TECH**BRIEF**

Development of Crash Modification Factors for Wrong-Way Driving Treatments

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This document is a technical summary of the FHWA report, *Developing Crash Modification Factors for Wrong-Way-Driving Countermeasures* (FHWA-HRT-22-115).

INTRODUCTION

The Federal Highway Administration (FHWA) Development of Crash Modification Factors (DCMF) Program was established in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes (FHWA 2022a). Forty State departments of transportation (DOTs) provided technical feedback on safety improvements to the DCMF Program and implemented new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI PFS) (FHWA 2022b), which functions under the DCMF Program.

This project evaluated the safety effectiveness of geometry and access management modifications and the installation of traffic control devices (TCDs) implemented as safety treatments against wrong-way driving (WWD) crashes at freeway locations. The ELCSI-PFS Technical Advisory Committee selected the safety evaluation of WWD treatments as one of the priorities of the PFS.

Study Objective

This evaluation assessed the potential to reduce WWD crashes of geometry changes, access management modifications, and deploy TCDs by developing crash modification factors (CMFs) and benefit–cost (B/C) ratios for the safety improvements. Practitioners can use the CMFs and B/C ratios for decisionmaking in the project development and safety planning processes.

BACKGROUND

WWD crashes represent a small portion of the total crashes on freeways and highways, but because most of these crashes are higher-speed, head-on collisions, they result in more fatalities than do other crash types. Multiple past efforts have documented implementation and testing of various strategies and devices to reduce wrong-way movements. Researchers have studied four main types of countermeasures:

- Geometric design elements, such as channelization and access management strategies.
- Conventional TCDs, such as signs, pavement markings, and signals.

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- Enhanced TCDs, such as oversized signs, additional signs, low-placed signs, and retroreflective strips on signposts.
- Intelligent transportation system strategies, including detection, active warning, and driver notification components.

WWD crashes occur as a result of one or more vehicles traveling in the opposite direction of the legal traffic flow. The act of driving in the opposite direction might be intentional or unintentional, but the definition of WWD crashes excludes crashes resulting from median crossover encroachment (FHWA 2019).

In the United States, WWD crash studies were conducted as early as the 1960s in States such as California (Tamburri and Theobald 1965). However, in the early 2000s, WWD crash studies gained attention from researchers in the United States and internationally. In general, past studies showed that WWD crashes normally represent a small percentage of all crashes: The special investigation performed by the National Transportation Safety Board (NTSB) (2012) found that WWD crashes normally make up less than 3 percent of all crashes. These crashes, however, tend to be more severe because the collisions are often head-on impacts (Vaswani 1973, 1977; Cooner, Cothron, and Ranft 2004; Finley et al. 2014; Tamburri and Theobald 1965).

WWD Crash Characteristics

The locations and characteristics of WWD crashes are crucial elements for evaluating the strategies to position potential countermeasures. A literature review revealed the following categories for crash locations:

- Land use setting (rural versus urban).
- Facility type (freeway versus arterial).
- Location within the facility (ramp, intersection, midblock, or main lanes).
- Location with respect to the travel lane (turning lane, through lane, left lane, etc.).

Studies show that WWD crashes are more likely to occur in urban areas. According to one nationwide study, approximately 57 percent of WWD crashes occurred in urban areas (Baratian Ghorghi, Zhou, and Shaw 2014). In one statewide study for Arizona, the results were slightly lower than at the national level, with approximately 53 percent of WWD crashes occurring in urban areas (Simpson and Bruggeman 2015). With respect to facility types, some studies tend to clearly indicate that WWD crashes tend to occur mostly on freeways compared to arterials and other primary highways, whereas other studies indicate a shift toward arterial roadways (Tamburri and Theobald 1965; Copelan 1989; Vaswani 1977; Ponnaluri 2016).

Studies that identified the origin of WWD crashes on freeways revealed the following sites are the primary locations where wrong-way traveling vehicles originate (Lathrop, Dick, and Nolte 2010; Morena and Leix 2012; Zhou et al. 2012; Kayes et al. 2019):

- Entrance and exit ramps.
- U-turns.
- Partial cloverleafs.
- Diamond interchanges.
- Incomplete or partial interchanges.
- Compressed diamond interchanges.

Exit ramps accounted for 5 of 10 WWD crashes in New Mexico and 31 of 110 in Michigan (Lathrop, Dick, and Nolte 2010; Morena and Leix 2012). Two recent studies added several characteristics of exit ramps that are associated with WWD vehicle entry (Kayes et al. 2019; Atiquzzaman and Zhou 2018):

- Exit ramps with obtuse or right angles.
- Exit ramps with channelized islands between lanes.
- Exit ramps that have multiple lanes.

