perspective.
2. Refining and Expanding LTS Criteria for Application in Delaware Levels of Traffic Stress

The chief deterrent to riding a bike in the U.S. is the high stress of riding without protection from the danger of fast and heavy motor traffic, or, more briefly, traffic stress. Some streets have low traffic stress, while others have high stress. Sometimes a treatment such as bike lanes is effective in eliminating most of the traffic stress; but other times even where there’s a bike lane, it can be very stressful.

Until recently, different methods had been developed for classifying streets by how comfortable or stressful it is to ride there; however, none is widely known or used for various reasons including burdensome data requirements, black-box formulas, inconsistencies, and failure to account for intersection effects and protected lane treatments.

In 2012, Mekuria, Furth, and Nixon proposed a new classification scheme that classifies streets into four levels of traffic stress (LTS) using simple rules that rely on data that’s either readily available or easy to acquire (Mekuria, Furth, and Nixon, Low-Stress Bicycling and Network Connectivity, Research report 11-19, Mineta Transportation Institute, 2012). The four levels of traffic stress are linked to Geller’s popular classification of people by their readiness to use a bike (https://www.portlandoregon.gov/transportation/article/158497).

- LTS 1: Suitable for children cyclists. Cyclists are either physically separate from traffic, or face a limited volume of low-speed traffic in which they rarely have to deal with more than one vehicle at a time.

- LTS 2: Limits traffic stress to what the mainstream adult population, those who are “interested but concerned,” can tolerate. Cyclists have to deal with multiple vehicles at a time only at low speeds and infrequently, or else they have a defensible place to ride that motor traffic, for the most part, stays out of. They are physically separated from high speed and multilane traffic. The criteria for LTS 2 correspond to design criteria for Dutch bicycle route facilities.
- LTS 3: A level of traffic stress acceptable to the "enthused and confident." Involves interaction with moderate speed or multilane traffic, or close proximity to higher speed traffic.

- LTS 4: A level of stress acceptable only to the "strong and fearless." Involves being forced to mix with moderate speed traffic or close proximity to high speed traffic.
Crossing busy streets without the protection of a signal can also involve traffic stress that deters people from using a bike. For example, a crossing in which a person crosses 4 lanes of 35 mph traffic without a crossing island wide enough to store a bicycle (7 ft wide) has a level of traffic stress of 3, something that will deter most of the adult population from a route with such a crossing.

The original LTS criteria were developed for the context of the city of San Jose, CA. While the general factors that create traffic stress apply across the country, the Delaware context offers situations that are not common in San Jose and therefore were not well accounted for in the original criteria. They include:

- DelDOT is interested in rural roads as well as urban streets, and so criteria were needed that recognized the effect of various shoulder widths, the effect of right turn lanes at unsignalized intersections, and the limited by real popularity of routes featuring wide shoulders on high speed rural roads such as Delaware’s Coastal Highway.
- DelDOT has average daily traffic (ADT) data for nearly all the roads in the state, making it available as an input value. ADT affects traffic stress when cyclists have to ride in mixed traffic.

**Revised LTS Link Criteria for Mixed Traffic**

Revised criteria for roads with bikes in mixed traffic are shown in Table 1. While many of the revisions were driven by considerations of rural roads, the criteria apply to urban as well as rural roads.
### Table 1: Revised Criteria for Cycling in Mixed Traffic

<table>
<thead>
<tr>
<th>Number of lanes</th>
<th>2-way ADT</th>
<th>&lt; 20 mph</th>
<th>25 mph</th>
<th>30 mph</th>
<th>35 mph</th>
<th>40 mph</th>
<th>45 mph</th>
<th>50+ mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlaned 2-way street (no centerline)</td>
<td>0-750</td>
<td>LTS1</td>
<td>LTS1</td>
<td>LTS2</td>
<td>LTS2</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
</tr>
<tr>
<td></td>
<td>751-2000</td>
<td>LTS1</td>
<td>LTS1</td>
<td>LTS2</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
<td>LTS4</td>
</tr>
<tr>
<td></td>
<td>2001-3000</td>
<td>LTS1</td>
<td>LTS1</td>
<td>LTS2</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
<td>LTS4</td>
</tr>
<tr>
<td></td>
<td>3000+</td>
<td>LTS2</td>
<td>LTS2</td>
<td>LTS2</td>
<td>LTS3</td>
<td>LTS4</td>
<td>LTS4</td>
<td>LTS4</td>
</tr>
<tr>
<td>1 thru lane per direction (1-way street or 2-way street with centerline)</td>
<td>0-750</td>
<td>LTS1</td>
<td>LTS1</td>
<td>LTS2</td>
<td>LTS2</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
</tr>
<tr>
<td></td>
<td>751-2000</td>
<td>LTS1</td>
<td>LTS1</td>
<td>LTS2</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
<td>LTS4</td>
</tr>
<tr>
<td></td>
<td>2001-6000</td>
<td>LTS2</td>
<td>LTS2</td>
<td>LTS2</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
<td>LTS4</td>
</tr>
<tr>
<td></td>
<td>6001+</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
<td>LTS4</td>
<td>LTS4</td>
</tr>
<tr>
<td>2 thru lanes per direction</td>
<td>0-6000</td>
<td>LTS2</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
<td>LTS4</td>
<td>LTS4</td>
</tr>
<tr>
<td></td>
<td>6001+</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
<td>LTS4</td>
<td>LTS4</td>
<td>LTS4</td>
<td>LTS4</td>
</tr>
<tr>
<td>3+ thru lanes per</td>
<td>any ADT</td>
<td>LTS3</td>
<td>LTS3</td>
<td>LTS4</td>
<td>LTS4</td>
<td>LTS4</td>
<td>LTS4</td>
<td>LTS4</td>
</tr>
</tbody>
</table>

A comparison against the original (2012) LTS criteria is shown in Table 2, with cells in yellow having a lower LTS and cells in purple a higher LTS than original. Changes and their rationale are:

- There is a small expansion of the region for LTS 1 – for very low volume streets with centerlines, recognizing that when volumes are low, drivers often behave as though there is no centerline.
- The region for LTS 2 expands a little also. It now includes 35 mph roads with less than 750 ADT and 30 mph roads with up to 2000 ADT that are unlaned or have 1+1 lanes. This recognizes that roads with low traffic volumes are attractive for bicycling even if traffic is going at moderately high speeds because with low traffic volumes, cyclists rarely encounter multiple cars at the same time.
- LTS has been lowered for low-volume 2+2 lane roads (and 2-lane one-way roads) with low volume (ADT ≤ 6000 for two-way, < 3000 for one-way) recognizing that when a multilane road has little traffic, cyclists can effectively treat the right lane as a bike lane because motor traffic can pass so easily using the left lane. Where prevailing speeds are 20 mph, as might be expected in a tight grid on a minor street with frequent stops (a common situation in older parts of Wilmington), LTS was lowered from 3 to 2; where prevailing speeds are 30-35 mph, LTS has been shifted from 4 to 3. Roads with 6 lanes (and one-way streets with 3 lanes) likewise see a shift of their LTS from 4 to 3 where speeds are 25 mph or less.
- The LTS 3 region has been expanded by including low volume roads with greater speeds than had been permitted under the original criteria.
- There is one situation for which LTS increases relative to the original criteria, which is on 2-lane roads with ADT > 6000. High volume, narrow roads like this, which are mostly found in urban areas, involve high traffic stress because encounters with cars are frequent and often require cyclists to deal with multiple cars at a time.
## Table 2: Revised versus Original Criteria for Cycling in Mixed Traffic

<table>
<thead>
<tr>
<th>Number of lanes</th>
<th>ADT</th>
<th>&lt;20 mph</th>
<th>25 mph</th>
<th>30 mph</th>
<th>35 mph</th>
<th>40 mph</th>
<th>45 mph</th>
<th>50+ mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlaned 2-way street (no centerline)</td>
<td>0-750</td>
<td>LTS 1</td>
<td>LTS 1</td>
<td>LTS 2</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td></td>
<td>751-2000</td>
<td>LTS 1</td>
<td>LTS 1</td>
<td>LTS 2</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td></td>
<td>2001-3000</td>
<td>LTS 1</td>
<td>LTS 1</td>
<td>LTS 2</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td></td>
<td>3001+</td>
<td>LTS 2</td>
<td>LTS 2</td>
<td>LTS 3</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td>1 thru lane per direction (1-way street or 2-way street with centerline)</td>
<td>0-750</td>
<td>LTS 1</td>
<td>LTS 1</td>
<td>LTS 2</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td></td>
<td>751-2000</td>
<td>LTS 1</td>
<td>LTS 1</td>
<td>LTS 2</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td></td>
<td>2001-6000</td>
<td>LTS 1</td>
<td>LTS 1</td>
<td>LTS 2</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td></td>
<td>6001+</td>
<td>LTS 2</td>
<td>LTS 2</td>
<td>LTS 3</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td>2 thru lanes per direction</td>
<td>0-6000</td>
<td>LTS 1</td>
<td>LTS 3</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td></td>
<td>6001+</td>
<td>LTS 3</td>
<td>LTS 3</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
<tr>
<td>3+ thru lanes per direction</td>
<td>any ADT</td>
<td>LTS 1</td>
<td>LTS 1</td>
<td>LTS 2</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
<td>LTS 4</td>
</tr>
</tbody>
</table>

Note: **Yellow represents** a lowering LTS compared to original criteria
Note: **Purple represents** an increase in LTS compared to original criteria

### Revised LTS Link Criteria for Bike Lanes and Shoulders

Existing criteria for bike lanes can be applied equally to shoulders on rural roads. However, considering the rural context, we felt a need to relax the maximum speeds for LTS 2 and LTS 3 to better reflect the protection than cyclists feel when riding in their own defensible space.

