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Evaluation of red RRFB implementation at freeway off-ramps and its effectiveness on alleviating wrong-way driving

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Abstract

Wrong-way crashes are a major cause for safety concern along freeways and limited access facilities. This study investigated three different aspects of the use of Rectangular Rapid Flashing Beacons (RRFBs): 1) different settings of red RRFBs and their perceived effectiveness on reducing wrong-way driving based on a public opinion survey, 2) the effect of active red RRFBs on the behavior of drivers traveling on adjacent roadways via a before-and-after study, and 3) the effectiveness of red RRFBs on alleviating wrong-way driving on freeway off-ramps by analyzing the percentage of vehicles turning back after observing the red RRFB activation. Based on the public opinion survey results, the most informative warning red RRFB combination was determined and implemented in this study. The evaluation of the impact of red RRFB implementation (at six I-275 off-ramps in Tampa, FL, USA) on driving behaviors along adjacent arterials indicated that the implementation of red RRFBs did not adversely impact driving behaviors on adjacent arterials. To determine the effectiveness of red flashing beacons and RRFBs on alleviating wrong-way driving on freeway off-ramps, video recordings of red flashing beacons and RRFBs mounted on wrong-way signs were analyzed. Red RRFBs were deemed to be a more effective countermeasure to deter wrong-way driving than red flashing beacons. Six-months of video data were collected for red flashing beacons mounted on wrong-way signs, and video data collection for red RRFBs mounted on wrong-way signs is currently underway. For red flashing beacons, a high percentage of wrong-way drivers in this study made a U-turn and went back in the correct traffic flow direction upon realizing they were traveling in the wrong direction. It is expected that red RRFBs will be more effective on alleviating wrong-way driving due to their capabilities to inform drivers of wrong-way driving than those from red flashing beacons. The video data analysis for red RRFBs will be presented in a separate paper.

Keywords: Wrong-Way-Driving; RRFB; Safety; Freeway-Off-Ramps

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1. Introduction

Although wrong-way crashes make up only about 3% of overall traffic accidents, they pose significant safety concerns for freeways and limited access facilities because they often result in serious injuries or fatalities (Cooner and Ranft, 2007). According to crash data supplied by the Florida Department of Transportation (FDOT), there were 1,173 statewide wrong-way crashes from 2003 to 2012, which resulted in 164 fatalities and 1,322 injuries. More than half of these crashes occurred late at night. A National Transportation Safety Board (NTSB) Special Investigation on Wrong-Way Driving (WWD) reports that a majority of drivers (59%) involved in wrong-way crashes were heavily under the influence of alcohol and/or drugs, with a blood alcohol content (BAC) of more than 0.15%, and 29% of other wrong-way drivers had a BAC level of 0%. The increased use of traffic control signs and pavement markings, as defined by the Manual on Uniform Traffic Control Devices (MUTCD) standards, may not be sufficient to notify drivers of their WWD.

Previous efforts proved that using yellow Rectangular Rapid Flashing Beacons (RRFBs) are very effective in alerting drivers to yield to pedestrians crossing streets. Therefore, it is reasonable to expect that red RRFBs mounted on "WRONG WAY" traffic signs (Fig. 1) at interstate off-ramps can operate in a similar fashion to notify wrong-way drivers of their incorrect driving action and deter any wrong-way movements onto freeways and limited access facilities. However, their impact on driving behavior on adjacent arterial roadways has been unknown. The intent of this research was to investigate 1) different settings of red RRFBs and their perceived effectiveness on reducing wrong-way driving based on a public opinion survey, 2) the effect of active red RRFBs on the behavior of drivers traveling on adjacent roadways via a before-and-after study, and 3) the effectiveness of red RRFBs on alleviating wrong-way driving on freeway off-ramps by statistically analyzing the overall percentage of vehicles discontinuing their wrong-way driving behavior and turning back at the RRFB locations after observing the red RRFB activation.