Partial cloverleaf interchanges represented approximately 61 percent of 31 crashes in Michigan and approximately 11 percent of 47 crashes in Illinois (Morena and Leix 2012; Zhou et al. 2012). In addition, the presence of a U-turn accounted for approximately 33 percent (4 of 12) and approximately 30 percent of crashes in New Mexico and Michigan, respectively (Lathrop, Dick, and Nolte, 2010; Morena and Leix, 2012).

TCDs

A recent study on divided highways found the following four strategies appear to deter WWD movements (Finley et al. 2018):

- DO NOT ENTER (DNE) and WRONG WAY (WW) signs on the outside of a wrong-way turn.
- Wrong-way arrow markings for the through lanes on the divided highway.
- The presence of a centerline in the median opening.
- Stop or yield lines when interior right-of-way treatments are provided.

These strategies could also be effective at preventing WWD events at high-speed divided highways and freeways.

Other countermeasures that have been of interest to researchers are flashing-based countermeasures, which include light-emitting diode (LED) signs and red rectangular flashing beacon (RFB) signs. Ozkul and Lin (2017) analyzed public opinion surveys and video data collected from six I–275 off-ramps in Tampa, FL, and concluded that the red rectangular rapid flashing beacons (RRFBs) are effective countermeasures to WWD incidents. According to their 6-mo video data, between 60 percent and 85 percent of the WWD vehicles performed corrective maneuvers when the red RRFBs were activated. Kayes, Al-Deek, and Sandt (2020) reported the percentage of self-corrected drivers was higher for RFB signs (69.4 percent) than for LED signs (48.1 percent) in comparison to ramps with nonflashing WWD countermeasures. Another study that compared the performance of two countermeasures for WWD—LED signs and RFB signs on I–70 in Florida—found that greater than 77 percent of the WWD incidents at the sites with RFB self-corrected, whereas approximately only 14 percent of the incidents self-corrected at sites with LED (Kayes et al. 2018).

STUDY DESIGN

The research team collected and assembled data for a cross-sectional estimation of the CMFs of interest (geometry and access management modifications, and installation of TCDs at freeway entry points). The study design was retrospective, whereby a robust database of case corridors (i.e., corridors in the vicinity of WWD crash locations) was supplemented with noncase corridors (i.e., corridors with no record of WWD crashes assembled in a similar way as the case corridors). The research team also decided to implement propensity score (PS)-based strategies to balance covariates in the analysis.

A cross-sectional retrospective evaluation enabled a large database to be developed. However, a retrospective analysis has the following important implications for the data collection and analysis stages:

- The countermeasures that can be evaluated are determined after the data collection, when an assessment of the prevalence of potential countermeasures is possible, because the data are collected on the basis of the history of WWD crashes rather than on the site characteristics.
- The retrospective distribution of variables (including the outcome variable) depends on the ratio of case-to-noncase locations and is different from the unconditional distributions obtained from a prospective design. Therefore, statistical methods used in risk analysis are appropriate to analyze retrospective designs because they produce odds ratios known to be independent of the two design types discussed. The unit of analysis for the evaluation was individual points of entry (POEs) because the countermeasures under evaluation would be identified at these locations. This decision required additional analytical efforts in sequence because the data collected included cases in which uncertainty existed about the true POE associated with each crash corridor.

DATA AND ANALYSIS METHODS

The empirical analyses were conducted using the statistical methods appropriate to the characteristics of the assembled datasets. The research team used generalized linear mixed model variants (binomial mixed) to obtain the safety effectiveness estimates of interest. For the analysis, the research team adopted the framework of PS weighting, setting the target population of sites at the overlap population as proposed by Li, Morgan, and Zaslavsky (2018). This choice of target population has a desirable small-sample exact balance property, and the corresponding weights minimize the asymptotic variance of the weighted average treatment effect within their class of weights (Li, Morgan, and Zaslavsky 2018). Under this scheme, the target population is the set of all sites that have comparable chances to be either in the upper quartile group (in terms of number of signs) or in the lower quartile group.

When estimating the average treatment effect of the countermeasure, this approach effectively curbs undue comparisons of sites from the lower quartile that are unlikely or ineligible to be in the upper quartile.