Revised criteria for shoulders and bike lanes *not* alongside a parking lane are given in Table 3, which changes versus the original criteria shown in Table 4. The most sweeping change is an expansion of the speeds for which LTS can be 3 rather than 4. This recognizes that "enthusied and confident" riders, who probably comprise the majority of recreational riders in rural areas, show a clear attraction for roads with shoulders, even where traffic speed is high, as evidenced by the popularity of bicycling along the coastal highway, a 2+2 lane divided highway with speed limit 55 mph, but with 12-ft shoulder that bikes may ride in.

The LTS 2 region also now accepts speeds up to 35 mph for 2-lane and 4-lane divided roads with bike lanes and no parking. Also, for consistency with mixed traffic criteria, 4-lane roads with bike lanes, very low volumes, and a prevailing speed of 25 mph or less have LTS 2.
### Table 3: Revised Criteria for Cycling in Bike Lanes and Shoulders

<table>
<thead>
<tr>
<th>Bike lanes and shoulders not adjacent to a parking lane</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 25 mph</td>
</tr>
<tr>
<td>Number of lanes</td>
<td>Bike lane width</td>
</tr>
<tr>
<td>1 thru lane per direction, or unlaned</td>
<td>6+ ft</td>
</tr>
<tr>
<td></td>
<td>4 or 5 ft</td>
</tr>
<tr>
<td>2 thru lanes per direction and divided</td>
<td>6+ ft</td>
</tr>
<tr>
<td></td>
<td>4 or 5 ft</td>
</tr>
<tr>
<td>4 lanes undivided</td>
<td>any</td>
</tr>
<tr>
<td></td>
<td>6+ ft</td>
</tr>
<tr>
<td></td>
<td>4 or 5 ft</td>
</tr>
<tr>
<td>3+ lanes per direction</td>
<td>6+ ft</td>
</tr>
<tr>
<td></td>
<td>4 or 5 ft</td>
</tr>
</tbody>
</table>

### Table 4: Revised versus Original Criteria for Cycling in Bike Lanes and Shoulders not Adjacent to a Parking Lane

Frequent bike lane blockage automatically triggers LTS 3 (or higher)

<table>
<thead>
<tr>
<th>Bike lanes and shoulders not adjacent to a parking lane</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 25 mph</td>
</tr>
<tr>
<td>Number of lanes</td>
<td>Bike lane width</td>
</tr>
<tr>
<td>1 thru lane per direction, or unlaned</td>
<td>6+ ft</td>
</tr>
<tr>
<td></td>
<td>4 or 5 ft</td>
</tr>
<tr>
<td>2 thru lanes per direction and divided</td>
<td>6+ ft</td>
</tr>
<tr>
<td></td>
<td>4 or 5 ft</td>
</tr>
<tr>
<td>4 lanes undivided</td>
<td>any</td>
</tr>
<tr>
<td></td>
<td>6+ ft</td>
</tr>
<tr>
<td></td>
<td>4 or 5 ft</td>
</tr>
<tr>
<td>3+ lanes per direction</td>
<td>6+ ft</td>
</tr>
<tr>
<td></td>
<td>4 or 5 ft</td>
</tr>
</tbody>
</table>

For bike lanes alongside a parking lane, only one change to the original criteria is proposed: where in the original criteria frequent bike lane blockage automatically triggered LTS 3, now frequent bike lane blockage calls for applying mixed traffic criteria. For completeness, and with an easier-to-follow format, those criteria are given in Table 5.
Table 5: Revised Criteria for Cycling in Bike Lanes Adjacent to a Parking Lane

If combined width of parking lane and bike lane < 12 ft or bike lane is blocked frequently, use mixed traffic criteria

<table>
<thead>
<tr>
<th>Number of lanes</th>
<th>Bike lane reach = Bike + Pkg lane</th>
<th>Parking turnover</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt; 20 mph</td>
<td>25 mph</td>
</tr>
<tr>
<td>1 lane per direction</td>
<td>15+ ft</td>
<td>any</td>
<td>LTS 1</td>
</tr>
<tr>
<td></td>
<td>14 ft</td>
<td>any</td>
<td>LTS 2</td>
</tr>
<tr>
<td></td>
<td>12 or 13 ft</td>
<td>low*</td>
<td>LTS 2</td>
</tr>
<tr>
<td></td>
<td>12 or 13 ft</td>
<td>high*</td>
<td>LTS 2</td>
</tr>
<tr>
<td>2+ lanes per direction</td>
<td>15+ ft</td>
<td>any</td>
<td>LTS 3</td>
</tr>
<tr>
<td></td>
<td>12-14 ft</td>
<td>any</td>
<td>LTS 3</td>
</tr>
</tbody>
</table>

*Absent local evidence, parking turnover can be assumed to be high in commercial areas and low otherwise

LTS Criteria for Unsignalized Intersection Approaches with Right Turn Lanes

While the original criteria address signalized intersections with right turn lanes and pocket bike lanes, they do not address unsignalized intersection approaches with right turn lanes. A common situation on Delaware’s rural roads is for a shoulder to be converted into a right turn lane on an unsignalized intersection approach in order to give right turning vehicles a chance to slow down outside the traffic stream.

Criteria for this situation were developed as part of this project; however, in the case studies they were not used because DelDOT does not have easy access to data on the presence of right turn lanes. Data on turn lanes may become more accessible in the future as new datasets covering signs and markings are developed.

Criteria for unsignalized intersection approaches with right turn lanes are given in Table 6. As indicated, right turn lanes may create added stress depending on two things:

- Whether the turn lane geometry is such that traffic in the turn lane will be going slow. The geometric conditions are that the turn angle must force vehicles to be going slow at the turn, and the turn lane must be short so that vehicle must have already decelerated to about 25 mph before entering the turn lane.
- Whether through bikes are allowed to use the turn lane (as opposed to being required to merge into the adjacent through traffic lane). In Delaware, thanks to a recent change in state law, cyclists in such a situation may use the turn lane even if they are not turning.

DelDOT guidelines for subdivision entries call for right angle intersections and converting a shoulder into a right turn lane for 150 ft prior to the intersection, sometimes converting the shoulder to an acceleration lane for an additional 150 ft beyond the intersection. Turn lanes meeting complying with these guidelines will not add additional stress to cyclists.
### Table 6: Level of Traffic Stress Criteria for Unsignalized Intersection Approaches with Right Turn Lanes

<table>
<thead>
<tr>
<th>Condition</th>
<th>Condition continued</th>
<th>LTS of the approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>The bike lane / shoulder continues either to the right of the right turn lane or as a pocket lane (to the left of the right turn lane)</td>
<td>&quot;Slow RT Lane&quot; condition applies, which is: RT lane length &lt; 150 ft AND turn deflection angle ≥ 75° AND RT lane begins afresh to the right of the thru lane</td>
<td>No effect&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>otherwise</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Through bikes are expected to ride in the RT lane</td>
<td>Slow RT Lane condition applies</td>
<td>No effect&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>otherwise</td>
<td></td>
<td>[Treat it as a mixed traffic segment, with the RT lane counting as a through lane]</td>
</tr>
<tr>
<td>Through bikes are expected to ride in the through lane</td>
<td>Slow RT Lane condition applies</td>
<td>[Treat it as a mixed traffic segment, with the RT lane not counting in the number of lanes]</td>
</tr>
<tr>
<td>otherwise</td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

Sometimes on approaches to subdivision entrances an auxiliary left-turn lane is created by diverting the through lane into the shoulder. That treatment *does* increase traffic stress for cyclists because it forces them into mixed traffic (and therefore level of traffic stress can be determined using mixed traffic criteria); it also creates a legally ambiguous situation for motorists passing a bike – are they allowed to use the left-turn lane? A more bike-friendly and legally consistent treatment is to keep the shoulder continuous, possibly widening it so that the combined width of the travel lane and shoulder is 20 ft. Then, when nobody is turning left, the shoulder is available for bicycle use, and when somebody turning left is blocking the travel lane, through cars can use the shoulder to pass on the right. If a bike happens to be in the shoulder at the same time that a left-turning car is blocking the through lane, right of way is unambiguous – the car entering the shoulder is crossing a lane line and therefore must yield to the bike.