Fig. 1. Red RRFBs mounted on "WRONG WAY" sign (Recreated from WUSF News, 2015)

1.1. Background

Wrong-way accidents are relatively infrequent; however, they are more likely to be fatal or involve serious injury when they occur on freeways and limited access facilities due to their high-speed/head-on nature. The causes of wrong-way accidents vary widely based on a multitude of factors. In the 1960s, wrong-way accidents were caused by driver confusion, on-ramp configurations, and freeway interchanges, problems that later were corrected with the addition of traffic signs, pavement markings, and other improvements at off-ramps. A California Department of Transportation (Caltrans) survey in the late 1980s revealed that drivers under the influence of alcohol were the most common causes of wrong-way accidents. Additional studies suggested that poor lighting conditions, driver fatigue, and the presence of older drivers also play a role in wrong-way accidents (Zhou et al., 2012). Table 1 depicts a range of possible contributing factors for the occurrence of wrong-way accidents.

Table 1. Contributing factors for wrong-way accidents (Recreated from *Zhou et al., 2012*)

Categories	Description
Traffic violation	• Driving under the influence (DUI) • Intentional reckless driving • Suicide • Test of courage • Escaping from a crime scene • Avoiding traffic congestion
Inattention	• Falling asleep at the wheel • Carelessness, absent-mindedness, distraction • Inattention to informational signposts
Impaired judgment	• Physical illness • Older adult driver • Drivers with psychiatric problems
Insufficient knowledge	• Lack of understanding of how to use the highway • Unfamiliar with infrastructure • Loss of bearings
Infrastructure deficiency	• Insufficient lighting • Insufficient field view • Heavy vegetation
Others	• Inclement weather

Accidents related to wrong-way driving on limited access highways involve much higher fatality rates than those of normal traffic accidents—about 20% higher—and have more severe consequences, such as a greater number of deaths or serious injuries (NTSB, 2012). Additionally, drivers ages 70 and over were found to have a significantly higher incidence of WWD (Cooner et al., 2003). This may be due to older adult drivers having driving impairments and lower performance levels in necessary skills such as nighttime vision, reasoning/judgment, and cognitive function (Edwards et al., 2009). Other driver errors that commonly were seen in crashes involving older adults were failure to observe and judge the speed of other vehicles, disregarding traffic signals, and performing improper turns (Alan and Spainhour, 2008).

A literature review confirmed that wrong-way accidents, when compared to normal traffic accidents, are more likely to occur during nighttime/early morning hours, tend to be more severe, and are more likely to affect males than females and that 50–70% of these crashes involve impaired drivers who were under the influence of drugs or alcohol (Cooner and Ranft, 2007). In addition, other studies state that driver personality is a predictive factor of risky driving (Sucha and Cernochova, 2016) and in most cases human behavior can also influence the geometric design of the roadway (Cickovic, 2016). In a study conducted by the Fatality Analysis Reporting System (FARS) involving 1,566 wrong-way fatal crashes on divided highways, approximately 60% involved alcohol, compared to approximately 7% of right-way drivers (NTSB, 2012). Furthermore, while analyzing the same data, it was observed that a majority of these wrong-way crashes involved BAC levels of 0.15% or more, significantly exceeding the legal limit of 0.08%.

The number of drivers continues to grow in Florida, and the frequency of traffic crashes increased by 12.65% (from 281,340 to 316,943) between 2012–2013 (Florida Department of Highway Safety and Motor Vehicles, 2014).

According to the NTSB, the average number of WWD fatalities in the U.S. between 2004 and 2009 was 360, or approximately 7 fatalities per state. Over the course of a 12-month period in 2014, Tampa, Florida, alone recorded 12 fatalities associated with WWD accidents—an alarmingly high number.

