Benefit–Cost Analyses of Rectangular Flashing Beacon Wrong-Way Driving Countermeasures on Toll Road Exit Ramps in Florida

Adrian Sandt¹, Haitham Al-Deek¹, Md Imrul Kayes¹, Patrick Blue¹, and Valentina Gamero¹

Abstract

In recent years, rectangular flashing beacons (RFBs) and other technologies have been used as wrong-way driving (WWD) countermeasures on limited access facilities. Studies have shown that these devices effectively reduce WWD, but no research has compared the financial benefits and costs of these countermeasures. Three different methodologies were used to conduct benefit–cost analyses for RFB WWD countermeasures installed on Central Florida toll road exit ramps. The studied benefits included savings from reductions in WWD crashes, non-crash events, and injuries, whereas costs included equipment, installation, and maintenance costs. For the first two methodologies, the reduction in WWD crash risk (WWCR) at the RFB-equipped ramps was determined. This WWCR considered non-crash WWD events, interchange design, and traffic volumes. Different measures of effectiveness (turn-around percentage of detected wrong-way vehicles at the RFB ramps and reduction in WWD 911 calls and citations at the RFB interchanges compared with similar comparison interchanges without RFBs) were used in these two methodologies to estimate the WWCR reduction and associated savings. For the third methodology, the relationship between WWD crashes and non-crash events was used to determine the average savings for WWD 911 calls and citations. Before–after analyses were then conducted to determine the individual reductions in WWD 911 calls and citations. Applying these three methods resulted in life-cycle benefit–cost ratios ranging from 2.49 to 4.10 (crash savings) and from 4.77 to 7.20 (injury savings). Other agencies could use these methodologies to determine the benefits of WWD countermeasures or other technologies with limited crash data.

Wrong-way driving (WWD) crashes can be severe, especially on limited access facilities owing to their high travel speeds. Reducing these crashes can improve safety and operations as they often result in injuries and fatalities causing extensive lane closures and traveler delays. There are many types of WWD countermeasures available for agencies to implement, including traditional signs and pavement markings, enhanced signs and markings (such as lowered signs or reflective pavement arrows), and intelligent transportation system (ITS) technologies with detection and notification capabilities. Examples of ITS WWD countermeasures include “Wrong Way” signs equipped with rectangular flashing beacons (RFBs) or light-emitting diodes (LEDs), detection devices, and cameras. Previous studies have shown that these technologies are effective at preventing wrong-way drivers from entering the mainline (1–5). However, the lack of WWD crash data makes it difficult to quantify the crash reduction and associated savings provided by these devices.

In this paper, three methodologies are developed that agencies can use to determine the crash and injury savings provided by ITS WWD countermeasures. The main components of these methodologies are a WWD crash risk (WWCR) reduction approach, before–after analyses using a comparison group, and examination of the overlap between WWD crashes and non-crash events (WWD 911 calls and citations). The WWCR reduction approach was originally developed by the authors to determine the optimal deployment locations for ITS WWD countermeasures (6, 7), but it can also be used to estimate the benefits of deployed countermeasures. These methodologies could be applied by any agency worldwide to

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estimate the benefits of these countermeasures and are especially useful when limited crash data are available. Using the calculated savings from these methodologies, benefit–cost ratios can be determined for these countermeasures.

To illustrate these methodologies, they are applied to RFB WWD countermeasures deployed by the Central Florida Expressway Authority (CFX) at toll road exit ramps. Figure 1 shows a typical RFB device installed on the CFX system. When a wrong-way vehicle is detected, the lights above and below the sign flash red. These red RFB WWD countermeasures are currently experimental devices, so they require initial FHWA approval to experiment. Using each of the three developed methodologies, benefit–cost ratios are calculated based on crash and injury savings for the expected lifespan of the devices and the entire implementation period (IP) through April 2019. Before discussing this application of the methodologies, previous research on WWD and benefit–cost analyses of ITS safety and operational improvements is reviewed. The research objectives are then defined and details are provided for all three methodologies. These methodologies are subsequently applied to the CFX RF Bs, with discussion of the significance of the results, how other agencies could utilize these methodologies, and ideas for future research.

Literature Review

Even though potential causes of and solutions to WWD have been studied since the 1950s (9), the quantity of WWD research has increased in the last decade. Two institutions at the forefront of this research are the Texas A&M Transportation Institute (TTI) and the University of Central Florida (UCF). TTI researchers have studied the characteristics of wrong-way drivers and WWD crashes, tested enhanced signage, and evaluated LED WWD countermeasures installed in San Antonio (2–4, 10, 11). This research included a benefit–cost analysis of these LED WWD countermeasures resulting in a benefit–cost ratio of 13.1, however details of this analysis were not found (12). UCF researchers have built models to predict WWD crashes and non-crash events using various roadway characteristics and driver demographics, developed an optimization approach to help agencies effectively deploy WWD countermeasures, surveyed drivers and law enforcement officers about WWD behavior, analyzed the factors that affect law enforcement response time to WWD events, and evaluated LED and RFB WWD countermeasures installed on toll roads in South and Central Florida (1, 5–7, 13–21). However, none of this previous research involved benefit–cost analyses of ITS WWD countermeasures.