<sup>1</sup> There is no effect if the base condition on the segment is either bike lane or mixed traffic. If the base condition is a separated bike lane, then the removal of physical separation means that LTS should be determined using criteria for ordinary bike lanes.
3. DelDOT Road Data Files and Data Issues

This section describes the two main enterprise road data files used for GIS analysis, other data sources, and data issues that had to be resolved for LTS analysis.

Road Inventory and E-911 Files
DelDOT has two main kinds of road data files it can use for level of traffic stress analysis, the county road inventory files and the E-911 file.

A road inventory file is maintained for each of Delaware’s three counties. Each one contains data on many attributes useful to LTS analysis including number of lanes, presence of a median, shoulder width, and ADT, and because it is routinely used for DelDOT’s pavement management system, the features and some of the attributes are kept up to date. At this time, efforts are also underway to integrate pavement markings and sign data into the road inventory file so that it can be used for better maintenance of management of these assets; those efforts should improve the quality of data on number of lanes, shoulder width, and add data on speed limit and passing zones.

The second main road file is the E-911 file, a map dataset used to support emergency response, such as finding the shortest path to a location with a distress call. This function requires a road file that is “routable,” meaning that every intersection is represented by a node, that links be only from one node to the next, and that they contain data on traffic circulation restrictions including one-way and turn restrictions. The road inventory files are not routable because they contain many links that pass right through intersections. For example, when a new side street is built that intersects an existing main road, a feature representing the side street is often added to the road inventory file without splitting the links on the main road and without taking care that the new feature ends exactly at the main road — because that level of precision is not needed for current functions of the road inventory file including pavement management and mapping. However, for the file to be routable, the main road link must be split at the junction into two links, the feature representing the new street and the two links that result from splitting must all end exactly at a single (x,y) location.

Low-stress connectivity analysis involves finding shortest paths and therefore requires the routability function that only the E-911 file has. However, most of the attributes of the road inventory file have not been copied to the E-911 file, a deliberate decision to prevent the well-known problems of having data reside in more than one location. Therefore, the road inventory file is also needed for LTS analysis; it is the file used for calculating level of traffic stress. Therefore, new data fields used for LTS classification are added to the road inventory file, not the E-911 file.

The road inventory file has a one-to-many or parent-child relationship with the E-911 file in the sense that a single feature (a single road link) in the road inventory file may be represented by multiple features in the E-911 file. A dictionary of this relationship maintained by DelDOT makes it easy to copy attributes of a parent link in the road inventory file to its child links in the E-911 file. Therefore the processing sequence used for LTS analysis is first to use the road inventory file to calculate LTS on each link, and then to push that LTS attribute onto a working copy of the E-911 file. As a result, working copy of the E-911 file will have LTS data for each link, but will not have the underlying attributes (e.g., number of lanes, shoulder width, ADT) that determined LTS.
Bikeable Shoulders, Bike Lanes, and Sidewalks

In an earlier effort, DelDOT created a dataset of roads with bikeable shoulders, defined as shoulders at least 4 ft wide. This file, which drew on the road inventory files as its starting point, was used as a source of shoulder width. The bikeable shoulders file also included data on known bike lanes.

Our case study in the Newark area showed that there were many errors with shoulder width data. The data — presence of a shoulder or bike lane and its width — was therefore checked against Google map data and corrected by Bike Delaware’s intern. There was not enough time in this project to extend that checking throughout the service area, and so errors probably persist and affect the results. An example of an error that was caught late in the project was that Centre Road immediately south of Lancaster Pike is coded as having 10 ft shoulders, which led to LTS being calculated as better than 4. In reality, there are 10 ft shoulders, but they disappear well in advance of signalized intersections when they are converted to right turn lanes.

For future work, manual editing of bike lane data will not be too onerous because there are relatively few bike lanes in the state. It was the feeling of DelDOT staff that the shoulder width data is more reliable in the more rural parts of the state. However, the example of Centre Road suggests that shoulder data deserves a closer look, particularly at points where shoulders are apt to disappear — on approaches to intersections and on bridges.

While the E-911 routable file is supposed to include sidepaths as distinct features (as does, for example, Google Maps), the version available to us did not include many sidepaths including those along Route 4 in southern Newark and those along Centre Road (ring along western side of Wilmington). For this project, we employed a workaround by setting the attribute “qProtected” to 1 on the parallel roadway, which gives the parallel roadway LTS 1. However, for the future, we recommend that DelDOT see to it that its routable files include those sidepaths as distinct features.

DelDOT also has a sidewalk inventory file. In general, it was not used because sidewalks are not considered to be bike route facilities. However, there are exceptions.

- Stand-alone paths (paths that are not along a road) through a park or campus should be considered bike facilities unless they are unbikeable (e.g., have stairs). In the Newark area case study, that meant including paths on the UD campus.
- Paths connecting off-road trails to cul-de-sacs or other roads are important parts of the network. In the Wilmington – Newark case study, work done in an earlier project had already added many such connectors, and we added more wherever we could see from Google Maps that there was a connection.
- Paths traversing median barriers. In Newark, where Casho Mill Road meets Elkton Road, an unbroken median makes it impossible for cars to get from Casho Mill to the residential service road on the southeast side of Elkton Road; however, a sidewalk path makes that connection possible for pedestrians and bikes. Adding it to the network created an important connection between two low-stress streets.

Other Data Editing Lessons

Some of the lessons learned in editing the road inventory data are summarized here.
Number of lanes has a fair number of errors. Roads with 2 lanes that are wide enough to have 4 lanes are often coded as having 4 lanes; an example is Kimberton Drive. This is not too time consuming to check because the state has relatively few multilane roads. It was checked and corrected manually in the case studies.

Speed limit data has a fair number of errors. For example, both Newport Gap Pike and Centre Road immediately south of Lancaster Pike have speed limits of 45 mph according to Google StreetView, but the inventory file shows speed limits of 35 mph.

ADT data are in their own layer, with a single line for roads even when the road is divided. However, in the Road Inventory File as well as the E-911 file, divided highways are represented as double lines about 40 ft apart. When initially transferring ADT data to the Road Inventory file’s network, the ADT data were applied only to one side of the roadway, and sometimes to neither roadway. To fix that, we increased the tolerance in our matching routine from 10 ft to 40 ft. ADT data thus applied to a divided road reflect traffic on the two-way road, not traffic on the individual carriageways.

In central Newark, Main Street and Delaware Avenue form a one-way pair that make up Route 2, and the ADT data are on a line matching Main Street. In this case, ADT was divided in two and applied to both streets, which in the analysis software are treated as true one-way streets rather than as one carriageway of a divided road.

ADT attribution errors can creep into the data. One example found in Newark is that 11,000 ADT is attributed to the section of South Chapel road that dead ends on the southern end of the UD campus at the Northeast Corridor RR tracks. We suspect it’s because Route 72 is also named South Chapel Rd, and that DelDOT’s ADT processing routine applies counts made in one spot along Route 72 to other segments of the same road, and this dead-end part of South Chapel is not part of Route 72, which at this spot uses a bypass road and bridge to cross the tracks.

Some Delaware roads have sidepaths, meaning a shared use path running alongside a road, such as along Route 4 going east from Newark. In DelDOT’s data files, sometimes they are represented as separate features, but other times the only feature is the road, an in the attribute table its bikeway type is MUP (multiuse path). Our analysis software will work with either representation; however, best practice is to represent sidepaths as separate features. That’s how Google Maps does it, for example. When it’s a separate feature, the data can correctly represent the side of the road on which it lies, accurately reflecting which side streets do and don’t require crossing the main road to access the sidepath.

We found that some sidepaths were entirely absent from the E-911 file, including the sidepaths along Route 4 and along S College Ave in Newark where it crosses the Northeast Corridor tracks. This was determined to be an error that the E-911 project needed to fix.

In the first version of the E-911 file that we worked with, there was no attribute indicating whether a line was a road, railroad, canal, or unimproved trail (the last three being unsuitable for transportation bicycling). DelDOT saw to it that a code was added to identify line types.

4. Visual Connectivity Analysis: Newark and Townsend Areas

A network with links classified by Level of Traffic Stress can be used to examine low-stress connectivity both visually and numerically. For the Newark and Townsend areas, a visual connectivity analysis was
conducted, with results presented at the Walkable Bikeable Delaware meeting in May, 2015. The Newark area is an example of an urbanized (part urban, part suburban) area in which bicycling needs are dominated by daily travel such as getting to work, school, and shopping as opposed to recreational travel (which still plays an important secondary role). The Townsend area exemplifies a rural or semi-rural area where recreational riding dominates (and where utilitarian cycling still plays an important, secondary role).

