PRELIMINARY EVIDENCE OF COMPLETE STREETS EFFECTS ON BUS OPERATIONS USING AUTOMATED DATA SOURCES

Abubakr Ziedan, Corresponding Author
Graduate Research Assistant
Civil & Environmental Engineering
University of Tennessee
311 John D. Tickle Bldg.
851 Neyland Drive
Knoxville, TN 37996-2313
Tel: 423-364-9229; Email: aziedan@utk.edu

Candace Brakewood, PhD
Assistant Professor of Civil & Environmental Engineering
University of Tennessee
320 John D. Tickle Bldg.
851 Neyland Drive
Knoxville, TN 37996-2313
Tel: 865-974-7706; Email: cbrakewo@utk.edu

Philip Pugliese, MBA
Chattanooga Area Regional Transportation Authority
1617 Wilcox Blvd, Chattanooga, TN 37406
Tel: 423-424-1348; Email: philippugliese@gocarta.org

Word count: 4,852 words text + 4 tables x 250 words (each) = 5,852 words

November 8, 2018
More than 1400 complete streets policies have been adopted in the period from 2004 to 2018 nationwide. This proliferation of complete streets policies across the United States has contributed to roadway redesigns and the introduction of bicycle infrastructure to enhance multimodal accessibility. These redesigns often result in a reduction of travel lanes that may affect both motorists and transit operators. This study explored the effects of a complete streets implementation on bus operations using Automated Vehicle Location (AVL) data. A single bus route and corridor in Chattanooga, Tennessee was examined as a case study to assess potential changes in bus speed and reliability following a roadway redesign, road diet, and the introduction of bicycle lanes. This investigation analyzed three periods to perform a comparative analysis between pre- and post-implementation to assess the impact of roadway design changes on bus mean speed and reliability. The findings demonstrate that bus speed was affected significantly in segments where the road design speed or road capacity was reduced, but this impact is limited to the PM peak period only when there was more traffic. The implementation of the complete streets design elements did not significantly affect bus reliability. The results suggest that in areas without significant congestion, complete streets implementation may not have a significant impact on transit operations. As cities continue to implement design features associated with complete streets policies, it will be important to consider the effects of these road changes on bus operations in the long term.

Keywords: Complete Streets, Bus Operations, Automatic Vehicle Location Data
INTRODUCTION

The complete streets movement over the past two decades has been accompanied by a shift in design focus to balance the needs of all roadway users. Today, more than 1400 complete streets policies have been adopted nationwide (1). The National Complete Streets Collation defines complete streets as “streets for everyone, designed and operated to enable safe access for all users, including pedestrians, bicyclists, motorists and transit riders of all ages and abilities” (2). As streets are designed to accommodate the needs of all road users, the main features of a complete street may include wider and better sidewalks, pedestrian refuge islands, bike lanes, transit lanes, center turn lanes and landscaping (3).

The increased number of adopted complete streets policies nationwide is pushing infrastructure changes and shifting the way that planners and engineers are looking at public right-of-way. Prior to the development of the complete streets concept, the priority was often automobile traffic, but now the priority is shifting toward non-motorized modes, including pedestrians and bicycles (3). Although complete streets projects attempt to improve accessibility for different modes of transportation, there is no single design for complete streets (2). Complete streets projects use different designs that can include all or some of the mentioned above features. These different complete streets designs such as road diets often include dedicated bike lanes.

Growth in bike ridership nationwide has resulted in more pressure on cities to provide safer and more accessible travel options for cyclists and increased demand for bike infrastructure such as protected bike lanes, regular bike lanes, and greenways. This new bike infrastructure may also affect road capacities in some cases, as public right-of-way is limited and the acquisition of wider right-of-way is expensive in most cases. Therefore, the introduction of new bike infrastructure may result in narrower vehicular lanes or fewer travel lanes. This reduced road capacity may affect the speed, volume and safety of the different road user groups including automobile traffic and public transit vehicles.