Due to the limitation of having a moderate two-State database with a relatively small number of crashes with confirmed POEs, the analyses were performed in two phases. In the first phase, only the subset of corridors that had crashes with confirmed POEs were considered. In the second phase, the analyses encompassed the larger database of corridors that had both crashes with known POEs and crashes with sets of their potential POEs weighted by the factors found linked to crash risk in the first phase.

DATA

The following three common data categories are required for crash-based evaluations:

- Crash data (including WWD flags and variables).
- Roadway inventory data.
- Traffic data.

Initially, the research team examined a variety of data sources and potential study locations that could yield enough data for the evaluation. The team procured candidate locations that would permit at least a few hundred WWD crashes for analysis, to be consistent with the selected retrospective cross-sectional study design. Table 1 shows the data sources that were pursued from Texas and Florida, the two States selected for the evaluation. The data sources in Florida are unrestricted, whereas access to Texas crash data is not available to the general public. However, the Texas DOT (TxDOT) allowed the research team access to these data sources.

For data manipulation and integration, the research team worked with GIS software (Esri™ 2019), spreadsheets,

Table 1. Available data sources in Texas and Florida.

STATE	CRASH DATA	TRAFFIC DATA	ROADWAY DATA
Texas	CRIS database, 2000–2019 (TxDOTa 2022)	CRIS database, 2000–2019 RHiNo database, 2014–2019. (TxDOTa 2022)	RHiNo database, 2000–2019. (TxDOTb 2022)
Florida	FDOT Open Data Hub, 2013–2016 (FDOT 2022)	FDOT Open Data Hub (2013–2016) (FDOT 2022)	FDOT Open Data Hub (FDOT 2022)

CRIS = Crash Records Information System; FDOT = Florida DOT; RHiNo = Roadway-Highway Inventory.

text files, and relational database software, where appropriate. Crash and countermeasure geolocations were the keys to data collection, reduction, and integration. However, any data without geolocation were integrated using appropriate database software and languages (Microsoft 2018). Finally, the data collection task included a quality assurance step by each team member and a final quality control step before the data analysis was conducted.

Definition of Crash Corridors

Because a limited number of WWD crashes matched to their corresponding POE was anticipated since the beginning of the study, the research team defined the following three stages of data collection for the study:

- In stage 1, case corridors were defined for each WWD crash, starting from the location of the crash, and continuing down in the wrong-way direction of travel until reaching a distance, *D*. Detailed data were then collected for all POEs within each WWD crash corridor.
- In stage 2, data were collected to determine whether the WWD crash in a corridor could have originated from one of the corridor's POEs. This determination required reviewing individual crash narratives in search of clues about the POE for each crash.
- In stage 3, the research team removed WWD crash corridors from the roadway network layer for a given facility of interest. Then, the research team selected random points of the remaining facilities of interest and considered the starting points of non-WWD corridors to be included in the analysis. Data for all POEs within each non-WWD corridor were then collected as in stage 2.

The definition of the distance, *D*, was based on reported traveled distances on freeways according to NCHRP Report No. 881 (Finley et al. 2018). The research team determined that $D = 6$ mi represents roughly the 85th percentile traveled distance between the POE and crash locations.

Corridors with confirmed crash-POE matches were analyzed during phase 1. The research team then used the results from the phase 1 analysis to produce crash risk estimates that would imply weights for each candidate POE in relation to a particular WWD crash for the phase 2 analysis. The phase 1 analysis produced estimates of WWD crash risk as a function of POE geometry, time of day, and position of the POE relative to the WWD crash location. In the phase 2 analysis, the research team analyzed all available corridors with POEs that were related to given WWD crashes. These data were weighted by the risk for WWD crashes based on the phase 1 analysis results.

ANALYSIS

Risk models with PS weights were developed for each WWD crash with known POEs. The weights were developed from PS models to represent the likelihood of a POE to belong to the upper quartile of the distribution of the number of select TCDs in display. CMFs were estimated by using the corresponding model coefficients in linear contrasts, which were representative of the conditions of interest, as appropriate.

Phase 1 Results

The following key groups of variables were considered in the model development for phase 1:

- The distance between each WWD crash and its confirmed POE.
- Annual average daily traffic.
- Multiple variables coding the time of day for each WWD crash.
- The type of traffic control at each POE.
- Variables coding geometric features of POEs.

After a round of modeling with the set of corridors with confirmed POEs, the research team arrived at the following results:

- Longer distances between the cross street and the beginning of a freeway off-ramp are most likely linked to a reduction in WWD crash risk.
- Time of day of WWD crashes influences the impacts of three other risk factors:
  - WWD crash/POE distance.

- Number of driveways and T intersections not signalized at frontage roads.
- Distinction between POEs connected to divided cross streets.