In general, economic evaluations of ITS technologies are rare, owing to data limitations and the lack of available methodologies (22). To aid in these evaluations, the United States Department of Transportation published a summary of ITS implementations in 2017, explicitly demarking benefits and costs (23). Noted benefits included improvements in safety, mobility, efficiency, productivity, energy/environment, and customer satisfaction, whereas costs included manufacturing, installation, and consumer costs (23). Benefit–cost analyses have been conducted on some ITS technologies, including ITS-based toll collection, automated speed enforcement, and in-vehicle backup sensors (22, 24, 25). The Highway Safety Manual contains multiple methods to determine the reduction in crashes as a result of applied countermeasures, which can be used to conduct benefit–cost analyses for these countermeasures (24, 26). However, these methods require sufficient crash data, which are not always available. To address cases where crash data are limited, this paper presents multiple methodologies that can be used to conduct benefit–cost analyses on WWD countermeasures. RFB WWD countermeasures are used as an example, but these methodologies can be applied to other types of countermeasures or technologies. No previous research has developed detailed benefit–cost methodologies for these types of devices or applied them to RFB WWD countermeasures.

Objectives

This paper has two main objectives: to show the crash and injury savings of the RFB devices installed on the CFX system and provide multiple methodologies that
agencies can use to estimate these savings for WWD countermeasures when there are limited crash data available. Benefits are calculated using comprehensive crash costs and comprehensive person-injury costs for the life-span of the RFBs and through April 2019. Previous research has shown that WWD crashes have higher fatality rates than other crashes (10, 11, 27–30). Therefore, injury costs could be more representative of the actual impacts of WWD crashes than crash costs. Although RFB devices do provide other benefits, such as reduced law enforcement response time, only the crash and injury savings are considered in this paper. Three different methods are used to estimate these savings. These methods utilize the optimization approach developed in (6, 7), before–after analyses for the RFB sites and similar control sites without RFBs, and the relationship between WWD crash and non-crash events to provide a range of potential benefits.

**Methodologies**

Depending on an agency’s preferences and available data, any or all of the three methods detailed below can be used to determine the crash and injury savings of WWD countermeasures. Method 1 does not require a minimum sample size of WWD events, whereas methods 2 and 3 do require a sufficient sample for the results to be statistically significant. However, Method 2 could be a more accurate representation of countermeasure effectiveness than Method 1, as it considers WWD behavior before the countermeasures were deployed. Method 3 is simpler, but less comprehensive than the other two methods, allowing agencies to more quickly determine benefits.

**Method 1: WWCR Reduction Using Turn-Around Percentage**

WWD crashes are difficult to predict owing to their rarity. Therefore, it is important to consider non-crash events as well as geometric and traffic factors when predicting these crashes. The authors previously developed a WWCR reduction approach consisting of a WWCR segment model and optimization algorithms to identify locations with high WWCR (7). The WWCR segment model predicts WWD crashes in multi-exit roadway segments based on WWD citations and 911 calls, interchange designs, and traffic volumes, whereas the optimization algorithms use the model results to identify individual exits or mainline locations with high WWCR. This approach was applied to the CFX toll road network, showing how it can help agencies identify the optimal deployment locations for WWD countermeasures. For this paper, it was used to estimate WWCR reductions at CFX ramps already equipped with RFBs.

The amount of WWCR reduction depends on the effectiveness of the RFBs. In this method, the percentage of wrong-way drivers who turned around as a result of the RFB countermeasures was used as the measure of effectiveness. This percentage was determined by examining the images of detected wrong-way vehicles to see how many turned around before entering the mainline. The WWCR reduction calculated using this method represents the potential WWD crashes that were prevented as a result of the vehicles turning around. Some of these vehicles could have turned around even if the RFBs were not present (so the actual RFB turn-around percentage might be lower than the value used), but this exact number is unknown owing to the absence of WWD detection devices before the RFBs were installed. To account for WWD behavior before the RFBs were installed, Method 2 can be used.

**Method 2: WWCR Reduction Using Reduction in WWD Events**

For Method 2, the WWCR reduction approach was still used, but the reduction in WWD events (citations and 911 calls) as a result of the RFBs was used as the measure of effectiveness. To determine this reduction, a before–after analysis was conducted on the RFB (treatment) sites and similar control sites. This analysis only considered WWD events where the vehicle entered the mainline to better identify how the RFBs reduced WWCR. Previous research has used various observational before–after studies (simple before–after, comparison group method, empirical Bayes, and Bayesian) to evaluate the effectiveness of different safety countermeasures (31–35). Of these, only the comparison group method uses comparison sites in this evaluation. Researchers have used the comparison group method to evaluate different safety countermeasures for many years (36, 37). This method has also been previously used to conduct before–after analyses on LED and RFB WWD countermeasures (1–5).