In light of these trends, this study provides preliminary evidence of the effects of a complete streets implementation on bus operations using automated data sources considering a single bus route in Chattanooga city as a case study. This paper proceeds as follows: first, prior research about complete streets implementation and the effects of road diets presented; the following section provides the objectives of this study; the next section provides background about the case study; data analysis and results follow this section; and the final section is conclusions and future research.

LITERATURE REVIEW

Many studies have evaluated the effects of complete streets policies and road diets on road user’s safety, motorists’ behavior, and traffic operations. The following review highlights key examples and findings of this research.

Smart Growth America (SGA) evaluated 37 complete streets projects nationwide. This evaluation showed that in most cases, there were more walking trips, more bike trips, more transit trips, and fewer vehicular collisions. These findings indicate that complete streets can provide safer streets and increase multimodal travel. However, automobile traffic volumes did not follow a consistent trend as the vehicular flow increased in 13 of these projects and decreased in 19 other projects (4).

Gates et al. (2007) provided an evaluation for the safety and operational effects of road diet conversions in Minnesota using speed and crash data for nine sites in Minnesota. These nine sites had Average Daily Traffic (ADT) ranging from 8,300 to 17,400 vehicles per day. This
study revealed that the number of total crashes was reduced by 44.2 percent for all sites where there was available crash data. This study also found a reduction in the mean speed and 85th percentile speed. However, these reductions were minor, and they were not expected to have a significant impact on traffic operations. It was recommended that center two-way left turn lanes (TWLTL) be used in roads with ADT less than 17,500 and a speed limit less than 40 mph. It is worth noting that this study did not address any impacts of road diets on transit operations (5).

Provence (2009) evaluated the impacts of the 25th Avenue road diet in San Francisco after a year of operation, and this study considered the effects on public transit. This road diet converted 25th Avenue from four lanes to two wide lanes with a two-way central turning lane. The evaluation revealed that the average bus trip length along this corridor was reduced by 6%, and the variation in bus travel times was reduced (6). The buses benefited from using 13’6” wide lane instead of 9 ft. lane and the reduced automobile traffic after the road diet. However, this road diet resulted in 13’6” wide travel lanes, which might not be achievable when introducing bike lanes. Furthermore, this study did not show how this change affected bus on-time performance.

These studies revealed various effects of complete streets and road diets, but there is limited prior research on the impact of complete streets implementation on bus operations. This study aims to begin to fill this gap in the literature.

OBJECTIVES
The objective of this study is to explore the potential effects of complete streets implementation on bus operations using Automatic Vehicle Location (AVL) data. Specifically, this analysis used bus route #4 in Chattanooga, Tennessee as a case study to evaluate the changes in bus speed and reliability along a corridor that was redesigned after the city of Chattanooga adopted a complete streets policy. This complete streets implementation included the introduction of dedicated bike lanes and the reduction in vehicle lanes along some sections of the bus route under study.

BACKGROUND
Chattanooga, Tennessee, is a mid-sized city with an estimated population of 179,139 (7). The city of Chattanooga adopted a complete streets policy by city ordinance in April, 2014 (8). Through this policy, the city of Chattanooga is committed to approach every transportation improvement project with the purpose to create safer, more accessible streets for all users (8). Following adoption of this policy, the city of Chattanooga redesigned two streets:

Brainerd Road and Martin Luther King, Jr. Boulevard (MLK Blvd.). The Annual Average Daily Traffic (AADT) was reported in 2016 as 26,999 and 12,481 vehicles per day for Brainerd Road and MLK Blvd., respectively (9). This redesign recommended implementation of a combination of bike infrastructure that included bike lanes and shared lane striping along Brainerd Road and a road diet on MLK Blvd. The redesign recommended bike infrastructure and pavement resurfacing on Brainerd Road on a segment of 1.87-miles from Seminole Drive to Moore Road associated with 5-MPH reduction in the speed limit in part of this segment. The MLK Blvd. road diet was recommended on a 2.6-mile segment from Georgia Avenue to Dodds Avenue, changing it from four lanes to three lanes with a two-way left turn lane. Bike lanes were also proposed on a segment of MLK Blvd. (Figure 1).