Visual Connectivity in the Newark Area

The presence or absence of low-stress connectivity in an area can be seen by drawing the network with higher-stress links erased or shown in a very light grey color (the latter helps distinguish open areas such as undeveloped forest from developed areas with destinations people might want to get to). Figure 1 shows the Newark area’s network with higher stress links successively erased.
Figure 1. Newark area networks at various levels of traffic stress.
Note: in all maps, green = LTS 1; blue = LTS 2; violet = LTS 3; grey = LTS 4; black = freeways.

a. All roads

b. LTS 3 and lower
Connectivity gaps are clearly evident in the maps with lower levels of traffic stress. The most important gaps are (a) those that surround an area, cutting it off from the rest of the network, and (b) those that
extend for a long distance that force cyclists to make long detours if they wish to avoid high stress links. An example of a long connectivity barrier in the LTS 2 network is shown in Figure 2 — a curvy line just east of downtown Newark for which there is no east-west crossing for several miles. Other long distance barriers are also evident such as one that roughly follows the Northeast Corridor tracks east of S. College Ave, with no north-south crossing, and one that follows the Delaware Turnpike (I-95).

Figure 2. An east-west barrier in the LTS 2 network

Marking selected destinations on a map helps one visualize connectivity to those destinations. In Figure 3, red circles represent three high schools in the Newark area as well as the main U Delaware campus. One can see that in the existing network (a):

- the southwestern-most high school is not on the low-stress network, but that with a small connector it could be linked to the Route 4 sidepath, creating low-stress connectivity to a significant population
- the southeastern high school is part of a very small low-stress island, cut off from nearly everything else
- Newark high school (the most central red circle) is also part of a very small low-stress island, with many low-stress streets nearby that could be easily connected
- The main UD campus (the northernmost circle) lacks direct connections to the north and west.

When a cycle track along Delaware Avenue in central Newark is added (b), one can also see how connectivity to both Newark High School and the main U Delaware campus dramatically improves.
Figure 3. High schools and the main U Delaware campus on the LTS map

a. Existing Network

b. With Delaware Avenue cycle track added
Visual Connectivity in the Townsend Area

Connectivity analysis can also be valuable for rural and semi-rural areas, where the main interest in bicycling is recreational riding in the countryside. A well-connected network of low-stress roads and paths makes an area attractive for recreational cycling, while large gaps discourage it. Figure 4 shows roads and trails in the Townsend area classified by LTS (the color scheme is the same as for Figure 1). In the existing network (a), one can see a large number of moderately low stress country roads (LTS 2, shown in blue) in the area; but how well are they connected? When links with LTS 3 and higher are erased (b), one can readily see that there is a north-south virtual barrier completely separating the eastern side of the network from the western side, essentially closing off all of the low-stress roads of the eastern half from the more populated western half, and that there is also an east-west virtual barrier with no north-south low-stress connections except far to the east.

Figure 4. Level of Traffic Stress Classification in the Townsend Area

- Existing network classified by LTS
Seeing these virtual barriers provides valuable guidance for designing network improvements. The highlighted gap at Route 1 shows how the decision to cut off Union Church Road when building Route 1, while perhaps a good idea for vehicular connectivity, drastically hurt bicycling connectivity. Possible ways to bridge this gap include:

- building an undercrossing under Route 1 at Union Church Road for pedestrians, cyclists, and wildlife
- creating a low-stress connection at the next northern Route 1 crossing by making extensive bicycling improvements to Pinetree Road and Blackbird Landing Road
- creating a low-stress connection at the next southern Route 1 crossing, where US 13 passes underneath Rt 1, by creating sidepaths along sections of Route 13 and Route 71.

In the southwest corner of the map, a section of a long east-west gap follows Route 15. One can see that a short section of sidepath between the Route 15’s junction with Sawmill Road and its junction with Ebenezer Church Road would create a low-stress link that bridges this gap, facilitating north-south travel. While ideally one might like to see all of Route 15 treated to be low-stress, treating only the short section between Sawmill Road and Ebenezer Church Road would be a project with relatively low cost yet high connectivity benefits.
5. Alternative Wilmington-Newark Greenway Alignments

While visual connectivity analysis is helpful for identifying needs and suggesting improvements, a decision-making process that involves multiple alternatives needs a way of quantifying connectivity. The original low-stress connectivity report cited earlier (Mekuria, Furth, and Nixon) described a method for quantifying low-stress connectivity. The next several sections of this report describe how that method was applied in evaluating the connectivity of alternative routings for a Wilmington-Newark greenway. This section describes how alternative alignments were generated; subsequent sections cover origin and destination data, some theoretical developments in measures of connectivity, and results.

Developing Improvement Alternatives

The “Newark to Wilmington Trail Study,” commissioned by DelDOT in association with Delaware State Parks and the Wilmington Area Planning Council and performed by Whitman, Requardt & Associates (2014), identified links that might be useful as part of a largely off-road trail route connecting Delaware’s two largest cities, Wilmington and Newark. Among the many factors by which route alternatives might be evaluated, DelDOT was interested in evaluating them with respect to the low-stress connectivity they would offer for everyday utilitarian trips.

The Trail Study presents a web of possible route options within which there are four main corridors:

- a northern corridor that stays north of Route 2.
- a central corridor
- a southern corridor – called in the report a second central corridor – that runs just north of the Delaware Turnpike
- a far southern corridor that runs south of Old Baltimore Pike

We developed an alternative for each of these corridors as well as a fifth alternative which adds a loop to the northern corridor to test its value in enhancing connectivity:

- northern corridor plus the Greenbank loop. The basic northern corridor crosses Centreville Road on Lancaster Pike; this alternative adds a loop following Greenbank Road that crosses Centreville Road near Price’s Corner.

These five alternatives are shown in Figures 5-7. In these figures, segments to be improved / constructed as part of an alternative are shown in red and purple, while segments shown in green are existing trails and trails expected to be completed soon regardless of the chosen alternative (for example, the final leg of the Industrial Track and Newark’s Delaware Ave. cycle track with logical neighborhood connections).
Figure 5: Central and Far South Alternatives
Figure 6: Northern and Southern Alternatives

Figure 7: Northern Alternative Extended with Greenbank Loop
In the GIS file we have shared with DelDOT, the trail improvements associated with each alternative can be identified using the field AltGrp as follows:

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Explanation</th>
<th>Values of AltGrp Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Existing trails</td>
<td>1</td>
</tr>
<tr>
<td>Base + Improvements</td>
<td>Trails slated for completion soon and therefore included as a part of every alternative</td>
<td>1, 50</td>
</tr>
<tr>
<td>Far South South</td>
<td></td>
<td>1,50, 327, 300, 303, 226, 304</td>
</tr>
<tr>
<td>Central North</td>
<td></td>
<td>1,50, 214, 267, 217, 207, 208, 224, 218</td>
</tr>
<tr>
<td>North + Greenbank Loop</td>
<td>North alternative plus branches that form a loop with extensions reaching Price’s Corner and Elsmere</td>
<td>1,50, 200, 220, 230, 208, 267</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,50, 100, 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,50, 100, 150, 110, 120, 140, 125,130</td>
</tr>
</tbody>
</table>

For the most part, the alternatives developed use segments identified in the Trail Study. However, they also include some segments that we propose where we identified connections that were more direct and seemed feasible, including:

- A route through Middle Run Valley State Park that follows existing mountain bike trails. A field visit suggests that this alignment has slopes that could be negotiated by the general public and could be widened enough to accommodate two-way travel. In our opinion, such a trail alignment need not be paved with asphalt; a stabilized but natural surface treatment that resists rutting during wet periods should be sufficient.

- To connect Newark to the western side of Middle Run Valley State Park, we propose a route that uses local streets plus a short trail connector that would have to be added between W Chapel Hill Dr and Nightingale Circle (where a public right of way appears to exist).

- At the eastern side of Middle Run Valley State Park, we propose reaching Polly Drummond Hill Road following the driveway of Pike Creek Bible Church, a more direct route than the looping Snow Goose Trail. The proposed trail could either share the church’s driveway (with permission) or develop a parallel path just outside its property line.

- A path along the southern border of Goldey-Beacom College in place of the circuitous route around its northern border. This southern route would probably require cooperation from the college, but it might be possible to secure that cooperation considering how much the trail project would improve access to the college, making it better accessible to students without a car. Higher education institutions like that often have to negotiate with local or state government regarding facility improvements, and cooperating on a trail alignment like this might play a role in such negotiations.