- WWD crash/POE distance is inversely proportional to the risk for WWD crashes. However, the interaction terms of this risk factor imply the following shifts in that trend:
  - The inverse relationship between WWD crash risk and WWD crash/POE distance is strengthened during the daytime. Shorter WWD crash/POE distances are more likely to occur during daytime than during nighttime.
  - The daytime risk of WWD crashes decreases with distance at a slower rate when additional driveways or unsignalized T intersections are present in POEs at frontage roads. This finding is intuitive because additional driveways or intersections represent increased chances of WWD maneuvers.
- In general, the frontage road configuration seems less prone to WWD crashes, but this trend varies with other variables in the model that are specific to frontage roads that have estimates in different directions. For example, the number of access points not signed on the frontage road is linked to an increase in WWD crash risk, whereas the number of signed access points is linked to a reduction in WWD crash risk.
- Regarding the facility type of the cross street, no difference in crash risk between divided and undivided cross streets at night exists, but the risk for a WWD crash during the daytime was significantly lower at divided facilities than at undivided facilities.

Phase 2 Results

Based on the results in phase 1, the research team incorporated the rest of the corridors for the next phase of analysis. Because the amount of the Texas data permitted subsets of appropriate sizes, the analyses were conducted by light condition (daytime or nighttime), facility type (either frontage road or ramps at intersections), and type of cross street (divided or undivided). From the developed models, CMFs were estimated for interventions involving geometry, access management, and TCDs. Table 2 summarizes statistically significant CMF estimates regarding geometry and access management interventions.

CMFs in Table 2 indicate that lengthening off-ramps and removing driveways from frontage roads could potentially reduce nighttime WWD crashes, whereas applying appropriate signage at T intersections and removing driveways at frontage roads were found to be effective against daytime WWD crashes. Next, Table 3 summarizes CMF estimates for WWD TCDs.

All CMFs in Table 3 indicate crash reductions for various base conditions and lighting levels. Next the research team performed similar analyses for the Florida database. However, given the reduced size of that database, only data representing off-ramps arriving at cross-street intersections were analyzed. Table 4 summarizes statistically significant results from the Florida analyses.

Although the magnitudes of the estimates are slightly more conservative for Florida, the estimates' directions are consistent with the findings in Texas.

Table 2. WWD crash CMFs for geometric features in Texas.

GEOMETRIC FEATURE	WWW CRASH TYPE	CMF	LOWER LIMIT (95% CL)	UPPER LIMIT (95% CL)	LOWER LIMIT (90% CL)	UPPER LIMIT (90% CL)	SIGNIF.
Additional 100 ft of frontage or off ramp[a]	Night	0.972	0.946	0.990	0.950	0.995	*
Driveway on frontage road removal[a]	Day	0.873	0.821	0.928	0.829	0.919	***
Driveway on frontage road removal[a]	Night	0.925	0.849	1.007	0.861	0.994	~
Add signage to T intersection on frontage road[a]	Days	0.635	0.442	0.912	0.468	0.862	*

~Significant at the 90.0 percent confidence level (CL).
*Significant at the 95.0 percent CL.
***Significant at the 99.9 percent CL.
[a]Base condition: frontage road intersecting divided cross street (urban and suburban).
Signif. = significance.

Table 3. WWD crash CMFs for TCDs at frontage roads in Texas.							
TCD	WWD CRASH TYPE	CMF	LOWER LIMIT (95% CL)	UPPER LIMIT (95% CL)	LOWER LIMIT (90% CL)	UPPER LIMIT (90% CL)	SIGNIF.
Additional WW_Sign[a]	Day	0.509	0.330	0.787	0.353	0.735	**
LANE_Path[a]	Night	0.416	0.201	0.860	0.225	0.767	*
STOP_Bar[a]	Night	0.129	0.026	0.652	0.033	0.505	*
One additional WW_Sign[b]	Night	0.153	0.028	0.637	0.037	0.833	*
Two additional WW_Signs[b]	Night	0.227	0.051	0.797	0.065	1.009	~
DNE, WW, or OW additional sign[c]	Night	0.623	0.402	0.965	0.431	0.900	*
STOP_Bar, WW_Arrow, or LANEUSE_Arrow[c]	Day	0.189	0.028	1.299	0.037	0.958	~
Presence of STOP_Bar, WW_Arrow, or LANEUSE_Arrow[c]	Night	0.227	0.051	1.014	0.064	0.800	~
Additional DNE_Sign[d]	Day	0.321	0.162	0.639	0.180	0.573	**
Additional DNE_Sign[d]	Night	0.640	0.424	0.905	0.452	0.966	*

~Significant at the 90.0 percent CL.
*Significant at the 95.0 percent CL.
**Significant at the 99.0 percent CL.
[a]Base condition: frontage road intersecting divided cross street (urban and suburban).
[b]Base condition: frontage road intersecting undivided cross street (urban and suburban).
[c]Base condition: off-ramp intersecting divided cross street (urban and suburban).
[d]Base condition: off-ramp intersecting undivided cross street (urban and suburban).
OW = ONE WAY.