The comparison group interchanges were used to determine the expected number of WWD events at the treatment sites if RFBs were not present. These comparison interchanges were in the same region and on the same types of roads as the RFB sites and had similar geometric designs and traffic volumes, but did not have RFBs. WWD event data (911 calls and citations) were collected for the treatment and comparison sites. There was an insufficient number of WWD crashes available for the before–after analyses conducted in this paper, but crash data can be included if enough data are available. Before and after periods of the same lengths are
recommended, but different lengths are acceptable as long as the same periods are used for the treatment and comparison sites. Any months where countermeasures were being installed were not counted in either the before or after periods.

Once the WWD events were collected for the before and after periods, equations 1 to 5 were used to determine the percentage reduction in WWD events at the treatment sites (33). Equation 1 calculates the expected number of WWD events at the treatment sites in the after period if there was no treatment \( N_{\text{estimated}, T, A} \).

\[
N_{\text{estimated}, T, A} = N_{\text{observed}, T, B} \times \left( \frac{N_{\text{observed}, C, A}}{N_{\text{observed}, C, B}} \right)
\]  

(1)

where

\[
N_{\text{observed}, T, B} = \text{observed WWD counts at treatment sites in before period}; \quad N_{\text{observed}, C, A} = \text{observed WWD counts at comparison sites in after period}; \quad \text{and} \quad N_{\text{observed}, C, B} = \text{observed WWD counts at comparison sites in before period}.
\]

Equation 2 estimates the variance of \( N_{\text{estimated}, T, A} \). This is used to determine the event modification factor (Equation 3) and variance of this factor (Equation 4), which is used to determine the factor’s statistical significance. Equation 5 calculates the percentage reduction in WWD events resulting from the treatment.

\[
\text{Var}(N_{\text{estimated}, T, A}) \approx N_{\text{estimated}, T, A}^2 \times \left( \frac{1}{N_{\text{observed}, T, B}} + \frac{1}{N_{\text{observed}, C, B}} + \frac{1}{N_{\text{observed}, C, A}} \right).
\]  

(2)

Event Modification Factor (EMF)

\[
\text{EMF} = \frac{N_{\text{observed}, T, A}}{1 + \left[ \frac{\text{Var}(N_{\text{estimated}, T, A})}{N_{\text{estimated}, T, A}^2} \right]}.  
\]  

(3)

Variance (EMF)

\[
\text{Var} = \frac{\text{EMF}^2 \left[ \frac{1}{N_{\text{observed}, T, A}} + \left( \frac{\text{Var}(N_{\text{estimated}, T, A})}{N_{\text{estimated}, T, A}^2} \right) \right]}{\left[ 1 + \left( \frac{\text{Var}(N_{\text{estimated}, T, A})}{N_{\text{estimated}, T, A}^2} \right)^2 \right]^2}.
\]  

(4)

Percentage Reduction in WWD Events

\[
\text{Percentage Reduction} = (1 - \text{EMF}) \times 100
\]  

(5)

where \( N_{\text{observed}, T, A} = \text{observed WWD counts at treatment sites in the after period} \).

Method 3: Reduction in WWD Events and Associated Savings

Unlike both previous methods, Method 3 does not utilize the WWCR reduction approach, which can be time-consuming for agencies to develop and implement. Instead, comparison group before–after analyses (like in Method 2) were used to determine the reductions in WWD citations and 911 calls at the treatment sites. Previous research by the authors has shown that WWD citations and 911 calls are a suitable surrogate for WWD crashes (13). Average crash and injury savings were calculated for WWD citations and 911 calls based on the relationship and overlap between WWD crashes and these events. These average savings and WWD event reductions were then used to estimate the total savings provided by the RFBs. This method requires a sufficient sample size of WWD citations and 911 calls for the before–after analyses to be accurate, but can provide results more quickly than methods 1 and 2. However, the results will not be as accurate as only WWD events are considered and not geometric design or other factors. WWD crash data can also be considered in this method if a sufficient sample size is available.

Determining Monetary Benefits and Costs

All three discussed methods require comprehensive crash and injury costs to determine the monetary benefits of the WWD countermeasures. They also require information on the costs of deploying and operating the devices to calculate benefit-cost ratios. For the benefits, the average cost of a WWD crash can be determined based on the severity distribution of WWD crashes and the comprehensive crash and injury costs for different severity levels. In Method 3, the average savings for a WWD citation and 911 call are needed. These can be calculated by identifying the citations and 911 calls that resulted in a crash, determining the costs for these crashes, then dividing these costs by the total number of citations and 911 calls. This procedure assumes that citations and 911 calls that do not result in a crash have a cost of US$ 0. Although this assumption is not completely accurate, as law enforcement and 911 call center operators do spend time responding to these events, these costs were not considered in this paper. Future research will consider these costs and additional benefits, such as reduction in law enforcement response time.

The considered costs are deployment and operations and maintenance (O&M) costs. Deployment costs can include purchase of equipment, design, construction, installation, and testing of the countermeasures before implementation. These are one-time costs that occur before the devices become active. O&M costs (system checks, cleaning, repair, etc.) occur every year for the lifespan of the countermeasures. There could be other additional costs, such as time spent responding to false alerts, but these will be examined in future research and are not considered in this paper.
Before determining benefit–cost ratios, the benefits and costs have to be converted to present values for the year the countermeasures were installed. Equation 6 converts future values into present values.

\[ PV = \frac{FV}{(1 + i)^n} \]  

where

- \( PV \) = present value;
- \( FV \) = future value;
- \( i \) = discount rate; and
- \( n \) = number of years between future year and present year.

