

Site-specific Safety Analysis of Diverging Diamond Interchange Ramp Terminals

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ABSTRACT

A site-specific analysis of the safety of Diverging Diamond Interchange (DDI) ramp terminals was conducted for the first time. Crash modification factors (CMFs) were developed for DDI ramp terminals for different crash severities. The ramp terminal CMFs complement the project-level DDI CMFs developed in previous research. Using data from twenty ramp terminals in Missouri, the safety evaluation was conducted using two before-after observational methods: Comparison Group (CG) and Empirical Bayes (EB). Due to inaccurate crash locations, a systematic crash location correction process was developed.

An extensive review of 8,400 individual crash reports was conducted for the calibration and safety evaluation. Both before-after safety evaluation methods produced consistent results. The DDI design replacing a conventional diamond decreased ramp terminal-related crashes for all severities. The most significant crash reduction was observed for fatal and injury (FI) crashes – 73.3% (CG) and 63.4%. Property damage only (PDO) crashes reduced by 21.0% (CG) and 51.2% (EB). The total crash frequency also decreased by 42.7% (CG) and 54.0% (EB). The EB CMF values for the DDI ramp terminal were: 0.366 for FI crashes, 0.488 for PDO crashes, and 0.460 for total crashes. This study also serves as a case study for conducting a site-specific analysis of ramp terminals or other interchange facilities. The methodology used in this study is transferable and can be used to quantify the safety effects of other innovative intersection and interchange designs.

INTRODUCTION

Alternative intersection and interchange designs offer creative solutions to improve safety and mobility in light of transportation funding shortages. The Diverging Diamond Interchange (DDI) design is one example of an alternative interchange design that has increased in popularity in the US. Since the opening of the first DDI in Missouri in 2009, 56 other DDIs have been constructed across the US with several more on the way (1). Despite their increased adoption, the safety of DDI design is still not well understood due to the lack of significant post implementation crash data.

A recent research study performed a collision diagram analysis before and after implementation at six locations in Missouri; the findings indicated that the DDI reduced severe angle crashes and traded them with less severe rear-end or sideswipe crashes (2,3). The project-level safety analysis of DDI conducted by Claros et al. (2) quantified the reduction in crash frequency for an entire interchange footprint. The project-level analysis combined all roadway facilities within the footprint i.e., ramp segments, ramp terminals, freeway segment, and speed-change lanes. The DDI design was found to significantly reduce crashes at all severity levels. The safety effectiveness estimates obtained could be used as a project-level Crash Modification Factor (CMF) for DDIs for an entire interchange footprint.

Another aspect of DDI safety that is currently being researched is the occurrence of wrong way crashes. Vaughan et al. (4) monitored five DDIs over a period of six months using video detection and reported that wrong way maneuvers commonly occurred when vehicles first entered the DDI and during nighttime conditions. They found, however, that none of the wrong way maneuvers witnessed during the study period resulted in a wrong way crash. In Missouri, Claros et al. (2) found that about 4.8% of all fatal and injury crashes occurring at the ramp terminal of a DDI were wrong-way crashes.

The current study aims to evaluate the safety effectiveness of DDIs at the site-specific level focusing on ramp terminals. The dataset consisted of ten operational DDIs from Missouri that have been opened for at least one year. The study methodology consisted of a safety evaluation using two observational before and after methods: Comparison Group (CG) and Empirical Bayes (EB). The study contrasts the methodological strengths and limitations of the two statistical methods when dealing with site-specific evaluations at interchanges. The CMF values for total, fatal and injury, and property damage only crashes for DDI ramp terminals were developed for the first time in this study. Since traffic movements on the crossroad are the most important difference between the operation of a DDI and a conventional diamond ramp terminal, CMFs capturing this difference provide valuable guidance to transportation agencies. Although this study utilized data from DDI sites in Missouri, the crash report review protocol, the calibration of ramp terminal Safety Performance Functions (SPF), and the safety evaluation methods used in the study can be applied to DDI data from other states. This study takes another step towards documenting the safety of DDI facilities.