With the acknowledgement of WWD in the 1960s, countermeasures were put in place to assist drivers, especially those of specific demographic groups who were found to be more at risk to engage in WWD behavior. Beginning in the 1970s, Caltrans began the implementation of lower-mounted traffic signs to effectively notify impaired drivers and/or older drivers of their incorrect driving behavior. The lowered sign was more obvious to drivers since it was directly in the path of vehicle headlight beams. Studies conducted by the Texas Department of Transportation (TxDOT) revealed that nearly 80% of WWD incidents occurred late at night and cited low visibility as the underlying cause. Flashing LED-bordered "WRONG WAY" signs were installed on 29 exit ramps on a corridor in San Antonio, TX, at which a high number of wrong-way crashes had previously occurred; results from an after-treatment study showed a 30% reduction in wrong-way crash frequency. Also, in response to high rates of WWD incidents, the Illinois Department of Transportation (IDOT) replaced nominal-sized "DO NOT ENTER" signs with larger ones at multiple exit ramps and installed pavement markings to increase visibility, resulting in a notable decrease in WWD behaviors (Pour-Rouholamin et al., 2015).

Many innovative ideas have been put in place to counter WWD. Various traffic devices and/or light combinations of active signage have been implemented, such as LED-illuminated signs (ITS International, 2014), dynamic message signs (DMS), internally-illuminated signs, and flashing beacons. Some mitigation strategies are more passive and lower-cost, such as the placement of reflective red wrong-way pavement arrows, as described in the MUTCD, which reflect light at night and provide drivers with the proper traffic flow direction. In addition, studies in Central Florida looked at multiple incident parameters and targeted countermeasures for wrong-way driving reductions (Rogers et al., 2015).

Recent technology solutions include the BlinkerSign® Wrong-Way and Do Not Enter Warning System, which features a solar-powered, dual radar detection and dispatch system (Fig. 2). Such technologically-advanced systems notify drivers, either visually and/or auditorily, of WWD behavior and send this information to the Traffic Management Center (TMC), which then dispatches law enforcement to the area of the WWD alert and also warns other drivers on the freeway through the use of DMS.

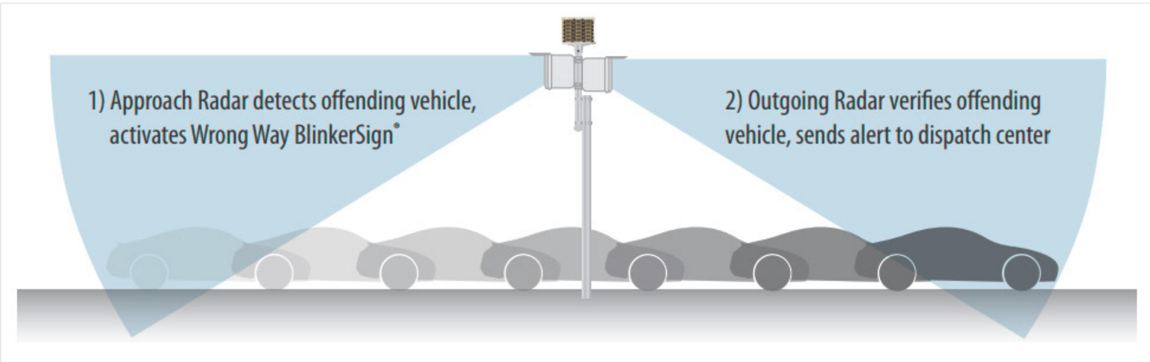

Fig. 2. Dual radar detection and dispatch alert for wrong-way vehicle detection (Traffic and Parking Control Company, 2014)

Geometric roadway design is another method used to discourage WWD (Pour-Rouholamin and Zhou, 2015). Roadways are designed to have smaller-than-normal corner radii at portions that are susceptible to WWD so that a wrong-way turning movement is difficult to achieve (Wolshon, 2004). Geometric designs such as divided crossroads, two-lane crossroads, and simple interchange types have been found to discourage WWD through their geometry (Campbell, 2012). Also, providing structural modifications to freeway off-ramps was found to mitigate WWD because these locations are the most frequent origin of wrong-way entry onto a freeway (Cooner and Ranft, 2008).

2. Research approach

This section highlights the methodologies undertaken to conduct a public opinion survey, a “before” and “after” data collection on the adjacent arterials to the freeway off-ramps of analysis, and WWD video data collection at the analysis freeway off-ramps.