A benefit–cost ratio can then be calculated by dividing the total benefits by the total costs. If this ratio is greater than 1.0, the benefits outweigh the costs, indicating that the WWD countermeasure has been a worthy investment. Using multiple methods to calculate benefit–cost ratios can provide a range of ratios and a better picture of the potential impacts of the devices, as illustrated in the following application of the described methodologies.

### Benefit–Cost Analyses of CFX RFB Countermeasures

CFX currently has RFB WWD countermeasures installed at 24 interchanges (35 exit ramps) on their toll road network in Central Florida. These RFBs were deployed in multiple phases, with the first site equipped in February 2015 and the most recent site equipped in June 2017. Each site contains two pairs of “Wrong Way” signs with RFBs above and below the signs, wrong-way detectors, and three cameras to capture images of detected wrong-way vehicles. There have been 497 detected wrong-way vehicles at these sites through April 2019, with 413 of these vehicles turning around (turn-around percentage of 413/497 x 100% = 83.1%). This value is a good representation of both daytime and nighttime conditions, as daytime had a turn-around percentage of 78.2% and nighttime had a turn-around percentage of 85.5%. Benefit–cost analyses were conducted on these RFBs using the methods previously described to determine the financial impacts of these devices.

To apply these methodologies, it is necessary to have WWD event data before and after the RFBs were installed. Two of the CFX RFB sites are at interchanges with no available before data, so these sites were excluded. Additionally, extensive modifications (additional ramps and changes in geometric design) were made to one interchange. As these modifications could have affected WWD frequency in the after period, this interchange was also excluded, leaving 21 interchanges (31 exit ramps) with RFBs for analysis.

### WWD Comprehensive Crash and Injury Costs

To determine the average comprehensive crash and injury costs of a WWD crash, 6 years of WWD crash data (2011–2016) for all Florida limited access facilities were collected and analyzed. Table 1 shows the distribution of the collected crashes and their accompanying injuries, along with comprehensive crash and injury costs, for each severity level. The comprehensive crash costs were obtained from the Florida Department of Transportation FDOT Design Manual (38), with the value for property damage only crashes representing the actual average reported damages in the WWD crash reports rather than the suggested value of $7,600. The comprehensive injury costs were obtained from the National Safety Council (39), as there were no specific injury costs for Florida. There were 315 WWD crashes involving 1057 people on Florida limited access facilities from 2011 through 2016, including 73 fatal crashes with 110 fatalities. Using the severity distribution of WWD crashes and comprehensive crash costs shown in Table 1 results in an average comprehensive crash cost of

<table>
<thead>
<tr>
<th>Severity level</th>
<th>Number of WWD crashes</th>
<th>Percentage of WWD crashes</th>
<th>Comprehensive crash costa</th>
<th>Number of injuries</th>
<th>Injury rate per WWD crash</th>
<th>Comprehensive injury costb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal (K)</td>
<td>73</td>
<td>23.17%</td>
<td>$10,560,000</td>
<td>110</td>
<td>0.349</td>
<td>$10,562,000</td>
</tr>
<tr>
<td>Severe injury (A)</td>
<td>52</td>
<td>16.51%</td>
<td>$599,040</td>
<td>148</td>
<td>0.470</td>
<td>$1,155,000</td>
</tr>
<tr>
<td>Moderate injury (B)</td>
<td>69</td>
<td>21.90%</td>
<td>$162,240</td>
<td>182</td>
<td>0.578</td>
<td>$318,000</td>
</tr>
<tr>
<td>Minor injury (C)</td>
<td>38</td>
<td>12.06%</td>
<td>$100,800</td>
<td>170</td>
<td>0.540</td>
<td>$147,000</td>
</tr>
<tr>
<td>Property damage only/</td>
<td>83</td>
<td>26.35%</td>
<td>$17,881</td>
<td>447</td>
<td>1.419</td>
<td>$48,700</td>
</tr>
<tr>
<td>No injury (O)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>315</td>
<td>100.00%</td>
<td>$2,598,537</td>
<td>1057</td>
<td>3.356</td>
<td>$4,563,158</td>
</tr>
</tbody>
</table>

Note: WWD = wrong-way driving.

aAll comprehensive crash costs (except for property damage only crashes) were obtained from the FDOT Design Manual, 2018 (38).
bAll comprehensive injury costs were obtained from Guide to Calculating Costs (39).
$2,598,537 per WWD crash. To determine the average comprehensive injury cost per WWD crash, injury rates (average number of injuries per WWD crash) were calculated for each severity level by dividing the number of injuries for each severity level by the total number of WWD crashes (which was 315). From Table 1, the average comprehensive injury cost is $4,563,158 per WWD crash.

**Before–After Analyses of WWD Events**

Before–after analyses of WWD citations, 911 calls, and combined WWD 911 calls and citations (WWD events) were conducted using the comparison group method. Table 2 shows the treatment and comparison interchanges, along with their geometry and 2017 average annual daily traffic volumes for the mainline and crossing roadway. The comparison interchanges are all on toll roads in Central Florida (like the treatment interchanges) and have similar geometric characteristics and traffic volumes to the treatment sites, but do not have RFBs.