The paper is structured in the following way. First, the DDI sites examined in the study are presented. The data requirements, including geometric, traffic, and crash variables, are discussed. Second, details of crash data processing are presented including the methodology developed to assign ramp terminal-related crashes and to correct crash reporting errors at interchange facilities. A total of 8,400 crash reports were manually reviewed in the study for calibration and safety evaluation. Next, the calibration of ramp terminal SPFs (5) for Missouri conditions is discussed. The calibration was conducted for the following four-leg ramp terminal with diagonal ramps (D4) types: signalized with two lanes, signalized with four lanes, and stop controlled. The applications of the two safety evaluation methods, including their strengths and limitations, are explained in the next section. The paper concludes with a discussion of the key findings and the quantification of ramp terminal CMFs for a DDI.

STUDY METHODOLOGY

Description of Sites

The dataset for the site-specific safety evaluation included ten operational DDIs in Missouri. Ten additional interchanges were used as control (comparison) sites for the CG method. Table 1 shows the characteristics of the DDIs and comparison sites. The DDI sites required data for before and after implementation. The data ranged from 36 to 51 months for the before period and 12 to 51 months for the after period. Sites with less than 12 months of after period data were not included in the study. Both before and after periods spanned the same months in order to account for seasonality. Additionally, data from the construction period was not included in the analysis. The posted speed limits on the crossroad ranged from 35 to 45 mph. The number of lanes (both directions combined) on the crossroad between the two ramp terminals also varied across DDI sites, ranging from 3 to 6 lanes. Additional information of the configuration type and distances between ramp terminals and adjacent intersections are shown in Table 1. Aerial images of the ten DDI sites are shown in Figure 1. Three of the DDIs were underpasses and the remaining seven were overpasses.

The characteristics of interchanges used as control sites for the CG analysis had to closely match the facility characteristics of the DDI sites before the DDI conversion. Identifying control sites for interchanges is more challenging than other facilities due to the complexity of their operations and the small number of interchanges. The nature of traffic control at the ramp terminals [stop control (ST), yield control (Y), protective permissive (PP) or protected only (PO)] was also an important consideration in selecting appropriate control sites. Lower half of Table 1 reports the characteristics of control sites selected in this study.

For calibrating the ramp terminal SPFs, the minimum sample size requirements recommended by the Highway Safety Manual (HSM) (6) were adopted. A total of 94 ramp terminals were used for calibration. The calibration sites met the base conditions of the SPFs, which included signal control type, number of through lanes, and designation area. A total of 30 sites were selected for D4 ramp terminal signalized with two lanes; 34 ramp terminals for D4 signalized with four lanes; and 30 ramp terminals for stop-control sites. These sites were obtained through random sampling across the state of Missouri.

Data Collection

The data collection consisted of extracting ramp terminal geometrics, traffic volume, signal operation, and crash data. The data was collected using different tools and databases. Geometric variables were collected using aerial images and the Automated Road Analyzer (ARAN) viewer from Missouri DOT's Transportation Management System (TMS), which allowed visualizing historical archives from previous years. Traffic volumes were also collected from the TMS database according to the facility and years of analysis. Due to some inconsistencies observed in crash reporting, crash data was collected for a buffer influence area beyond the interchange physical and functional footprint to capture ramp terminal queue related crashes on crossroads and freeways. Crash data for DDIs and comparison sites was collected for the before and after periods. For the calibration sites, crash data was collected for three years—2010 to 2012.