2.1. Public opinion survey to determine the most effective and informative red RRFB combination

A public opinion survey was developed to collect the public’s perception of the most effective and informative red RRFB combination. Surveys were distributed to a representative cross-section of the population, with 33% between ages 16–29, 33% between 30-59, and 33% ages 60 and over. Other information collected from the survey included participant demographics, opinions regarding WWD, personal driving behavior, and ethical decisions concerning driving while under the influence of alcohol and/or drugs.

Prior to the completion of the survey, participants were shown pre-recorded field videos from the viewpoint of a driver (Fig. 3) traveling in the wrong-way direction on a freeway off-ramp. As the vehicle advanced towards the off-ramp, red RRFBs were activated via radar detection of the WWD vehicle. The videos were recorded in a nighttime setting, with the Florida Highway Patrol (FHP) closing the off-ramps to traffic for safety purposes, because a large portion of WWD behaviors statistically occur during these times.

Fig. 3. Screen capture of video shown to survey participants to determine most effective and informing red RRFB combination

Survey participants were divided into two groups and were shown one of two sets of videos. The first set showed WWD through a pair of RRFBs on both the left and right side of the roadway installed on a long and wide geometry interchange (northbound Fowler Avenue off-ramp at I-275 in Tampa), and the second set was recorded on a short and narrow geometry interchange (southbound Fowler Avenue off-ramp at I-275 in Tampa). The long-wide and short-narrow interchange geometries (which covers almost all types of off-ramp geometries) were used in this research to account for the visibility variability a driver will encounter when traveling on different types of off-ramps. The red RRFBs were located 625 ft and 425 ft from the intersection of the off-ramp and the adjacent arterial for the long-wide and short-narrow off-ramp geometries, respectively. Each set of videos was a compilation of nine RRFB and wrong-way sign combinations on the roadway, as follows:

- Right side “WRONG WAY” sign with RRFBs activated at top of sign
- Right side “WRONG WAY” sign with RRFBs activated at bottom
- Right side “WRONG WAY” sign with RRFBs activated at both top and bottom
- Left side “WRONG WAY” sign with RRFBs activated at top
- Left side “WRONG WAY” sign with RRFBs activated at bottom
- Left side “WRONG WAY” sign with RRFBs activated at both top and bottom
- Both left and right side “WRONG WAY” signs with RRFBs activated at top
- Both left and right side “WRONG WAY” signs with RRFBs activated at bottom
- Both left and right side “WRONG WAY” signs with RRFBs activated at both top and bottom

2.2. “Before” and “After” data collection methodology to evaluate driving behaviors on adjacent arterials

Following the distribution of the public opinion surveys, video camera trailers were set up at six study sites in Tampa (northbound and southbound off-ramps at the Interstate 275 interchanges of Bearss, Fletcher, and Fowler avenues) to record driving behavior on the corresponding off-ramp’s adjacent arterial roadway during nighttime. The main reason for this analysis was to determine whether the reflections of the red RRFBs adversely impact driving behavior on the adjacent arterial. These results were requested by Federal Highway Administration (FHWA) to apply for a Request for Experiment (RFE) to the MUTCD so that the red RRFBs can be tested on Florida roadways.

Video data were collected for two nights at each of the six sites. The research team reviewed the video recordings at all sites and documented the occurrence of three specific driving behaviors (sudden deceleration, sudden stop, and sudden lane changing) to use as “before/baseline” (before red RRFB implementation) data. After obtaining the video data for the “baseline” scenario, red RRFBs mounted on “WRONG WAY” signs were installed by FDOT at the corresponding northbound and southbound off-ramps of the six study sites. In the “after” red RRFB implementation portion, the data collection was conducted by using two methods—manual (button) triggering of the red RRFBs and vehicular triggering of red RRFBs through radar detection. For the vehicular triggering of the red RRFBs, the Florida Highway Patrol closed the study off-ramps to traffic for three nights for safety purposes. During the “after” data collection of manual triggering and vehicular triggering, driving behaviors on the adjacent arterials were video-recorded and also visually observed/documented by field personnel. The “after” video data were then reviewed to maximize the accuracy of the visually observed/documented driving behaviors such as sudden deceleration, sudden stop, and sudden lane changing behavior. The “after” driving behavior data were then compared to the “before/baseline” driving behavior data to evaluate significant differences, if any, and to address any operational or safety concerns observed.