The city of Chattanooga implemented the earlier mentioned bike infrastructure in December 2017 for Brainerd Road and in April 2018 MLK Blvd. However, the segment on MLK Blvd. that was implemented in April 2018 was only one mile from Georgia Avenue to Central Avenue (Figure 1).
The implementation of the proposed bike infrastructure and road diet was expected to affect bus route #4. Bus route #4 connects downtown Chattanooga to Hamilton Place mall, which is the largest shopping mall in the city of Chattanooga. Bus route #4 is the busiest route in the Chattanooga Area Regional Transportation Authority (CARTA) network with a headway of 15-minutes from 05:00:00 until 18:30:00 and 30 minute headways after that on weekdays. The outbound direction of bus route #4 runs from downtown Chattanooga along MLK Blvd., Brainerd Road, Lee Highway and Shallowford Road to the end of the route at Hamilton Place mall. The inbound direction travels along McCallie Avenue towards downtown instead of MLK Blvd. (Figure 1). The previously mentioned bike infrastructure along Brainerd Road affected bus route #4 in both directions (inbound and outbound). For the MLK Blvd road diet, only the outbound direction of bus route #4 was affected.

There are five timepoints in each direction of bus route #4, which are shown in Figure 1. Timepoints are public transit stops along routes for which transit vehicles are scheduled to pass at specific time (10). Transit providers typically measure on-time performance at these locations to evaluate transit system performance. For the outbound direction of bus route #4, the impacted section on MLK Blvd. is located between the 4th & Market timepoint and the Bailey & Willow timepoint, while the Brainerd Road bike infrastructure are located before and after Brainerd & Germantown timepoint (Figure 1). For the inbound direction of bus route #4, the Brainerd Road bike infrastructure is located before and after Brainerd & Germantown timepoint, similar to the outbound direction (Figure 1). This study assesses the impacts of the bike infrastructure and the road diet on bus operations for both directions of bus route #4.
FIGURE 1 Bus route #4 Corridor and Timepoints
DATA ANALYSIS

Public transportation providers have benefited from Intelligent Transportation Systems (ITS) to collect data to evaluate their operational performance and provide real-time information to transit users. Automated Vehicle Location (AVL) is one the most common types of ITS technologies used by transit providers to evaluate operating performance like schedule adherence, headway regularity, service reliability, and bus bunching (11). AVL systems can provide data at the stop level, which offers the opportunity for transit agencies to conduct in-depth investigations of their system and track the effect of different changes. This study used CARTA’s AVL data to evaluate the effects of complete streets implementation on bus operations in Chattanooga.

Period of Analysis

Three periods were selected to perform a comparative analysis. Each of these analysis periods is five consecutive weekdays, as follows:

1. **Before period**: the weekdays 23-Oct to 27-Oct 2017 were selected to represent the base case scenario prior to any changes;
2. **After period 1**: the weekdays 22-Jan to 26-Jan 2018 were selected to represent after the Brainerd Road bike infrastructure implementation;
3. **After period 2**: the weekdays 18-Jun to 22-Jun 2018 were selected to represent after both the Brainerd Road bike infrastructure and MLK Blvd. road diet implementation.

None of the selected days were holidays or major events. In addition, these analysis periods were chosen at least one month after the implementation of each of the changes to allow time for road users to adapt.

Measures

For each of the analysis periods, the following data were extracted from CARTA’s database for bus route #4:

- **On-Time Performance (OTP)**. These data were extracted for both directions, and it shows the number of on-time, early, and late trips by timepoint. CARTA’s database marks an on-time trip if it arrives at the timepoint within the range less than one minute before the scheduled time and no later than five minutes after the scheduled time.
- **Segment running time**. These data were extracted by trip for both directions. This shows the scheduled and actual running time per segment.
- **Timepoint arrival time**. This shows the actual arrival time of a vehicle at each timepoint; it is used to calculate the actual headway.
- **Headway reliability**. This measure shows the percentage of bunched trips, gapped trips, and trips spaced acceptably for each direction. CARTA marks a ‘Gap’ if the actual headway exceeds the scheduled headway and a ‘Bunch’ if the actual headway is less than 90% of the scheduled headway.