TABLE 1 DDI and Comparison Sites Characteristics

DDI SITES LOCATION	Opening Date	Periods (Months)		Crossroad			Conf. Type ⁴	Pedestrian Facility	Ramp Terminal Spacing (ft.)	Dist. To Adjacent Street (ft.)
		Before	After	Speed (mph) ¹	AADT ²	Lanes ³				
RT-13/I-44, Springfield, MO	6/21/2009	51	51	40	25215	4	Over	Median	530	320/685
I-270/Dorsett Rd., Maryland Heights, MO	10/17/2010	35	35	35	31405	6	Under	Roadside	480	265/635
James R. Exp./National Av., Springfield, MO	7/12/2010	38	38	40	31809	6	Over	Median	630	530/580
US-65/MO-248 Branson, MO	11/20/2011	44	22	35	31640	3	Over	Median	740	580/1795
I-435/Front St., Kansas City, MO	11/6/2011	44	22	40	23926	4	Under	Median	420	530/1955
Chestnut Exp./Route 65, Springfield, MO	11/10/2012	36	24	40	23351	4	Under	Roadside	370	160/475
US-60/Kansas Expy., Springfield, MO	8/18/2013	36	12	45	26002	5	Over	Median	600	470/1000
US-67/Columbia St., Farmington, MO	9/5/2012	36	24	40	11003	4	Over	None	700	800/420
I-70/Woods Chapel Rd., Blue Springs, MO	9/26/2013	36	12	40	16704	5	Over	Roadside	550	580/400
I-70/Stadium Blvd., Columbia, MO	10/14/2013	36	12	40	37951	3	Over	Median	420	380/550
COMPARISON SITES LOCATION	Median	Left Turn Signal IN ⁵	Exit Ramp Right Signal ⁶	Crossroad			Conf. Type ⁴	Pedestrian Facility	Ramp Terminal Spacing (ft.)	Dist. To Adjacent Street (ft.)
				Speed (mph) ¹	AADT ²	Lanes ³				
US-60/US-160, Springfield, MO	Marking	PO/PO	Y/Y	50	18757	5	Over	None	680	290/1000
I-170/Page Av., Overland, MO	Raised	PO/PO	Y/Y	40	33946	6	Under	None	400	530/550
US-65/Division St., Springfield, MO	Raised	PP/PP	Y/Y	45	12129	4	Over	None	440	220/440
US-65/Branson Hills Pkwy., Branson, MO	None	PP/PP	Y/Y	35	16717	5	Over	Roadside	680	430/430
I-435/23 rd Trfy., Kansas City, MO	Raised	PO/PO	Y/Y	45	20847	6	Under	None	310	890/225
US-65/Battlefield Rd., Springfield, MO	Raised	PP/PP	SC/SC	40	22452	4	Over	None	475	575/800
US-60/Campbell Ave., Springfield, MO	Raised	PO/PO	Y/Y	40	35107	5	Over	Roadside	600	350/390
US-67/MO-8, Desloge, MO	None	F/F	ST/ST	35	11657	4	Under	None	320	540/360
I-70/Little Blue Pkwy., Independence, MO	Raised	PO/PO	Y/SC	40	15730	6	Over	Roadside	680	1050/980
US-63/Grindstone Pkwy., Columbia, MO	Marking	PP/PP	SC/SC	50	32960	5	Over	None	470	250/260

Notes:

¹ Posted speed limit;² AADT of 2014 for reference purpose only;³ Lanes between ramp terminals (both directions combined). Some crossroads may be unbalanced with different number of lanes in each direction;⁴ Interchange crossroad configuration: overpass or underpass;⁵ IN = Left turns on crossroad segment between ramp terminals, PP = Protective Permissive, PO = Protected Only, F = Free;⁶ Y = Yield, SC = Signal Control, ST = Stop Control.



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RT-13/I-44 **FIGURE 1 Aerial Images of DDIs Used in the Study** I-270/Dorsett Rd.

Springfield, MO

Maryland Heights, MO

Crash Report Review

Crash reporting is the process of compiling information regarding the circumstances of a roadway crash and its participants. A police officer is in charge of documenting all relevant information on a crash report form. This officer is typically from a local police jurisdiction such as a city or county but can also be from the state highway patrol, such as the Missouri State Highway Patrol (MSHP). In the state of Missouri, the format of the crash report is the Missouri Uniform Accident Report MUAR (2002-2011) (7) and Missouri Uniform Crash Report MUCR (2012-present) (8). Both formats provide detailed instructions on how to complete the form. MSHP is the state depository for traffic crash reports with the responsibility of training officers to complete the reports following the Statewide Traffic Accident Records System (STARS) standards.