- For the central corridor, a new alignment is proposed between Newport and Old Churchmans’ Road. From Newport, it closely parallels the Northeast Corridor tracks to the north using local streets to water company property (thus requiring its cooperation). It crosses the Christiana
River near the water company plant (requiring a new footbridge) and then follows an existing dirt road to the Stanton Christiana Road, an old Route 7 alignment that has an underpass under the Northeast Corridor tracks, yet has nearly no traffic because it’s been dead-ended. The proposed alignment uses that underpass to switch to the south side of the Northeast Corridor tracks, then parallels the tracks to take advantage of their underpass under Route 7. Using that underpass may or may not require Amtrak’s cooperation – it seems that the underpass is wide enough that a path along its southern boundary would be well removed from Amtrak property, but we have not confirmed this. After crossing Route 7, the alignment turns south parallel to Route 7 for a short distance and then turns onto Ogletown Stanton Road, the former alignment of Route 4 that has now been dead-ended and therefore has very little traffic. Compared to the alignment identified in the Trail Study that runs along the northern edge of the Delaware Turnpike, this newly proposed alignment is more direct, requires far less new trail, involves less wetland encroachment, and gives trail users a delay-free and danger-free crossing of Route 7. However, it requires a footbridge over the Christiana River and the cooperation of the water company and, possibly, Amtrak.

The Trail Study also identified a far-far-south corridor that goes south from Newark to Glasgow and then east to New Castle. That corridor was not considered in this study because it involves too much out-of-line travel to be considered a Newark-to-Wilmington route option for utilitarian travel. That is not to pass judgement on whether this corridor should be implemented; but it should be evaluated for what it is, a combination of a Newark-Glasgow trail and a Glasgow-New Castle trail.

Features Added to the GIS File
For the most part, the features (that is, links) used in our alternatives are a subset of those identified in the Trail Study and part of its GIS file. Features that we added can be identified as those for which the field “NU Comment” (a field we added) is not empty. Standard terms used in this comment field are:

- “Street” = it’s a street section that will either get a sidepath (if it is a through street) or is suitable for mixed traffic (if it’s a local street)
- “added” = off-road section we propose
- “bridge” is mentioned wherever a bridge is known to be needed
- “single track” = an existing section of single track trail that we propose upgrading

Approaches to Downtown Wilmington
The Trail Study identified only two approaches downtown Wilmington, one along Brandywine Creek, which we use for our northern alternative and one along the Industrial Track which our other alternatives follow. Like the Trail Study, we were unable to identify a viable central approach into Wilmington from Elsmere.

Emphasizing Directness
A strict requirement of a trail route is that every segment be either traffic-free or has have very low traffic stress (LTS 1), which can be achieved by either following quiet, local streets or by using sidepaths along busier streets. Beyond that basic requirement, they aim try balance the competing aims of directness and offering users a beautiful natural environment. Utilitarian travel accords far greater importance to directness, and therefore our alternatives – developed with connectivity in mind – include several alignments that are more direct than those found in the Trail Study, They include:
• The central alternative alignment described earlier from Newport to Old Churchman’s Road
• The alignment around the southern edge of Goldey-Beacom College described earlier
• The alignment through Middle Run Valley Park described earlier, which is far less roundabout than an alignment that departs Newark going due north for about 3 miles in White Clay State Park before turning east.
• In Newark, a direct extension of the Delaware Avenue protected lanes east of Library Avenue through the College Square development to Marrows Road instead of the circuitous alignment in the Trail Study.

Street-Trail Connections and Minor Branches
GIS files that were not developed with bicycle connectivity in mind are likely to lack short links representing connections between an off-road trail and the street network. We carefully checked all of the off-road alignments in our alternatives and added connecting features where maps indicate that they exist.

In addition, wherever maps indicated that a short branch path could be built to connect to neighborhoods or important destinations, we added features and included them in our alternatives. Wherever a small incremental investment can increase a route’s value by connecting more homes and destinations, including it as part of the alternative is consistent with maintaining a cost-benefit balance. The more populated the area connected with either homes or destinations, the longer and more costly a branch path is justified. Examples of branches included in the alternatives were:

• Where the northern alternative follows New Linden Road, we propose a 600 ft branch path along the side of Skyline Drive from New Linden Road to the entrance to Carousel Park. From that entrance, existing paths lead to important destinations including the New Castle County offices and John Dickinson High School.
• Where the northern alternative follows Lancaster Pike, we included a branch loop to Red Clay Drive in order to connect to the campus of Agilent. (Private funding might pay for a short loop like this.)
• The central alternative includes a branch along Churchman’s Road to connect to New Castle County Community College. Most of this branch uses an existing sidepath; the only investment needed is widening 650 ft of sidewalk around where Churchman’s passes under Route 7.
• Both the southern and far-south alternatives include short branches connecting the nearby Christiana Mall.

Major Branches
Branches that involve considerable additional investment should be analyzed as distinct alternatives. To illustrate, our analysis includes both a basic northern alternative and a northern alternative extended by adding an alignment we call the Greenbank loop. Between Newport Gap Pike @ Hercules Rd and Centre Road @ Lancaster Pike, the basic northern alternative follows the most direct route, which follows Hercules Rd and Lancaster Pike. The Greenbank loop adds a second route between those points, following Newport Gap Pike to Greenbank Road, then across a small creek to Alberton Park and through the neighborhood to Centre Road where it crosses Little Mill Creek and then continues to Lancaster Pike.
The Greenbank Loop also includes two minor branches that enhance its connectivity value at little incremental cost. One is the Willow Run Trail connecting Centre Road to the V.A. Hospital and to existing trails in Elsmere. The other is a Price’s Corner branch that follows Greenbank Road to Price’s Corner, crosses underneath Route 2 along Centerville Road, and then runs along the edge of the Walmart property to connect to the neighborhood at Washington Avenue.
6. Origin and Destination Data

The heart of numerical connectivity analysis is determining the degree to which origins and destinations are connected with low-stress routes, subject to acceptability limits on distance and detour. In principle, any type of origin or destination can be considered. For this study, origins are homes based on Census block data, and destinations are jobs based on the Census Bureau’s Longitudinal Employer-Household Dynamics (LEHD) data. The distribution of population and jobs in the study area, which is New Castle County north of the Chesapeake & Delaware Canal, is shown in Figure 8.

![Map showing population and employment distribution]

**Figure 8. Population and Employment Distribution in New Castle County North of the C&D Canal**

Census blocks were used for origins. Census blocks are polygons that usually outline areas bounded by, but uncut by, streets and physical barriers such as rivers and railroads. In a city, a census block is typically exactly what we think of as a “block” — land bounded on four sides by a street. Outside of cities, blocks can be rather large.
LEHD employment data ("jobs") is also given at the census block level. This database, which draws on tax withholding data that all employers provide to the IRS, has the advantage of being readily available across the US. Jobs were assigned to the node nearest to the polygon centroid. For very large blocks in undeveloped areas, which often have a single large employer, manual editing was done to ensure that a block’s jobs were assigned to a node on the side of the block with an entrance to the employment site.

The LEHD database has weaknesses that make it a less than ideal source of data on job location. Because businesses having multiple sites such as chain retailers often use a state-level headquarters address rather than the actual work location, number of employees can be artificially high at blocks that have headquarters locations and low at blocks that have branch locations. Examples of likely, significant distortions in the case study data include:

- The Bank of America headquarters in northern Newark has, according to LEHD data, far more employees than would be indicated by the building size or the parking lot size; by the same token, blocks with retail bank locations likely have fewer employees, according to LEHD data, than in reality.
- Christiana Health Care apparently uses only one address for all of its employees, which is its headquarters near Churchman’s Crossing. Thus, the block with that headquarters is attributed more employees than it should, and blocks with its hospitals and clinics are attributed fewer employees than they should have.
- The small number of jobs at the Christiana Mall, according to LEHD data, is probably an artifact of chain retailers using a headquarters location rather than the actual work location in its IRS filings.
- All of the University of Delaware employment is concentrated at one point on the main campus, when in fact employment locations are distributed over a rather wide area in Newark, some of which have better access than other to the bicycling network.
- School employees are probably allocated to school district headquarters rather than to school itself.

In many other respects, however, the LEHD data appears to reflect reality well. For example, along much of Route 2 there are a large number of shops in that are not chains, and the data in fact shows employment all along the route. The data also show a high concentration of employment in downtown Wilmington, as expected.

DelDOT has another ongoing project developing a more reliable data source on job locations. When ready, it can be readily substituted to become the source of destination data.