Using these data, additional performance measures were calculated. For each of these operational periods, the mean speed per segment was calculated by dividing the segment length by average running time. Percent OTP was calculated as the number of on-time trips divided the total number of trips. The headway coefficient of variation was calculated by dividing the standard deviation of headways by the average headway (12).
After performing these calculations, four measures were selected for comparison between the three analysis periods (before period; after period 1; and after period 2) for four different operational periods (AM peak from 05:00:00 to 08:59:59; midday from 09:00:00 to 14:59:59; PM peak from 15:00:00 to 18:59:59; and evening from 19:00:00 to midnight) for each direction of bus route #4. The four selected performance measures were mean segment speed, percent OTP by timepoint, headway reliability, and headway coefficient of variation. For mean segment speed and OTP by timepoint, T-tests were conducted at a confidence level of 95% to assess the statistical significance between the different analysis periods.

RESULTS
The results of this analysis are divided into two sections. The first section focuses on bus mean speed per segment and how it is affected by the implemented road changes. The second section compares three measures of reliability of bus route #4 before and after the road changes: percent OTP by timepoint, headway reliability, and headway coefficient of variation.

Speed
The mean speed per segment was compared for the three analysis periods (before period; after period 1; after period 2) for the different operational periods (AM peak; midday; PM peak; and evening). There were no statistically significant changes in the AM peak, midday, and evening operational periods (results not shown). However, there were some statistically significant changes for mean speed per segment in PM peak period.

For the outbound direction of bus route #4, there was a statistically significant decrease in the speed in the segment between the Bailey & Willow timepoint and the Brainerd & Germantown timepoint after implementing the Brainerd Road bike infrastructure. This statistically significant decrease is likely due to the reduction of the speed limit by 5 MPH in this segment of Brainerd Road after implementing the Brainerd Road bike infrastructure (Table 1). Along with this noticeable decrease in Bailey & Willow to Brainerd & Germantown segment mean speed, there was a statistically significant increase in the mean speed in the segment between the Brainerd & Walmart timepoint and the Hamilton Place mall timepoint (Table 1). It appears that the operators were trying to “catch up” in the last segment of this route.

After the MLK Blvd. road diet, there was a speed decrease by about 0.7 MPH in bus mean speed in the segment between the Market & 4th timepoint and the Bailey & Willow timepoint (Table 1). The reduction in bus mean speed in this section was a statistically significant decrease. However, similar to Brainerd Road, it seems that bus operators drove faster in the other segments, which was likely to achieve similar levels of on-time performance.

This finding about speed is different from what was reported by a previous study evaluating a road diet in San Francisco; the San Francisco study showed that after a road diet, bus travel times were reduced, which means that speed was increased (6). However, the road diet in San Francisco had buses using 13’6” lanes instead of 9 ft. lanes, which helped to increase the speed. In this case study, the lane width remained 10 ft. before and after the road diet.
### TABLE 1 Outbound Direction Mean Speed Comparison - PM Peak Period

<table>
<thead>
<tr>
<th>Segment</th>
<th>Mean Speed (MPH)</th>
<th>Before Period vs After Period 1</th>
<th>Before</th>
<th>After 1</th>
<th>Difference</th>
<th>Before Period vs After Period 2</th>
<th>Before</th>
<th>After 2</th>
<th>Difference</th>
<th>After Period 1 vs After Period 2</th>
<th>After 1</th>
<th>After 2</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market &amp; 4th to Bailey &amp; Willow (MLK Blvd. road diet)</td>
<td></td>
<td>11.45</td>
<td>11.49</td>
<td>0.04</td>
<td>11.45</td>
<td>10.72</td>
<td>- 0.73**</td>
<td>11.49</td>
<td>10.72</td>
<td>- 0.77**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bailey &amp; Willow to Brainerd &amp; Germantown (Brainerd bike infrastructure)</td>
<td></td>
<td>17.47</td>
<td>15.51</td>
<td>- 1.96**</td>
<td>17.47</td>
<td>16.32</td>
<td>- 1.15</td>
<td>15.51</td>
<td>16.32</td>
<td>0.81</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brainerd &amp; Germantown to Brainerd &amp; Walmart (Brainerd bike infrastructure)</td>
<td></td>
<td>14.30</td>
<td>14.45</td>
<td>0.15</td>
<td>14.30</td>
<td>14.74</td>
<td>0.44</td>
<td>14.45</td>
<td>14.74</td>
<td>0.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brainerd &amp; Walmart to Hamilton Mall (Last segment)</td>
<td></td>
<td>13.35</td>
<td>14.27</td>
<td>0.92**</td>
<td>13.35</td>
<td>14.50</td>
<td>1.15***</td>
<td>14.27</td>
<td>14.50</td>
<td>0.23</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Significance: * p<0.10; ** p<0.05; *** p<0.01