Unfortunately, consistency in crash reporting is difficult to achieve in practice due to various reasons. Some reasons include the differing experience level of police officers and supervisors, resources, available training, and crash report processing errors. One type of inconsistency is the inaccurate reporting of crash locations on freeway interchanges, the so-called crash landing problem. Currently, there is also no criterion to assign a crash to a facility based on queue-related conditions. The Missouri DOT practice considers a threshold of 132 feet from the center of an intersection. This is a significant problem for the safety analysis of freeway interchanges because of the importance of locating crashes on the appropriate interchange component, such as ramp terminals. Therefore a crash review methodology was needed, and it was developed for reviewing crash reports and assigning them to the appropriate interchange facilities, including ramp terminal crashes. The main objective of reviewing individual crash reports was to determine and verify if crashes actually occurred due to one of the ramp terminals of an interchange. Therefore, all crashes that were “*ramp terminal related*” were of interest. Ramp terminal related means that a crash occurred due to the ramp terminal geometric design, operational performance, and the influence of these factors in driver behavior. According to common crash reporting practices at intersections, crashes that are within a specified threshold from the center of the intersection or functional area are considered intersection-related crashes (5-6, 9). However, there are some specific exceptions to this practice. For instance, a crash that occurs beyond the specified threshold on the exit ramp segment or crossroad legs that are caused by queuing from the ramp terminal, is still ramp terminal related. Rear-end and sideswipe crashes due to the queued traffic from the ramp terminal are also considered ramp terminal related crashes (10). Figure 2 shows a diagram of the functional area of ramp terminals and the areas of queue related crashes at a conventional diamond interchange.

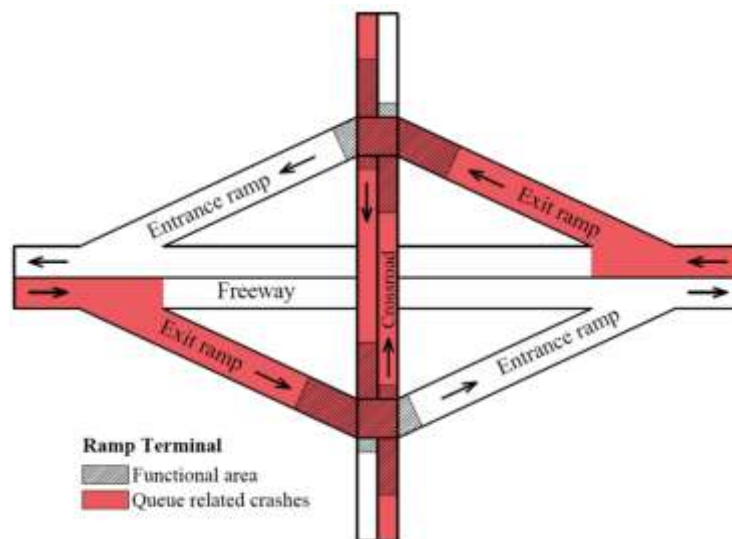


FIGURE 2 Ramp Terminal Functional and Queue Related Areas

Crash Report Information

Three items of interest were extracted from every crash report. These items were the location of crash, collision diagram, and narrative/statement of the police officer. These items had information overlap and were cross-checked for consistency with each other. When one of the items was incomplete, the other two items were used to fill in the gaps.

Location This section of the crash report provided a description of the specific location of the crash, i.e. the road in which the crash was assigned, the roadway direction, distance from reference location, and intersecting road. These fields helped to identify the road on which the crash occurred and the distance from the intersecting road. The accuracy of the distances and the reference point varied according to the officer who filled out the report.

Collision Diagram The collision diagrams on the crash report showed the circumstances and location of the crash. The legend provided crucial information for interpreting the direction of travel of each vehicle involved in the crash. The amount of detail contained in the collision diagrams depended upon the reporting agency and personnel. If the crash was reported afterwards at the police station or through a phone call, the crash report might not even have a collision diagram.

Narrative/Statements The narrative contained a written description of the crash and statements collected from witnesses and/or people involved in the crash. The details in this section were also subject to the experience and expertise of the reporting personnel.