Converting Polygon Data to Point Data
To connect census blocks to the road and trail network, the population and employment of a block are distributed equally over the "true intersections" along the border of that block. A "true intersection" is a node with degree 3 or more, that is, a node touched by at least 3 links. Thus, for a typical rectangular city block with a node at each corner, one fourth of the block's population and one fourth of its employment are allocated to each of the corners. Cul-de-sacs are usually represented as short links that reach into the interior of a census block, with a single degree node at the interior end and a 3-degree node where the cul-de-sac makes a T-junction with a boundary road.
An example of block-to-node allocation is shown in Figure 9. The nodes and links of the street network are shown as lines and circles, with nodes of degree three or greater as larger circles. (The figure’s background is a visual map.) One can see that the highlighted block has 6 nodes with degree three or greater lying within it or within 20 m of its boundaries. Therefore, one sixth of this block’s population and employment will be allocated to each of those nodes.

Figure 9: The population and employment of a block is allocated to the nodes in the street-trail network with degree 3 or greater enclosed within a 20 m buffer of the block.

As a practical matter, this polygon-to-node transformation is accomplished first by importing the road and trail network, excluding only freeways, to NetworkX, a freely available software utility, where it is abstracted as an undirected graph consisting of nodes and links. Next, for each census block, we identify all of the nodes within a 20 m buffer of the polygon. We then discard those whose degree of incidence is less than 3, because curved roadways are sometimes represented by a large number of very short links joined by nodes with degree of incidence of only 2; excluding nodes of degree 2 prevents those curved roadways from being overrepresented. The population of the block is then divided by the number of qualifying nodes, and each node’s share is then added to the population at the node. Note that a given node will typically be allocated population from multiple blocks; in the case of a rectangular grid, a node will be allocated one fourth of the population of each of its four incident blocks.
7. New Developments in Numerical Measures of Connectivity

The Wilmington-Newark alternatives evaluation introduces three innovations to connectivity analysis. One is a propensity function, which smooths the all-or-nothing dichotomy of previous the connectivity analysis done in Mekuria, Furth, and Nixon (2012). The second is expressing connectivity as an equivalent number of bike-accessible jobs. The third is the using a target ideal condition bike share to convert the connectivity measure into a measure of potential bike trips.

Distance and Detour Based Propensity

It is well known that bicycling for utilitarian purposes becomes less attractive as absolute distance increases. It is also recognized that there is also a limit to how far out of their way people will go to use a low-stress route compared to the shortest path that is legal for bicycling. In our seminal report (Mekuria, Furth, and Nixon, 2013), both were dealt with in ways that have abrupt mathematical boundaries. For absolute distance limits, it simply chose an arbitrary limit (e.g., 6 miles) and limited the analysis to trips whose shortest path did not exceed that limit; and to account for detour, it also set an arbitrary limit, with no penalty for trips that deviate by less than 25% from the shortest route and completely excluding paths that deviate more than 25%.

Because Wilmington and Newark are about 14 miles apart, it seemed necessary to develop a more nuanced way to deal with both the distance and detour limits. With large population concentrations at the two ends of the route, a small change in a single arbitrary limit could unduly influence results by changing whether important midway destinations such as Christiana Health Care, Goldey-Beacom College, New Castle County offices, and the Christiana Mall are accessible or inaccessible to those populations. To that end, we developed a propensity model that aims to account for the relative attractiveness of a trip between an origin and a destination as a function of the distance between them, both absolutely and relative to the direct distance between that pair of points (the distance using any road except freeways).

The propensity model is described mathematically in Appendix A. Propensity is a value between 0 and 1 that aims to be proportional to (but not the same as) the probability that a traveler will use a bicycle. A propensity of 1 applies to the most favorable conditions—trip length is under 4 miles and involves less than 33% detour relative to the shortest path. (If the shortest path from origin to destination is less than 3.33 mi, then the critical trip length at which propensity begins to decline is not 4 miles, but rather 1.2 times the shortest path distance.) A propensity of 0 applies if there is no connection at the target level of traffic stress, if the absolute distance exceeds 14 miles, or if then detour exceeds 100%. As distance increases beyond 4 miles or the (shorter) critical distance, propensity declines exponentially, being halved with every additional 3 miles. And as the degree of detour increases beyond 33%, propensity falls linearly, reaching 0 when there is a 100% detour.

A propensity function gives greater value to connecting points that people are likely to bike between than to connecting points that are so distant or involve so much detour that that few people would be willing to make that ride. Thus, results obtained using a propensity function will be roughly proportional to the likely number of bicyclists that will use the network. In addition, the smoothing effect of the propensity function makes results less sensitive to the (necessarily arbitrary) distance and detour boundaries chosen and therefore more reliable.
Equivalent Number of Jobs that Are Bike-Accessible

The raw numerical home-to-work connectivity score for any given network alternative and any given LTS is the sum, summed over every possible OD pair, of the product of three terms:

- The number of jobs at the destination node
- The fraction of the study area population at the origin node
- Propensity of bike travel from the origin to the destination at the specified LTS

Mathematically, this score is a weighted sum of jobs, with each job weighted by (a) the likelihood that the job-holder lives at various origins (with every origin equally likely) and (b) the propensity of using a bike to get to that job from that origin. Therefore, it can be interpreted as the **equivalent number of jobs in the study area that are bike-accessible at a specified LTS**.

The term “equivalent number of jobs that are bike-accessible” deserves further explanation. Suppose, for example, the raw connectivity score is 30,000. This does not mean that there are 30,000 jobs that are bike accessible while the rest of the jobs in the study are inaccessible, because accessibility is a continuous function rather than all-or-nothing. It could, however, mean that there are 60,000 jobs that, on average, are 50% accessible. That is equivalent to there being 30,000 jobs that are (fully) accessible.

Potential Home-to-Work Bike Trips

Because propensity is, by design, proportional to the probability of a person choosing to use a bike, the raw score can be converted into a likely or potential number of work-based bicycling trips by applying a proportionality factor equal to the ratio of probability of choosing bike to propensity. Because propensity under “ideal connectivity conditions” is 1 ("ideal connectivity conditions" means that at LTS 2, trip length is under 4 miles and detour is under 33%), a reasonable way of determining the appropriate ratio is to specify the fraction of people facing ideal connectivity conditions who will choose to ride a bike.

It is difficult to state what that fraction is today, and even harder to project what it will be in the future because the choice of using a bicycle depends heavily on attitudes towards bicycling, which are rapidly changing in society. Given the complications of forecasting bicycle use, a reasonable position for an agency investing in bicycling facilities is to establish a target for the share of cyclists who, facing ideal connectivity conditions, will use a bike for work trips. Until DelDOT establishes such a target, a reasonable value to use is 20%.

Multiplying the equivalent number of bike-accessible jobs at LTS 2 by this parameter then yields the number of potential bike trips:

\[
\text{Potential bike trips} = (\text{equivalent number of bike-accessible jobs at LTS 2}) \times (\text{target bike share under ideal connectivity})
\]

The rationale behind this formula is that if the target bike share under ideal connectivity is 0.2, then each bike-accessible job with good connectivity can be considered 0.2 potential bicycle trips.
8. Results for Newark-Wilmington Trail Alternatives

Equivalent Number of Accessible Jobs by LTS

Figure 11 and Table 7 show the first measure of network connectivity for the different trail alternatives, the equivalent number of bike-accessible jobs for each level of traffic stress. “Base” is the existing network, and “Base + improvements” adds improvements common to every alternative as described earlier, which include the final leg of the Industrial Track and Newark’s Delaware Ave. cycle track.

First, it is instructive to see how, for any alternative, equivalent number of accessible jobs declines sharply as the LTS cutoff becomes lower. Consider the “Base + improvements” alternative.

- Of the 271,000 jobs in the study area, the equivalent of 122,700 are bike-accessible at LTS 4. This dropoff is not for lack of network connectivity (because at LTS 4 all roads except limited access highways are usable) but rather because the long distance between many home and work locations results in a low propensity for using a bike. For example, if a home location and job location are 7 miles apart, the job is only “half” accessible from that home, and if they are 10 miles apart, only 25% accessible from that home. The sum of 122,700
- The equivalent of 32,800 are bike-accessible at LTS 3. This drop from LTS 4, a drop of nearly 75%, shows that there are many connections that simply cannot be made without resorting to riding on LTS 4 roads, something that few people are willing to do.
- The equivalent of 6,545 are bike accessible at LTS 2, which is only 5.3% of the number accessible at LTS 4. This shows how sparse and disconnected the LTS 2 network is.
- The equivalent of 1,340 are bike accessible at LTS 1, indicating the even greater sparsity and disconnectedness of the LTS 1 network.