2.3. WWD video data collection methodology at freeway off-ramps to determine effectiveness of WWD countermeasures

To determine the effectiveness of existing red flashing beacons and proposed red RRFBs mounted on wrong-way signs on alleviating WWD on freeway off-ramps, video data were collected. For red flashing beacons, six-month video data were collected from two off-ramp sites in the Tampa Bay region (Alexander St. and I-4 in Plant City, FL and Busch Blvd. and I-275 in Tampa, FL). These sites have been flagged as high frequency WWD sites and were chosen specifically for this analysis. The video data collection for red RRFBs mounted on wrong-way signs at six study sites is currently underway and unavailable for the current analysis. Both sites with red flashing beacons mounted on wrong-way signs are off-ramps that are equipped with top and bottom red flashing beacons, similar to the red RRFB-equipped sites, and are also activated upon radar detection of a WWD vehicle. This type of countermeasure is less aggressive in its flashing compared to red RRFBs and, therefore, the results obtained from these sites are expected to be conservative and can only improve compared to the sites equipped with red RRFBs. This is mainly due to the fact that red RRFBs flash more rapidly compared to red flashing beacons and, therefore, get the attention of drivers at a much higher level.

The video data that were collected and analyzed represent a six-month period (October 2015–March 2016), immediately after the red flashing beacons mounted on wrong-way signs were installed in the field. The data consist of a 60-second recording of the WWD vehicle from the time it triggers the front radar to the time it either passes the

WWD countermeasure towards the interstate or abruptly stops when the driver realizes his WWD behavior. The analysis criterion to determine the effectiveness of the WWD countermeasure was chosen as the "return rate in percent," which correlates to the WWD driver realizing his WWD action upon radar detection and activation of the countermeasure. This return rate refers to the vehicle making a U-turn and going back in the correct direction of traffic flow upon countermeasure activation.

3. Results

A total of 296 public opinion surveys were collected. Survey answers were recorded manually into a database as raw data, which were used to create pivot tables and pie charts for every question and demographic factor, showing a representation of the survey participants in its entirety. Observed driving behavior types (sudden deceleration, sudden stops, and sudden lane changing) from both the "before/baseline" and "after" video data recordings were compiled into tables and organized by their respective sites. The observed driving behavior types at each of the six study sites were used to further analyze the statistical significance between driving behavior types on the adjacent arterial before and after RRFB implementation. The WWD videos were also reviewed at the two off-ramp locations with red flashing beacons mounted on wrong-way signs, and the behavior of the WWD vehicles was observed upon radar detection and countermeasure activation. These were then entered into spreadsheets per each analysis month, the return rate of the vehicles that made a U-turn and corrected their WWD were calculated, and an average return rate was reported for the overall initial analysis time period of six months.

3.1. Public opinion survey

The public opinion survey answers were assembled, and the results were placed into a pie chart format as depicted in Fig. 4, which represents I-275 at Fowler Avenue "Long and Wide Off-Ramp". These results did not show a major difference between the long-wide and short-narrow off-ramp geometries and were consistent among all three age groups (16-29, 30-59, 60+). A significant majority of both the long-wide (72%) and short-narrow (67%) off-ramp geometry survey participants (69.5% overall), preferred the RRFB combination that featured the top and bottom flashing lights on the left and right sides of the roadway. Because of the study population's overwhelming favor for this combination, this red RRFB combination was implemented at the six selected I-275 off-ramps for the "after" study.