For the inbound direction of bus route #4, there was no clear trend or statistically significant changes for mean speed in the segments with bike infrastructure in the PM peak period (Table 2). The only statistically significant changes were in the last segment, where there was a 0.69 MPH increase in mean speed in Jan-2018 compared to Oct-2017 and a 1.00 MPH decrease in mean speed in Jun-2018 compared to Jan-2018 (Table 2). Speed changes might be because June and October have more extended daylight hours than January, which could affect the traffic patterns in the PM peak period. However, additional investigation for the inbound direction is needed to provide insight into these unanticipated changes, since there were no road changes implemented in this segment.

### TABLE 2 Inbound Direction Mean Speed Comparison- PM Peak Period

<table>
<thead>
<tr>
<th>Segment</th>
<th>Mean Speed (MPH)</th>
<th>Before Period vs After Period 1</th>
<th>Before</th>
<th>After 1</th>
<th>Difference</th>
<th>Before Period vs After Period 2</th>
<th>Before</th>
<th>After 2</th>
<th>Difference</th>
<th>After Period 1 vs After Period 2</th>
<th>After 1</th>
<th>After 2</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamilton Mall to Brainerd-Walmart</td>
<td></td>
<td>14.53</td>
<td>14.76</td>
<td>0.23</td>
<td>14.53</td>
<td>14.52</td>
<td>- 0.01</td>
<td>14.76</td>
<td>14.52</td>
<td>- 0.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brainerd &amp; Walmart to – Brainerd &amp; Germantown (Brainerd bike infrastructure)</td>
<td></td>
<td>15.85</td>
<td>15.48</td>
<td>- 0.37</td>
<td>15.85</td>
<td>16.16</td>
<td>0.31</td>
<td>15.48</td>
<td>16.16</td>
<td>0.68</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brainerd &amp; Germantown to McCallie &amp; Willow Street (Brainerd bike infrastructure)</td>
<td></td>
<td>20.88</td>
<td>20.12</td>
<td>- 0.76</td>
<td>20.88</td>
<td>21.24</td>
<td>0.36</td>
<td>20.12</td>
<td>21.24</td>
<td>1.12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>McCallie &amp; Willow Street to Market &amp; 4th (Last segment)</td>
<td></td>
<td>9.82</td>
<td>10.51</td>
<td>0.69**</td>
<td>9.82</td>
<td>9.51</td>
<td>- 0.31</td>
<td>10.51</td>
<td>9.51</td>
<td>- 1.00**</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Significance: * p<0.10; ** p<0.05; *** p<0.01
Reliability

Three measures were selected to evaluate the effects of complete streets policy implementation on bus reliability: percent OTP by timepoint, headway reliability, and headway coefficient of variation for both directions of bus route #4. The main findings of these three reliability measures are highlighted below.

Timepoints Percent OTP

For the outbound direction, there were no statistically significant changes between the different analysis periods (Table 3). The observed differences were small variations and do not provide any evidence of bus OTP changes associated with the Brainerd Road bike lanes and the MLK Blvd. road diet. Furthermore, the difference in OTP between these analysis periods at the Hamilton Place mall timepoint was always less than 1% (Table 3). This minimal change in the percent of on-time trips at the last timepoint supports the assumption that operators drove in manner such that they would arrive on-time at the last timepoint of the outbound direction of bus route #4.