Review and Assignment Procedure

STEP 1: Crash Location Review The first step in reviewing the crash reports was to determine the specific location of the crash. Initially, the travelway name, orientation, and direction of travel of the vehicle or vehicles involved are determined. The three fields of a crash report described earlier were used to find the specific location of the crash with respect to the interchange orientation. Additionally, an aerial photograph was used to locate and visualize the facilities of the interchange. The information provided in the location, collision diagram, and statement/narratives was sometimes inconsistent within the same report. Therefore, as a general rule, consistency in at least 2 out of the 3 sections was needed.

STEP 2: Crash Circumstances Review The second step of the review consisted of the examination of the crash events and related circumstances. The statements provided by the witnesses and people involved in the crash had to be carefully interpreted, because those were personal opinions, interpretations, and claims. Such statements might have been made to protect their own interests and to prevent negative consequences. A driver-made claim had to be confirmed by the officer's narrative. The narrative of the officer not only described the crash events but also stated the results of the investigation.

STEP 3: Assignment of Crashes to Ramp Terminals The assignment of crashes to the correct ramp terminal was the critical step of the entire review process. Crashes that were ramp terminal related were assigned to one of the two ramp terminals of the interchange. Some crashes were further eliminated, because they were rare events not related to the geometric design or operation of the interchange. The following list provides examples of such rare events encountered while reviewing the crash reports:

- Vehicle avoiding or hitting a wild animal in the functional area of the ramp terminal
- A crash generated by vehicles pulling over because of an emergency vehicle
- A crash generated due to police pursuit
- Vehicle malfunctioning or tire exploding
- Property damage by object flying out of a vehicle (e.g. windshield breakage or paint damage)

- Fatal or injured driver due to a drive-by shooting
- Crashes due to the presence of a work zone at the ramp terminal

Crashes in which a driver was distracted by a secondary task were not considered rare events. For instance, crashes involving cell phone use, lighting up a cigarette, drinking water, putting on sunglasses, or picking up an item from the passenger seat were not excluded, since other interchange-related factors also contributed to the crash.

Calibration of Ramp Terminal SPFs

The calibration of SPFs is the process of adjusting predicted crash frequency to reflect local conditions. The calibration accounts for factors such as driver behavior, crash reporting practices, and climate conditions (6). For collecting calibration data, a master list of sites was generated for signalized and stop controlled conventional diamond interchanges in Missouri. Sites were randomly selected from the master list to generate the sample set for calibration. Only sites whose geometric and operational conditions remained unchanged during the years used for calibration were included. If a site did not meet this criterion, another site was randomly sampled from the master list to replace it. The HSM recommends a dataset of 30 to 50 sites and at least 100 crashes per year for calibration (6). While signalized facilities satisfied these two HSM requirements, stop control facilities did not meet the ‘100 crashes per year’ requirement due to the low demand on these facilities. After the calibration sample set was established, data was collected to obtain the predicted crashes using the corresponding SPFs and CMFs presented in the supplemental chapters of freeway facilities in the HSM (5). Additionally, the observed crashes were collected for the period of three years between 2010 and 2012. The calibration factor is the ratio between the sum of observed and predicted crashes across all sites. Equation 1 shows the calibration factor calculation recommended by HSM (6).

$$C_i = \frac{\sum_{all\ sites} Observed\ Crashes}{\sum_{all\ sites} Predicted\ Crashes} \quad (1)$$

Safety Effectiveness Evaluation

The HSM defines safety effectiveness evaluation as the process of estimating change in safety due to a treatment, project, or group of projects. The evaluation of treatment safety effectiveness is critical to providing statistically rigorous estimates for decision-making and policy development (6). The design of before and after observational methods consists of using the before period to estimate what would have been the expected crashes in the after period had the treatment not been implemented and comparing that estimate with the actual observed crashes in the after period (11). In this study, the safety evaluation of DDI ramp terminals was examined using two before and after observational methods—Comparison Group (CG) and Empirical Bayes (EB). The HSM recommends at least 10 to 20 sites for a safety evaluation, and for the CG method, a minimum of 650 aggregated crashes at comparable sites (6).