Since RFBs were installed at the 21 analyzed treatment interchanges between February 2015 and January 2017, these months were not considered in the analyses. The before and after periods were November 2012 to January 2015 (27 months) and February 2017 to April 2019 (27 months), respectively. WWD event data for these periods were provided by Florida Highway Patrol and filtered to only include events that occurred near the treatment or comparison sites. WWD crashes were not used as there were insufficient crashes during the study period and certified crash data were not available after 2016. Any 911 calls in which the wrong-way vehicle turned around on the ramp (confirmed by images from the RFB devices or reports from traffic management center (TMC) operators) were not used in the analyses as the wrong-way vehicle did not enter the mainline. All overlap within and between the citation and 911 call data sets was removed to ensure the sets were independent and each data point corresponded to a unique WWD event.

Figure 2 shows the total number of WWD 911 calls and citations for the treatment and comparison groups. The number of WWD events increased for both groups in the after period, with the comparison group having a higher rate of increase. These increases could have been caused by the 13.3% increase in the number of licensed drivers for the Central Florida area in the after period and increased driver reporting of WWD events as a result of media campaigns. It is likely that these factors affected the treatment and comparison sites similarly (since they are near each other and have similar driver populations).

### Table 2. Treatment and Comparison Interchanges

<table>
<thead>
<tr>
<th>Treatment interchange</th>
<th>Geometry</th>
<th>Mainline AADT (thousands of vehicles per day)</th>
<th>Crossing AADT (thousands of vehicles per day)</th>
<th>Comparison interchange</th>
<th>Geometry</th>
<th>Mainline AADT (thousands of vehicles per day)</th>
<th>Crossing AADT (thousands of vehicles per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR 408 Exit 1</td>
<td>Two leg directional</td>
<td>55.1</td>
<td>32.8</td>
<td>SR 408 Exit 6</td>
<td>Partial diamond</td>
<td>66.5</td>
<td>18.5</td>
</tr>
<tr>
<td>SR 408 Exit 2</td>
<td>Partial cloverleaf</td>
<td>67.0</td>
<td>28.5</td>
<td>SR 408 Exit 20</td>
<td>Partial cloverleaf</td>
<td>80.0</td>
<td>18.9</td>
</tr>
<tr>
<td>SR 408 Exit 4</td>
<td>Full diamond</td>
<td>73.5</td>
<td>33.5</td>
<td>SR 408 Exit 22</td>
<td>Partial cloverleaf</td>
<td>25.8</td>
<td>41.0</td>
</tr>
<tr>
<td>SR 408 Exit 5</td>
<td>Full diamond</td>
<td>70.0</td>
<td>34.5</td>
<td>SR 414 Exit 8</td>
<td>Full diamond</td>
<td>38.5</td>
<td>17.9</td>
</tr>
<tr>
<td>SR 408 Exit 7</td>
<td>Partial diamond</td>
<td>66.5</td>
<td>24.5</td>
<td>SR 417 Exit 6</td>
<td>Two leg directional</td>
<td>54.6</td>
<td>21.8</td>
</tr>
<tr>
<td>SR 408 Exit 8</td>
<td>Full diamond</td>
<td>75.5</td>
<td>43.0</td>
<td>SR 417 Exit 12</td>
<td>Partial cloverleaf</td>
<td>49.5</td>
<td>95.0</td>
</tr>
<tr>
<td>SR 408 Exit 13</td>
<td>Two leg directional</td>
<td>139.5</td>
<td>27.0</td>
<td>SR 417 Exit 14</td>
<td>Full diamond</td>
<td>49.3</td>
<td>27.8</td>
</tr>
<tr>
<td>SR 408 Exit 19</td>
<td>Full diamond</td>
<td>82.3</td>
<td>25.0</td>
<td>SR 417 Exit 19</td>
<td>Full diamond</td>
<td>45.5</td>
<td>11.7</td>
</tr>
<tr>
<td>SR 414 Exit 6</td>
<td>Partial diamond</td>
<td>38.5</td>
<td>8.7</td>
<td>SR 417 Exit 22</td>
<td>Full diamond</td>
<td>63.8</td>
<td>35.5</td>
</tr>
<tr>
<td>SR 414 Exit 9</td>
<td>Partial cloverleaf</td>
<td>42.3</td>
<td>28.8</td>
<td>SR 429 Exit 8</td>
<td>Partial cloverleaf</td>
<td>26.7</td>
<td>11.7</td>
</tr>
<tr>
<td>SR 417 Exit 11</td>
<td>Partial cloverleaf</td>
<td>49.0</td>
<td>48.0</td>
<td>SR 429 Exit 19</td>
<td>Full diamond</td>
<td>25.6</td>
<td>36.5</td>
</tr>
<tr>
<td>SR 417 Exit 23</td>
<td>Partial cloverleaf</td>
<td>82.0</td>
<td>14.5</td>
<td>SR 429 Exit 26</td>
<td>Full diamond</td>
<td>72.8</td>
<td>8.7</td>
</tr>
<tr>
<td>SR 417 Exit 24</td>
<td>Partial cloverleaf</td>
<td>82.0</td>
<td>6.6</td>
<td>SR 429 Exit 33</td>
<td>Other</td>
<td>38.5</td>
<td>26.0</td>
</tr>
<tr>
<td>SR 417 Exit 34</td>
<td>Partial cloverleaf</td>
<td>82.3</td>
<td>56.0</td>
<td>SR 528 Exit 2</td>
<td>Partial cloverleaf</td>
<td>91.8</td>
<td>21.0</td>
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<td>SR 417 Exit 37</td>
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<td>85.3</td>
<td>42.5</td>
<td>SR 528 Exit 3</td>
<td>Partial cloverleaf</td>
<td>86.8</td>
<td>73.3</td>
</tr>
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<td>SR 429 Exit 24</td>
<td>Partial cloverleaf</td>
<td>68.8</td>
<td>16.8</td>
<td>SR 528 Exit 11</td>
<td>Partial cloverleaf</td>
<td>76.4</td>
<td>54.3</td>
</tr>
<tr>
<td>SR 429 Exit 29</td>
<td>Full diamond</td>
<td>81.0</td>
<td>6.0</td>
<td>SR 528 Exit 12</td>
<td>Partial cloverleaf</td>
<td>89.2</td>
<td>12.2</td>
</tr>
<tr>
<td>SR 451 Exit 33</td>
<td>Other</td>
<td>13.6</td>
<td>34.0</td>
<td>SR 528 Exit 37</td>
<td>Two leg directional</td>
<td>45.3</td>
<td>3.7</td>
</tr>
<tr>
<td>SR 528 Exit 9</td>
<td>Partial cloverleaf</td>
<td>85.5</td>
<td>19.8</td>
<td>SR 528 Exit 45AB</td>
<td>Partial cloverleaf</td>
<td>37.8</td>
<td>25.7</td>
</tr>
<tr>
<td>SR 528 Exit 13</td>
<td>Full diamond</td>
<td>83.4</td>
<td>29.3</td>
<td>SR 528 Exit 46</td>
<td>Partial cloverleaf</td>
<td>47.4</td>
<td>25.7</td>
</tr>
</tbody>
</table>