<table>
<thead>
<tr>
<th>Timepoint</th>
<th>OTP (%)</th>
<th>Before Period vs After Period 1</th>
<th>Before Period vs After Period 2</th>
<th>After Period 1 vs After Period 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market &amp; 4th</td>
<td>81.10</td>
<td>79.44 - 1.66</td>
<td>81.10 76.72 - 4.38</td>
<td>79.44 76.72 - 2.72</td>
</tr>
<tr>
<td>Bailey &amp; Willow</td>
<td>68.15</td>
<td>74.10 5.95</td>
<td>68.15 74.79 6.64</td>
<td>74.10 74.79 0.69</td>
</tr>
<tr>
<td>Brainerd &amp; Germantown</td>
<td>63.87</td>
<td>70.08 6.21</td>
<td>63.87 67.92 4.05</td>
<td>70.08 67.92 - 2.16</td>
</tr>
<tr>
<td>Brainerd &amp; Walmart</td>
<td>80.21</td>
<td>78.72 - 1.49</td>
<td>80.21 72.21 - 8.00</td>
<td>78.72 72.21 - 6.51</td>
</tr>
<tr>
<td>Hamilton Mall</td>
<td>96.49</td>
<td>96.46 - 0.03</td>
<td>96.49 96.64 0.15</td>
<td>96.46 96.64 0.18</td>
</tr>
</tbody>
</table>

Significance: * p<0.10; ** p<0.05; *** p<0.01

For the inbound direction, there was a statistically significant improvement for OTP at the Brainerd & Germantown and McCallie & Willow timepoints between Oct-2017 and Jan-2018. (Table 4). One possible cause for these improvements in OTP could be long-term effects of the road resurfacing associated with Brainerd Road bike infrastructure. However, more analysis periods should be considered to confirm if this improvement is due to long-term effects of resurfacing or if it is due to other factors, since there were no clear trends for the mean speed.

Additionally, there was a statistically significant OTP increase at the Brainerd & Walmart timepoint from Jan-2018 to Jun-2018; however, there were not any road changes implemented in the segment between the Hamilton Place mall timepoint and the Brainerd & Walmart timepoint (Table 4). This unexpected improvement confirms the need for other analysis periods to conduct in-depth investigation for the inbound direction OTP to find out if these changes are related to road resurfacing or not.
### TABLE 4 Inbound Direction Timepoints - On-Time Performance Comparison

<table>
<thead>
<tr>
<th>Timepoint</th>
<th>OTP (%)</th>
<th>Before Period vs After Period 1</th>
<th>Before Period vs After Period 2</th>
<th>After Period 1 vs After Period 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Before</td>
<td>After 1</td>
<td>Difference</td>
</tr>
<tr>
<td>Hamilton Mall</td>
<td>83.23</td>
<td>82.69</td>
<td>- 0.54</td>
<td></td>
</tr>
<tr>
<td>Brainerd &amp; Walmart</td>
<td>86.18</td>
<td>81.90</td>
<td>- 4.28</td>
<td></td>
</tr>
<tr>
<td>Brainerd &amp; Germantown</td>
<td>72.54</td>
<td>75.23</td>
<td>2.69</td>
<td></td>
</tr>
<tr>
<td>McCallie &amp; Willow</td>
<td>67.21</td>
<td>68.95</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td>Market &amp; 4th</td>
<td>78.41</td>
<td>83.18</td>
<td>4.77</td>
<td></td>
</tr>
</tbody>
</table>

*Significance: *p<0.10; **p<0.05; ***p<0.01

**Headway Reliability**

This section considers headway reliability, which is measured as the percent of bunched trips, gapped trips, and acceptably spaced trips for each analysis period.

For the outbound direction, the acceptably spaced trips were 51.86%, 55.43% and 52.79% of the total trips for Oct-2017, Jan-2018 and Jun-2018, respectively (Figure 3). The percentages of bunched trips and gapped trips were also comparable (Figure 3). These comparable percentages show that there was no major impact for these road changes on headway reliability for the outbound direction.