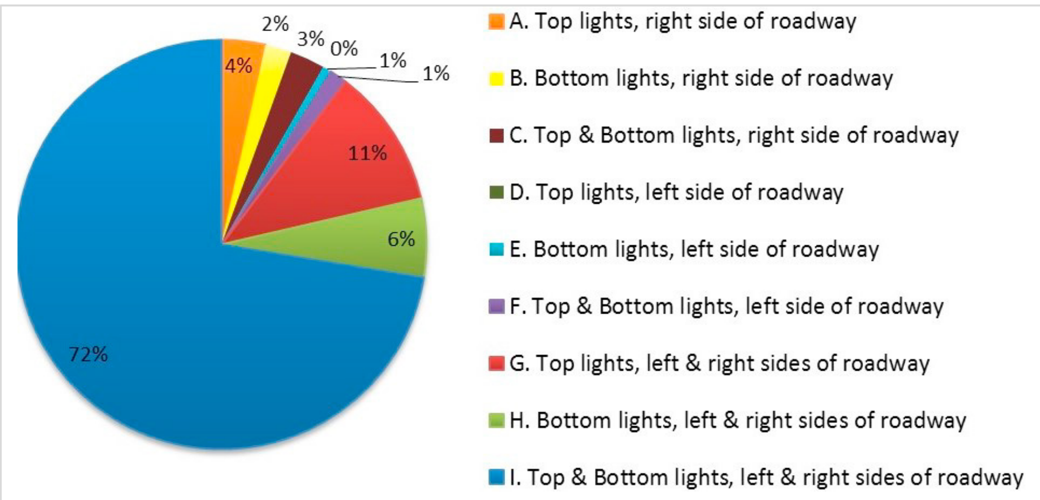

Fig. 4. Sample results from public opinion survey

3.2. "Before" and "After" data analysis for driving behaviors on adjacent arterials

Data collected from the "before" and "after" study methodology were compiled into a series of tables, organized by each off-ramp site. It was observed from these data that at baseline, the sites had some instances of the three driving behaviors of interest— sudden deceleration, sudden stop, and sudden lane changing. Once the "after" red RRFB implementation data were analyzed, it was observed that there were fewer or a similar number of instances of sudden deceleration, sudden stop, and sudden lane changing observed when compared to the "before" data. Therefore, these findings indicate that the red RRFB flashing has little to no adverse effect on driving behavior on the adjacent arterial.

During vehicular triggering of the red RRFBs, additional behaviors also were observed by drivers in other cars, such as honking or calling the police when witnessing the wrong-way research vehicle entering the wrong off-ramp. Such behaviors were related to the actual witnessing of the wrong-way driver and not associated with the effects of the red RRFB flashing/implementation. However, such behavior is considered positive since it demonstrates that drivers familiar with the area will try to warn wrong-way drivers and/or try to notify the authorities.

The "before/baseline" data were compared to both WWD vehicle-triggered and manually-triggered red RRFB data collection to determine if the red RRFB implementation had a negative impact on the traffic operations and safety of the adjacent arterials of the off-ramps.

Student's t-tests are commonly used to compare two sets of quantitative data when samples are collected independent of one another. Therefore, to compare the "before" and "after" red RRFB implementation data on sudden deceleration, sudden stops, and sudden lane changing behavior, t-tests (formulas 1 and 2) were used to determine statistical significance and to test whether there were differences between the two groups on the same variables.

$$S_{\bar{X}_1-\bar{X}_2} = \sqrt{\frac{s_1{}^2}{n_1} + \frac{s_2{}^2}{n_2}} \quad (1)$$

$$|t - calculated| = \left|\frac{\bar{X}_1-\bar{X}_2}{S_{\bar{X}_1-\bar{X}_2}}\right| \quad (2)$$

where,

$\bar{X}_1$ = Mean percentage of first set (before study) of observations to total
$\bar{X}_2$ = Mean percentage of second set (after study) of observations to total
S_1 = Standard deviation of first set (before study) of values
S_2 = Standard deviation of second set (after study) of values
n_1 = Total number of observations in first set (before study)
n_2 = Total number of observations in second set (after study)

For each of the six study off-ramps, three two-tailed t-tests were performed to determine the negative impacts of red RRFB implementation on the driving behaviors on the adjacent arterial, such as impact types of sudden deceleration, sudden stops, and sudden lane changing. For each of these two-tailed t-tests, a 95% confidence interval (95% CI) was sought, and the null hypothesis was set as the following:

H_0: The implementation of red RRFBs has no impact for a studied impact type on the adjacent arterial driving behaviour when compared to the before-implementation driving behaviour data on the same adjacent arterial.