Note: AADT = average annual daily traffic.
Therefore, the main difference between the treatment and comparison sites is the presence of RFBs at the treatment sites in the after period.

Using the data shown in Figure 2 and equations 1 through 5, the modification factors and percentage reductions for WWD citations, 911 calls, and combined events were calculated. These results are shown in Table 3. There was a 66.3% reduction in WWD 911 calls, 53.8% reduction in WWD citations, and 58.3% reduction in combined WWD events at the RFB sites. All these results were significant at $a = 0.05$ significance level or lower, indicating that the RFB countermeasures have significantly reduced WWD. Based on the expected counts determined from Equation 1, the RFBs reduced the number of WWD 911 calls by 50, the number of WWD citations by 9.6, and the number of combined WWD events by 58 during the after period. As the after period was 27 months (2.25 years), these reductions are equivalent to 22.2 WWD 911 calls, 4.3 WWD citations, and 25.8 WWD events per year.

**Table 3. Results of Before–After Analyses on CFX RFBs**

<table>
<thead>
<tr>
<th>WWD data type</th>
<th>Modification factor</th>
<th>Percentage reduction</th>
<th>Significance level</th>
<th>Expected count at treatment sites in after period with no treatment</th>
<th>Observed count at treatment sites in after period</th>
<th>Reduction in after period because of RFBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>911 Calls</td>
<td>0.337</td>
<td>66.3%</td>
<td>0.01</td>
<td>84</td>
<td>34</td>
<td>50</td>
</tr>
<tr>
<td>Citations</td>
<td>0.462</td>
<td>53.8%</td>
<td>0.05</td>
<td>27.6</td>
<td>18</td>
<td>9.6</td>
</tr>
<tr>
<td>Events</td>
<td>0.417</td>
<td>58.3%</td>
<td>0.01</td>
<td>110</td>
<td>52</td>
<td>58</td>
</tr>
</tbody>
</table>

Note: WWD = wrong-way driving; CFX = Central Florida Expressway Authority; RFB = rectangular flashing beacons.

**Benefit–Cost Analyses**

For all the benefit–cost analyses, a discount rate of 4% was used, as stated in the *FDOT Design Manual, 2018* (38). A service life of 10 years was used for the RFBs, which is the recommended service life for similar devices, such as warning flashers and pedestrian hybrid beacons (40). All costs for the RFB sites were provided by CFX. The deployment costs (equipment, design, and construction/installation) ranged from $82,560 to $171,500 per site, while annual O&M costs were $6,315 or $6,585 per site depending on the type of detection technology used (radar or laser). RFBs were deployed at five sites in 2015, 24 in 2016, and two in 2017. Using Equation 6, the present values of the installation and O&M costs for the installation year of 2015 were $5,571,135 for the life cycle and $4,483,533 through April 2019. These same costs were used for all three methods, but the benefits were calculated differently for each method.