Similar to the outbound direction, the percentage of trips with acceptable spacing were 52.31%, 56.78% and 55.05% for Oct-2017, Jan-2018 and Jun-2018, respectively (Figure 3). These results demonstrate that bike infrastructure on Brainerd Road did not have a noticeable effect on headway reliability for the inbound direction of bus route #4. These outcomes imply that headway reliability is likely not affected by these road changes in the short term.

**FIGURE 2 Bus Route #4 Headway Reliability**
Headway Coefficient of Variation
The last reliability measure used in this study was headway coefficient of variation. Headway coefficient of variation is a commonly used performance measure for high frequency transit service (12). Although the peak period headway is 15 minutes for bus route #4 (which is greater than the typical threshold of headways of 10 minutes or less for high frequency routes), this measure was used to provide additional insight into the level of reliability.

The change in headway coefficient of variation for the outbound direction did not follow a trend for both directions of bus route #4 (results not shown). This confirms that both Brainerd Road bike infrastructure and MLK Blvd. road diet did not have a noticeable effect bunching for both directions.

These three measures of reliability – OTP, headway reliability, and headway coefficient of variation – provide early evidence that bus reliability for this route was not significantly affected by the Brainerd Road bike infrastructure and the MLK Blvd. road diet.

CONCLUSIONS AND FUTURE RESEARCH
As more complete streets policies are adopted nationwide, the demand for multimodal roads is increasing. Providing roadway space for non-motorized modes affects both traffic and transit operations. Although prior studies have evaluated different impacts of complete streets implementation, there are a limited number of studies considering the impacts on transit operations. This study evaluates a single bus route and corridor in Chattanooga, Tennessee as a case study to assess potential changes in bus speed and reliability following a roadway redesign, road diet, and the introduction of bicycle lanes.

This analysis shows that after implementing bike infrastructure on Brainerd Road, the only segment impacted significantly was in the middle of the route. A reduction in bus mean speed in this segment was expected since the speed limit was reduced by 5-MPH after implementing bike infrastructure. Furthermore, after the MLK Blvd. road diet, the bus mean speed in the first segment had a statistically significant decrease of 0.7 MPH in the PM peak period. There was also a statistically significant increase in the mean speed in the last segment, which was likely because bus operators appear to be trying to reach the end of the route on time. These findings suggest that changes in roadway design speed and reductions in travel lanes affect bus speeds.

The second part of the analysis focused on the impacts of complete streets implementation on bus reliability. This part of the analysis shows that although the bus mean speed decreased significantly in the affected segments after implementation of the Brainerd Road bike infrastructure and the MLK Blvd. road diet, on-time performance (OTP) was not significantly affected and the operators were able to attain the similar levels of OTP after these road changes. Assessment of headway reliability showed that bunching percentages were similar before and after analysis periods, indicating that bunching was not affected by the Brainerd Road bike infrastructure or MLK Blvd. road diet in the short term. The change in headway coefficient of variation between these analysis periods did not follow a clear trend, which suggests that headway coefficient of variation was not affected by the bike infrastructure and the road diet. Taken together, these three reliability measures imply that levels of reliability on bus route #4 were not impacted in the short term.

In summary, this study provides preliminary evidence that road diets have limited impact on bus speeds and reliability in the short term. However, it is important to note that the buses considered in this study were operating in areas without high levels of congestion from vehicular traffic and that only a short time period had passed after the implementation of the
infrastructure changes. Future work should investigate the long-term effects of complete streets implementation on bus operations. Specific to Chattanooga, it would be useful to analyze additional time periods in the future to investigate the unpredictable changes in the inbound direction of bus route #4. In addition, similar evaluations should be conducted for different complete streets projects in other regions on roads with different levels of vehicular traffic; this is likely to be a fruitful area for future research in light of the increasing number of complete streets projects throughout the country.

**AUTHOR CONTRIBUTION STATEMENT**

The authors confirm contribution to the paper as follows: study conception and design: A. Ziedan, C. Brakewood, P. Pugliese; data collection: A. Ziedan; analysis and interpretation of results: A. Ziedan, C. Brakewood, P. Pugliese; draft manuscript preparation: A. Ziedan, C. Brakewood, and P. Pugliese. All authors reviewed the results and approved the final version of the manuscript.

**REFERENCES**