Using the table of percentage points of the t-distribution, a t-critical value of 1.960 was obtained for degrees of freedom of larger than 120 (depicted with "infinity" in the tables) and a tail probability of 0.025, which corresponds to 95% CI for a two-tailed t-test.

According to the t-test criterion, since the absolute value of the t-calculated values that belong to each study off-ramps were found to be less than the t-critical value obtained from the t-distribution critical values table, it is found that we fail to reject the null hypothesis as described above. It was concluded that the implementation of the red

RRFBs has no impact for sudden deceleration, sudden stops, and sudden lane changing on the driving behavior on the adjacent arterial to the off-ramp.

3.3. WWD video data analysis at freeway off-ramps

As described in section 2.3, WWD video data were collected from two off-ramp sites (Alexander St. and I-4 in Plant City, FL and Busch Blvd. and I-275 in Tampa, FL) in the Tampa Bay region. These sites are flagged as high-frequency WWD sites and were chosen specifically for analysis. The data were recorded into spreadsheets, and the return rates were calculated for WWD vehicles that discontinue their WWD and make a U-turn upon radar detection and WWD countermeasure activation. Tables 2 and 3 depict the overall average return rate calculated for both of the off-ramp sites analyzed. The return rate was calculated by taking the “returned” vehicle count and dividing it by the sum of the “returned” and the “did not return,” which represents the total number of actual WWD field activations.

Table 2. Alexander St. @ I-275 off-ramp sites wrong-way driving video analysis

Month	Returned	Did Not Return	Return Rate
October '15	13	1	93%
November '15	16	2	89%
December '15	11	1	92%
January '16	15	3	83%
February '16	10	5	67%
March '16	1	0	100%
Total	66	12	85%

Table 3. Busch Blvd. @ I-275 off-ramp sites wrong-way driving video analysis

Month	Returned	Did Not Return	Return Rate
October '15	0	0	N/A
November '15	1	0	100%
December '15	1	0	100%
January '16	0	1	0%
February '16	1	1	50%
March '16	0	0	N/A
Total	3	2	60%

As observed from the WWD video data results for the Alexander St. @ I-275 and Busch Blvd. @ I-275, 85% and 60%, respectively, of the vehicles that triggered the radar and activated the red flashing beacons received the WWD warning message. The drivers of these vehicles positively reacted to the countermeasure by turning their vehicle around in the correct direction of traffic. Both of these are high return rates and hint at the possibility that not only older adults and the non-familiar driver population, but also some slightly-impaired drivers are successfully warned by the countermeasure. Therefore, these return rate values were found to be good indicators of the effectiveness of the flashing red beacons to alleviate WWD on freeway off-ramps.

4. Conclusions

Wrong-way crashes are a major cause of safety concerns along freeways and limited access facilities. Despite providing the necessary signage and pavement markings per the MUTCD, wrong-way entry onto limited access facilities is still occurring.

Based on a public opinion survey conducted for this study, a significant majority (69.5%) of participants selected the combination of placing “WRONG WAY” signs on both the left and right sides of an interstate off-ramp with red RRFBs activated at the top and bottom as the method that most attracts their attention and informs them of their WWD action. In addition, about 58% of participants selected the non-dimmed flashing red RRFBs over the dimmed option.

Field observations and detailed results from a series of statistical data analyses presented in this paper clearly demonstrated that driving behaviors on adjacent arterial roadways are not adversely affected by the implementation and flashing of red RRFBs at the off-ramps of freeways and limited access facilities.

In addition, as described in section 3.3., the "return rate" analysis of the WWD video data showed that 85% and 60% of the vehicles that triggered the radar and activated the red flashing beacons, received the flashing WWD warning message. The drivers of these vehicles positively reacted to this warning message by turning their vehicle around in the right direction of traffic. It is expected that red RRFBs will be more effective on alleviating wrong-way driving due to their higher intensity and speed compared to red flashing beacons. Future research might focus on obtaining specific information (age, gender, etc.) on wrong-way drivers to determine if there are significant differences between differing age groups and gender in their response to WWD countermeasures.

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