**Method 1.** The WWCR segment model and optimization algorithm developed by Sandt, Al-Deek and Kayes, with the RFB turn-around percentage of 83.1% resulted in an average WWCR reduction of 1.105 per year (7). This suggests that the 31 analyzed CFX RFB sites prevented slightly more than one WWD crash per year. Multiplying this reduction by the average WWD crash and injury costs of $2,598,537 and $4,563,158 resulted in annual savings of $2,871,460 and $5,042,424, respectively. Note that the savings were less in 2015 and 2016 (as RFBs were not installed at all 31 sites) and will be less in 2025 and 2026 (since some sites will reach the end of their service lives before others). Accounting for these aspects and converting all the savings to 2015 present values resulted in lifecycle crash savings of $22,840,646 and injury savings of $40,109,293. The IP savings were $7,401,361 (crash savings) and $12,997,153 (injury savings). With these savings, the life-cycle benefit–cost ratios were ($22,840,646 / $40,109,293) = 4.10 using crash savings and ($40,109,293 / $12,997,153) = 3.02 using injury savings. The IP benefit–cost ratios were ($7,401,361 / $4,483,533) = 1.65 using crash savings and ($12,997,153 / $4,483,533) = 2.90 using injury savings. These benefit–cost ratios are all greater than 1.00, indicating that the life-cycle benefits of the RFBs will significantly outweigh the costs and that the RFBs have already recouped their costs as of April 2019.

**Method 2.** In this method, the WWD event reduction percentage of 58.3% shown in Table 3 was used instead...
of the turn-around percentage of 83.1%. This change resulted in an average WWCR reduction of 0.776 per year, which equates to average annual crash savings of $2,015,535 and injury savings of $3,539,379. Conducting the life-cycle analysis and converting to present values resulted in crash savings of $16,032,306 (benefit–cost ratio of 2.88) and injury savings of $28,153,515 (benefit–cost ratio of 5.05). The IP crash savings were $5,195,164 (benefit–cost ratio of 1.16) and the injury savings were $9,122,962 (benefit–cost ratio of 2.03). All these ratios are less than the corresponding ratios from Method 1, but are still greater than 1.00.

**Method 3.** For Method 3, the average crash and injury savings per WWD 911 call and citation were estimated. There were 3404 WWD 911 calls on Florida limited access facilities from 2011 to 2016, with 87 resulting in a crash. Using the comprehensive crash and injury costs in Table 1, these 87 crashes had a total crash cost of $226,986,862 and a total injury cost of $406,118,700. Therefore, the average crash and injury costs were $66,682 and $119,306 per WWD 911 call, respectively. Looking at WWD citations, there were 1053 citations, of which 165 resulted in a crash. These crashes had a total crash cost of $63,294,667 (average of $60,109 per citation) and total injury cost of $168,658,700 (average of $160,170 per citation). The before–after analyses showed that the RFBs provided annual reductions of 22.2 WWD 911 calls and 4.3 WWD citations. Multiplying these reductions by the average savings resulted in annual crash savings of $1,481,831 (911 calls) and $265,465 (citations) and annual injury savings of $2,651,251 (911 calls) and $683,391 (citations). Adding these values, conducting the life-cycle analysis, and converting to present values resulted in crash savings of $13,849,221 (benefit–cost ratio of 2.49) and injury savings of $26,567,518 (benefit–cost ratio of 4.77). The IP crash savings were $4,548,930 (benefit–cost ratio of 1.01) and the injury savings were $8,726,395 (benefit–cost ratio of 1.95). These ratios are lower than the previous methods, but are all still greater than 1.00.

**Summary.** Table 4 shows the results obtained for all three methods. The life-cycle benefit–cost ratios range from 2.49 to 4.10 using crash savings and 4.77 to 7.20 using injury savings, whereas the IP ratios range from 1.01 to 1.65 using crash savings and 1.95 to 2.90 using injury savings. These results show that the life-cycle benefits of the RFBs significantly outweigh the costs for all three methodologies. They also show that using multiple methods to determine benefit–cost ratios can provide a more comprehensive understanding of the possible benefits than just using a single method.

**Conclusion**

Benefit–cost analyses are important tools to help agencies understand the effects and value of ITS devices. A lack of data can make it difficult to determine the benefits of these devices, especially for ones used to reduce infrequent driving behaviors, such as WWD. This paper presents three methods that can be used to conduct benefit–cost analyses on ITS WWD countermeasures or other similar devices. All three methods were applied to RFB WWD countermeasures deployed on CFX toll road exit ramps. An agency could use any or all of these methods to determine benefit–cost ratios for their WWD countermeasures depending on data availability and preferences. Method 2 is recommended if sufficient data are available, as this method considers the effectiveness of the countermeasures and the WWD behavior before the countermeasures were installed and at similar sites without the countermeasures. Method 1 is recommended if sufficient WWD event data are not available, whereas Method 3 is recommended if an agency desires to quickly obtain benefit–cost ratios. The best understanding of the countermeasures can be obtained by using all three methods to get a range of potential benefit–cost ratios.