Table 4. WWD crash CMFs for geometric features at nonfrontage roads in Florida.							
GEOMETRIC FEATURE	WWWW CRASH TYPE	CMF	LOWER LIMIT (95% CL)	UPPER LIMIT (95% CL)	LOWER LIMIT (90% CL)	UPPER LIMIT (90% CL)	SIGNIF.
Remove ramp lane[a]	Night	0.489	0.324	0.737	0.346	0.691	***
Additional DNE or WW sign[a]	Day	0.729	0.522	1.018	0.550	0.966	~

~Significant at the 90.0 percent CL.
***Significant at the 99.9 percent CL.
[a]Base condition: frontage road intersecting either divided or undivided cross street.

Economic Effectiveness

The research team estimated the economic viability of applying additional WW signs at potential POEs, with benefits derived from the ability of the sign to prevent WWD crashes. The estimated B/C ratio is 29.08 for this treatment. The team found the treatment to be beneficial, even when adding redundant signs. Repeating the calculations for the installation of two additional WW signs instead of one resulted in a B/C ratio of 21.96, or a B/C ratio of 13.83 when four such additional signs were installed.

Similarly, the research team estimated the benefit of installing DO NOT ENTER signs. The estimated B/C ratio is 55.7 for this treatment. The treatment was found to be beneficial, even when adding redundant signs. When the research team repeated the exercise for the installation of two additional DNE signs instead of one, the resulting B/C ratio was 37.4, or a B/C ratio of 21.1 when installing four such signs.

CONCLUSIONS

The objective of this study was to perform rigorous safety effectiveness evaluations of WWD crash countermeasures at freeways. Specifically, the study focused on the safety effectiveness of geometric features, access management strategies, and TCDs as potential countermeasures for WWD crashes. The study had a retrospective cross-sectional design, and the analysis was performed by using generalized linear mixed binomial models. The research team compiled safety data from 1,460 POEs in Texas and 644 in Florida, representing 463 and 256 WWD crashes, respectively, for 3-yr periods in each State. The team supplemented the datasets with non-WWD crash locations at each State, yielding 2,722 POEs for evaluation in Texas and 697 POEs in Florida for evaluation, with 375 and 110 WWD crashes, respectively, after data filtering and cleaning. Due to the limited number of crashes, the evaluations were performed by differentiating between only daytime and nighttime conditions. In addition to the crash data, the research team collected geometry information and traffic volumes at study locations. The team could only identify the true POE for a small fraction of the data in Texas by reviewing crash narratives, leaving the rest of the datasets with unknown origin of the WWD maneuver that led to the corresponding WWD crash.

All statistically significant CMFs were found in the analyses for the larger database in Texas, and two statistically significant CMFs were found in the Florida data. For geometric features, significant findings corresponded to both frontage roads and off-ramps to surface roads in Texas and off-ramps to surface roads in Florida. These analyses found that the chances of WWD crashes tend to be higher at locations with more ramps or ramp lanes and reduced at locations with longer ramps. Regarding CMFs for access management, the analysis of Texas sites with POEs at frontage roads produced CMFs indicating that adding vertical signage to frontage T intersections is linked to a statistically significant reduction of daytime WWD crashes. The same analyses found that WWD crash incidence tends to be lower with each removed driveway at frontage roads (between off-ramps and crossing roads), in terms of both daytime and nighttime WWD crashes. Finally, regarding TCDs, the Texas analyses found WWD crash reductions associated with adding WW signs, DNE signs, STOP signs, OW signs, and pavement markings for turning lane paths as well as at locations where stop bars are present on frontage road approaches when intersecting crossing roads. Similarly for Florida, statistically significant CMFs were found for removing ramps or ramps lanes at intersections with off-ramps and for additional WW and DNE signs at these locations.

The economic evaluation of deploying WW and DNE signs found large B/C ratios, with values greater than 1.0 indicating that these countermeasures are expected to produce more safety benefits than costs and therefore their installation is justified.

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