Figure 11: Number of Equivalent Bike-Accessible Jobs for LTS 1-3 for each Trail Alternative.
Table 7: Number of Equivalent Bike-Accessible Jobs by Level of Traffic Stress and Potential Work Trips for each Trail Alternative

<table>
<thead>
<tr>
<th></th>
<th>LTS 1</th>
<th>LTS 2</th>
<th>LTS 3</th>
<th>LTS 4</th>
<th>Potential Work Trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Network</td>
<td>909</td>
<td>4,379</td>
<td>25,777</td>
<td>121,950</td>
<td>876</td>
</tr>
<tr>
<td>Base + Improvements</td>
<td>1,338</td>
<td>6,545</td>
<td>32,800</td>
<td>122,684</td>
<td>1,309</td>
</tr>
<tr>
<td>Far South</td>
<td>1,811</td>
<td>7,881</td>
<td>35,445</td>
<td>122,844</td>
<td>1,576</td>
</tr>
<tr>
<td>South</td>
<td>1,373</td>
<td>7,585</td>
<td>36,614</td>
<td>122,901</td>
<td>1,517</td>
</tr>
<tr>
<td>Central</td>
<td>1,540</td>
<td>8,206</td>
<td>37,638</td>
<td>123,027</td>
<td>1,641</td>
</tr>
<tr>
<td>North</td>
<td>1,525</td>
<td>7,447</td>
<td>36,378</td>
<td>122,786</td>
<td>1,489</td>
</tr>
<tr>
<td>North + Greenbank Loop</td>
<td>1,797</td>
<td>7,763</td>
<td>36,800</td>
<td>122,802</td>
<td>1,553</td>
</tr>
</tbody>
</table>

The same pattern of sharply declining connectivity as LTS is lowered applies to all of the alternatives.

Looking then at the five improvement alternatives, one can see that:

a) They all offer substantial increases in connectivity at all levels of traffic stress compared to “Base + improvements”

b) The Central Alternative creates greater connectivity than the other alternatives at every LTS except LTS 1, for which the Far South and North + Greenbank Loop alternatives show the most improvement.

Potential Bike-to-Work Trips

Table 7 also shows the number of potential bike-to-work trips for the different alternatives using a target bike share under ideal connectivity conditions of 20%. One can see how much this performance measure improves when the basic set of improvements is added to the network (including completion of the Industrial Track and Newark’s Delaware Ave. protected bike lanes), increasing from 876 to 1,309, and then how much more it improves with any of the trail alternatives. From this table, one can conclude that any of the trail alternatives would substantially increase bike-to-work connectivity in New Castle County.

To better compare the trail alternatives with other, it is helpful to examine the number of potential bike-to-work trips they add relative to “Base + Improvements” (Figure 12). The Central alternative clearly offers the greatest improvement – an addition of 332 potential home-to-work trips, which is a 25% improvement compared with the “Base + Improvements” scenario. The Far South alternative is a clear the second best.
Figure 12: Potential Home-to-Work Bike Trips Added by Different Trail Alternatives, Assuming that Ideal Connectivity Bike Share = 20%

The superior performance of the Central alternative can be attributed to its directness and to its connecting important mid-corridor job centers such as Christiana Health Care and NCC Community College. The worst performing alternative is North, which is considerably less direct and passes through an area with lower population and job density. The Far South alternative performs considerably better than the South alternative, even though it connects Newark to Wilmington less directly. One possible explanation is that the Far South alternative gets a lot of benefit from extending the Newark network of low-stress routes, already relatively extensive, south to Glasgow; this segment of the route deserves to be explored on its own if the full Far South alternative is not chosen. Another possible explanation is that the South alternative, by staying close to the Delaware Turnpike, passes through areas with low population and job density.

Adding the Greenbank Loop to the North alternative, with extensions to Price’s Corner, the Wilmington VA Hospital, and Elsmere, increases its incremental number of potential work trips by 33%. This shows the benefit of supplementing a basic alignment with branches that extend it to nearby population and job centers. However, even with the Greenbank loop added, the North alternative still performs worse than Central and Far South. This is probably because its access into downtown Wilmington along the Brandywine River is relatively indirect.

Conclusion and Comments on the Wilmington – Newark Trail Alternatives Analysis
This section demonstrates the feasibility of using low-stress connectivity as a measure for evaluating alternatives. The methodological advances of this project that allow connectivity to be translated into a predicted number of bicycle trips make it even more powerful, although users should be aware that such predictions are rough and are based on an arbitrarily selected target bike share for ideal connectivity.
This study also demonstrated how an alternatives analysis changes when connectivity becomes an important metric on which alternatives are to be evaluated. The alternatives must then be formulated in a way that aims at that connectivity target. For this study, that principle meant:

- Trying to make alignments as direct as possible, knowing that effective connectivity falls as the travel distance and detour between two points increases. For this study, several new segments were proposed for the north and central alignments to make them more direct.
- Adding low-cost branches that connect to nearby neighborhoods, employment sites, and trails. Branches that add connectivity at low incremental cost should be made part of any trail project whenever possible, and even if it isn't possible to make them part of a project as it is formally constructed, branches that are likely to be added later as separate projects should still be included in the alternatives analysis. For this study, several such branches were added such as branches connecting to the Christiana Mall for trail alternative passing close to the mall.
- Adding longer distance, higher cost branches should also be considered because they can leverage the main alignment by adding considerable connectivity at relatively little cost. This study demonstrated that principle in considering the addition of a loop branch to the northern alternative that increased the alternative's connectivity contribution by 33%.

This study also demonstrates the value of using of local streets as part of a trail alignment. Before, standard practice in trail design required that trails be physically separated from all motor vehicle traffic. In this study, the criterion used is that the alignment has to have low traffic stress, a requirement that can be met using low-speed, low-volume local streets. That creates the possibility for alignments that are both less expensive and more direct. One such example is in our northern alternative between Newark and Middle Run part; another is in our central alternative, heading west from Newport along streets that parallel the Northeast Corridor tracks.

This study did not focus on improvements within the city of Wilmington. It is likely that low-cost treatments in downtown Wilmington could extend the low-stress network through its business district, strongly improving connectivity for all of the alternatives. Strong benefits for both commuting and recreation would also follow from creating a low-stress alignment connecting the Brandywine River and Industrial Track trails through the downtown.

In creating alternatives with a connectivity target in mind, the largest gap that appeared to us was the lack of low-stress route between Elsmere and downtown Wilmington. DelDOT should examine the feasibility of creating such a route, which would probably require a combination of treatments including road diets, protected bike lanes, and bike boulevard treatments (i.e., traffic diversions, contraflow, and speed control to make local streets suitable for through bicycling).

Among the alternatives examined, the Central alternative was clearly superior in terms of connectivity. It is the most direct (i.e., shortest) and it passes through some zones of concentrated population and employment between Wilmington and Newark. A newly proposed alignment for a section of this path between Newport and Route 7 – just north of the Northeast Corridor tracks instead of along the Turnpike – contributes to this better performance by increasing directness. It also offers users a more pleasant environment for bicycling.

Funding limitations may lead DelDOT to consider prioritizing segments within an alignment. While this study did not formally calculate the incremental connectivity gains of individual segments, the principles
behind connectivity suggest that the most valuable segments to improve are those that extend an existing low-stress route and connect to areas of high population or employment concentration. That means that the greatest gains are likely to come from trail segments close to Wilmington and close to Newark, as well as to improvements within Wilmington that extend the reach of these trails. It is our opinion that the greatest connectivity gains would come from the following:

1. The path along the Christiana River from the Industrial Track to Newport (part of the Central alignment). This path would directly extend the Industrial Track trail into an area of concentrated population. It would also be highly valued for recreational use.
2. A path from the University of Delaware to the Delaware Technical Community College, following the Central alignment with a branch along Churchman’s Road to the community college. In Newark, the Delaware Avenue cycle track and Pomeroy Trail already provide a backbone for collection / distribution, and there would be a lot of incremental value in extending that network toward the high employment zone near Churchman’s Crossing and the community college.
3. Creating low-stress routes through downtown Wilmington that extend the reach of the Brandywine River and Industrial Track trails to important downtown destinations and, if possible, connecting the two trails.
4. Creating a low-stress route from Elsmere to downtown Wilmington, if a feasible alignment can be found.

Software Tools Provided to DelDOT

A goal of this project from the outset was to give DelDOT the capability of doing low-stress connectivity analysis so that DelDOT can use it routinely in the future to evaluate proposed improvements. This section describes the software tools that we have provided and left for DelDOT to use.

This software remains the property of Northeastern University. DelDOT is granted permission to use this software directly. Consultants, advocates, and other branches of Delaware government are also granted permission to use it on projects for DelDOT or any other branch of Delaware government. Further distribution of this software is not permitted.
9. Conclusion

Case studies done in New Castle County have demonstrated the feasibility of doing Level of Traffic Stress and low-stress connectivity analysis as a means of evaluating the existing bicycling network and for evaluating improvement projects.

Maps of low-stress connectivity make gaps in the low-stress network apparent and point out where critical investments are need to bridge virtual gaps. This has been demonstrated in both an urban and a rural context.