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**Table 4.** Crash and Injury Savings and Benefit–Cost Ratios for CFX RFBs

<table>
<thead>
<tr>
<th>Calculated benefits</th>
<th>Method 1</th>
<th>Method 2</th>
<th>Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP crash savings</td>
<td>$7,401,361</td>
<td>$5,195,164</td>
<td>$4,548,930</td>
</tr>
<tr>
<td>IP benefit–cost ratio (crash savings)</td>
<td>1.65</td>
<td>1.16</td>
<td>1.01</td>
</tr>
<tr>
<td>Life-cycle crash savings</td>
<td>$228,840,646</td>
<td>$16,032,306</td>
<td>$13,849,221</td>
</tr>
<tr>
<td>Life-cycle benefit–cost ratio (crash savings)</td>
<td>4.10</td>
<td>2.88</td>
<td>2.49</td>
</tr>
<tr>
<td>IP injury savings</td>
<td>$129,977,153</td>
<td>$9,122,962</td>
<td>$8,726,395</td>
</tr>
<tr>
<td>IP benefit–cost ratio (injury savings)</td>
<td>2.90</td>
<td>2.03</td>
<td>1.95</td>
</tr>
<tr>
<td>Life-cycle injury savings</td>
<td>$40,109,293</td>
<td>$28,153,515</td>
<td>$26,567,518</td>
</tr>
<tr>
<td>Life-cycle benefit–cost ratio (injury savings)</td>
<td>7.20</td>
<td>5.05</td>
<td>4.77</td>
</tr>
</tbody>
</table>

Note: IP = implementation period; CFX = Central Florida Expressway Authority; RFB = rectangular flashing beacons.
Method 1 used the WWCR reduction approach developed by Sandt, Al-Deek, and Kayes, and the percentage of turn arounds at the CFX exit ramps equipped with RFBs to estimate the reduction in WWD crashes owing to these devices (7). There was a turn-around percentage of 83.1% at the CFX RFB ramps through April 2019, resulting in an estimated annual WWCR reduction of 1.105 per year based on WWD crashes and non-crashes from 2011 to 2015, interchange designs, and traffic volumes. This corresponded to total crash savings of $22,840,646 and total injury savings of $40,109,293 for the 10-year lifespan of the RFB devices. With these savings, the life-cycle benefit–cost ratios were 4.10 (crash savings) and 7.20 (injury savings), with IP benefit–cost ratios of 1.65 (crash savings) and 2.90 (injury savings).

Method 2 also used the WWCR reduction approach, but used a comparison group before–after analysis to determine the reduction in non-crash WWD events (911 calls and citations) at the RFB sites. This statistically significant reduction (α = 0.01) of 58.3% resulted in an estimated annual WWCR reduction of 0.776 for all 31 RFB sites. The total life-cycle savings were $16,032,306 (crash savings) and $28,153,515 (injury savings), with life-cycle benefit–cost ratios of 2.88 (crash savings) and 5.05 (injury savings) and IP benefit–cost ratios of 1.16 (crash savings) and 2.03 (injury savings).

For Method 3, the WWCR reduction approach was not used. Instead, before–after analyses were used to determine the individual reductions in WWD 911 calls and citations at the RFB sites. The average crash and injury savings per WWD 911 and citation were also calculated and used to determine the annual savings as a result of reductions in these non-crash events. The before–after analyses showed statistically significant reductions of 66.3% for 911 calls (α = 0.01) and 53.8% for citations (α = 0.05) owing to the RFBs. Average crash costs were $66,682 per 911 call and $60,109 per citation, whereas average injury costs were $119,306 per 911 call and $160,170 per citation. Using these average costs, the total life-cycle savings were $13,849,221 (crash savings) and $26,567,518 (injury savings) for these non-crash WWD events. The corresponding benefit–cost ratios were 2.49 (crash savings) and 4.77 (injury savings) for the life cycle and 1.01 (crash savings) and 1.95 (injury savings) through April 2019.

This paper shows how the crash savings of WWD countermeasures can be determined when crash data is limited. For all three methods, the calculated IP benefit–cost ratios were greater than 1.00, indicating that the benefits of the RFBs have already outweighed the costs, even though most of them have been deployed for less than 3 years. These results indicate that RFB WWD countermeasures are worthwhile investments that should be considered for deployment at limited access facility exit ramps. Future research will consider other benefits (such as reduction in law enforcement response time and delay as a result of WWD crashes) and costs (such as time spent by TMC operators responding to false alerts) of these devices to provide a more comprehensive understanding of their impacts. Using the methods discussed in this paper, any agency (in the United States or worldwide) can accurately estimate the safety benefits of WWD countermeasures with limited crash data.

Author Contributions
The authors confirm contribution to the paper as follows: study conception and design: A. Sandt, H. Al-Deek, M. Kayes; data collection: A. Sandt, H. Al-Deek, M. Kayes, P. Blue, V. Gamero; analysis and interpretation of results: A. Sandt, H. Al-Deek, M. Kayes; draft manuscript preparation: A. Sandt, H. Al-Deek, M. Kayes, P. Blue, V. Gamero. All authors reviewed the results and approved the final version of the manuscript.

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