Numerical connectivity analysis has been shown to be feasible for evaluating both an existing network and future scenarios, making it a potential tool for evaluating alternatives. In this project, we have demonstrated how raw connectivity scores can be reduced to more easily understood quantities — an equivalent number of accessible jobs, and the potential number of home-to-work trips.

In terms of methods, this project has developed several innovations. They are:

- A refined set of LTS criteria that can be used when ADT data is available, as is the case for most Delaware non-local roads.
- A propensity model that accounts for the effect that increasing trip length and detour have on a person’s propensity to use a bike. This model is a substantial improvement compared to all-or-nothing methods that had been used previously, and is particularly valuable in a case study area that extends beyond a single city.
- Two new measures of network connectivity, which are the equivalent number of bike-accessible jobs and the number of potential home-to-work bike trips.

The methods used for doing level of traffic stress classification and connectivity analysis have been automated and software tools delivered to DelDOT that gives them the capability of LTS and connectivity analysis in the future. Those software tools remain the property of Northeastern University, but may be used on projects for DelDOT and other branches of Delaware government.

Regarding data sources, this project’s case studies have shown that DelDOT’s data resources make it possible to calculate level of traffic stress on its roadways and do connectivity analysis. However, we have also pointed out numerous deficiencies in that data that need attention for LTS and connectivity analysis to be accurate. As automatically gathered data on road markings, signs, and pavement width becomes available, data availability and quality will further increase. This study, for example, did not account for the stress associated with turning lanes because data on turn lanes was not available; in the not too distant future, DelDOT will be able to add that facility to its LTS tool. However, some manual editing and data cleaning is still needed.

The quality of Census Bureau LEHD data as a source of job location data leaves something to be desired. By locating jobs at the mailing address of companies that file tax information, jobs located at a company’s branch locations are often attributed to its headquarters location, resulting in overstating jobs at company headquarters and understating jobs at malls and commercial areas with retail branches. DelDOT would do well to seek a better source of job location data. An ongoing project being conducted by the University of Delaware for DelDOT may soon offer a better source of job location data,
While the connectivity analysis done in this project looked only at home-to-work connectivity, home-to-work trips DelDOT could explore connectivity analysis to specialized destinations, including schools, public facilities (libraries, swimming pools), shopping locations, and major recreational areas.
A Model for Bicycling Propensity Accounting for Distance and Detour

Peter Furth

12/18/15

Time Substitution and the Utility / Disutility of Exercise and Exposure

Bicycling involves not only a time cost like other modes of travel, but also physical effort and exposure to outdoors. These latter two factors involve some disutility – you have to exert yourself, and you might become cold / hot / wet – but they also confer benefits. Humans need physical exercise to stay healthy; however, there is a time / distance limit at which one’s need for daily exercise is satisfied and beyond which the exercise benefit become overshadowed by the disutility of continued exertion. Humans also benefit from spending time outdoors; it is pleasurable, sometimes even exhilarating, and it contributes to psychological health. Again, however, there is a time limit beyond which the benefits to being outdoors begin to diminish and become overshadowed by the disutility of exposure.

In addition, time spent bicycling substitutes, at least in part, for time that would have been spent traveling by another mode, usually driving or transit. To the extent that time is substituted, the net disutility of time spent bicycling can be heavily discounted. If my 4-mile commute takes 22 minutes by bike and is substituting for a 15 minute commute in a car, I am consuming only 7 minutes net to get 22 minutes of exercise and fresh air. That’s quite a bargain!

The distance limit within which the disutility of riding additional mile is strongly negated by the benefits of riding are governed by three factors:

- A time / distance limit at which additional exercise ceases to be considered beneficial. A reasonable limit is 4 miles, corresponding to 22 minutes of exercise (a bike speed of 11 mph is assumed). This figure corresponds well with health recommendations to get at least 30 minutes of exercise per day, recognizing that many people perceive benefits continuing to 45 or 60 minutes of exercise.

- A time / distance limit at which the positive aspects of exposure to the outdoors no longer outweigh the negative aspects. This limit varies a lot from person to person and varies a lot with the weather. Again, 4 miles (22 minutes’ travel at an average pace) is a plausible value.

- A time / distance limit at which people don’t consider additional travel time as a substitution for travel by another mode but rather a penalty from being forced to use a circuitous route. Following a low-traffic-stress route can require cyclists to follow a circuitous route. Detour factor
is the ratio of the length of the low-stress route to \( L_{mhh} \), the minimum trip length using roads of any level of traffic stress other than limited access roads on which bicycling is not permitted. Cyclists are readily willing to accept a small level of detour, up to a detour factor of roughly 1.2, in order to enjoy a less stressful route. Additional travel distance beyond that limit is not considered as a substitute for travel by an alternative mode, but rather as the penalty that a person imposes on themselves for wanting a low-stress route. Therefore, the time cost involved in travel beyond this detour limit carries significantly greater disutility.

Combining the limits described here, we propose that the propensity to ride a bike begins to diminish at 4 miles or 1.2 times the minimum bike distance (that is, 1.2 \( L_{mhh} \)), whichever is shorter.

To model the decline of propensity with distance beyond this limit, we propose an exponential decay function, commonly used in travel demand modeling, with propensity halving every 3 miles. This means, for example, that compared to people with a direct, low-stress bike route to destinations 4 miles away, those with direct, low-stress routes to destinations 7 miles away are half as likely to use a bike, and those 10 miles away are one quarter as likely. The corresponding parameter for the exponential model is \( \alpha = \ln(0.5)/3 = 0.231 \).

A Second Detour Effect

Detour or circuitry has a second effect on demand besides the extra distance involved. Humans are shortest-path seekers, with an innate psychological resistance to paths involving a lot of detour. Often, people won’t look for a route that involves what to them is an abnormal level of detour, and therefore won’t be aware of such routes. Even if they become aware of a circuitous low-stress route to reach their destination, emotionally, many will discount the existence of such an alternative if the detour factor is too large.

We propose for detour factors between 1.333 and 2.0, the fraction of people who will consider a potential route declines linearly from 1 to 0, and that everybody will reject a route whose detour factor exceeds 2.

Proposed propensity model

The proposed model has five externally specified parameters:

- \( L_{crit} = 4 \text{ mi} = \text{Critical distance after which additional distance lowers propensity} \)
- \( \alpha = 0.231 = \text{exponential delay parameter corresponding to 3 miles as the additional distance for which propensity to bike is halved} \)
- \( d_{norm} = 1.2 = \text{normal detour factor below which bicycling time is considered to substitute for travel time by an alternative mode} \)
- \( d_{low} = 1.333 = \text{lower limit at which detour is considered excessive} \)
- \( d_{hi} = 2.0 = \text{upper limit at which detour is considered excessive} \)

The propensity formula for four ranges of trip length are:

\[
\text{if } L \leq L_{1}, \quad p = 1
\]
if $L_1 \leq L \leq L_2$, \hspace{1cm} p = e^{-\alpha(L-L_1)}$

if $L_2 \leq L \leq L_3$, \hspace{1cm} p = e^{-\alpha(L-L_2)} \frac{L_3 - L}{L_3 - L_2}$

if $L > L_3$, \hspace{1cm} p = 0$

where

$L = \text{trip length}$

$L_1 = \min(L_{\text{cri}}, L_{\text{min}} \ast d_{\text{norm}})$

$L_2 = L_{\text{min}} \ast d_{\text{low}}$

$L_3 = L_{\text{min}} \ast d_{\text{hi}}$

This model is plotted here for different values of $L_{\text{min}}$. The dotted line is a the simple propensity model $\exp(-\alpha(L-4))$, capped at 1.

Hills and Walking Distance

Hills can be accounted for in this model by replacing trip length $L$ with an effective trip length in which the length of steeply sloped segments is scaled upward. We do not propose to add this feature for analyzing bike networks in Delaware because hills there play a minor role, and because adding this feature would require integrating a data source that includes elevation.
At very short distances, people will prefer to walk than ride a bike. While this could be accounted for by lowering bicycling propensity for very short trip lengths, we propose instead to account for it by defining a cycling distance range with a lower limit around 0.5 miles and upper limit around 12 miles and, for any given origin, limiting destinations under consideration to those for which $L_{mtb}$ lies in that range.
ATTACHMENT G3

LEVEL OF SERVICE COMPARISON
LOS – No Build Scenario – AM
LOS – Interim Hybrid Scenario – AM
LOS – Long Term Hybrid Scenario – AM
LOS – Long Term Hybrid Scenario – AM Hays Interchange
LOS – Long Term Hybrid Scenario – AM Greenfield Intersection
LOS – No Build Scenario – PM
LOS – Interim Hybrid Scenario – PM
LOS – Long Term Hybrid Scenario – PM
LOS – Long Term Hybrid Scenario – PM Hays Interchange
LOS – Long Term Hybrid Scenario – PM Greenfield Intersection