Comparison Group Method

The concept of the Comparison Group (CG) is to identify a group of untreated facilities, similar to the treated facilities before the DDI, to estimate the measure of how safety would have changed for the treatment group. The assumption is that different factors influence safety in the same manner for treatment and comparison groups during before and after periods (11). Each comparison site was carefully selected to resemble traffic, geometry, and crash frequency of the treatment site before the DDI implementation. Also, a comparison site was selected from the same jurisdiction as the DDI site to ensure

similar driving population. The suitability of the comparison group was verified using the sample odds ratio test (6, 11).

The CG method also uses the HSM crash prediction methodology. It uses SPFs along with the corresponding CMFs and calibration factor (C_i) to predict crashes for each treated and comparison group facility with the before period characteristics:

$$N_{pred} = N_{spf} \times C_i \times (CMF_1 \times CMF_2 \times \dots \times CMF_j) \quad (2)$$

Where,

$$\begin{aligned} N_{pred} &= \text{predicted crash frequency (crashes/year);} \\ N_{spf} &= \text{predicted crash frequency for ramp terminal SPF (crashes/year)} \\ C_i &= \text{calibration factor for ramp terminal SPF;} \\ CMF_j &= \text{crash modification factor specific to a site type characteristic } j. \end{aligned}$$

The CG method is a significant improvement from other statistical methods such as the Naïve method (which considers only observed crash data) because it accounts for unrecognized or unmeasured causal factors. However, it does not account for regression to the mean bias. The reliability of CG results is anchored upon the assumption of similarity between comparison and treatment sites. Also, the CG method cannot consider treatment sites in which the observed crash frequency in the after period is equal to zero. Thus, it may underestimate the effectiveness of a treatment. In fact, a treatment may have been the most effective at locations where the observed crash frequency during after period was zero (6).

Empirical Bayes Method

For observational before-and-after studies, it is important to understand the underlying reasons for implementing a treatment. Sites chosen for implementing a treatment typically have either operational or safety problems. Thus, a selection bias is introduced into the sample. The Empirical Bayes (EB) method accounts for these sample selection issues and the resulting regression to the mean bias. The EB method also introduces the geometric, operational, surrounding area, and local condition characteristics into the prediction of crashes. The local conditions were included via the calibration factor (C_i).

SPFs have an additional parameter called the overdispersion parameter (k), which is calculated as part of the estimation process. As its name implies, it provides a measure of the overdispersion of the prediction from the SPF, which is a measure of the quality of the prediction. A larger overdispersion parameter leads to a greater variability in the prediction. The expected crash frequency in Equation 3 is calculated as the weighted average (w) of the observed crashes and the SPF predicted crash frequency.

$$N_{exp} = w \times N_{pred} + (1 - w) \times N_{obs} \quad (3)$$

Where the weight is determined using the overdispersion parameter of the SPF:

$$w = \frac{1}{1 + k \times N_{pred}} \quad (4)$$

And,

$$\begin{aligned} w &= \text{weight;} \\ k &= \text{overdispersion parameter of SPF;} \\ N_{pred} &= \text{predicted crash frequency using SPF;} \\ N_{obs} &= \text{observed crash frequency} \end{aligned}$$

This expected crash frequency is then compared with the observed crash frequency for the after period, using the odds ratio, as shown in Equation 5.

$$OR = \frac{N_{obs(after)}}{N_{exp(after)}} \quad (5)$$

Where,

OR = odds ratio;
 $N_{obs(after)}$ = observed crash frequency after treatment;
 $N_{exp(after)}$ = expected crash frequency in after period (with no treatment).

The comparison of expected and observed crash frequency for the after period forms the basis for deriving the safety effectiveness as shown in Equation 6. In equation 6, OR' is the adjusted odds ratio that accounts for regression to the mean. For more details on computing the adjusted odds ratio, the reader is referred to the HSM (6) or Hauer (11).

$$Safety\ Effectiveness\ (\%) = 100 \times (1 - OR') \quad (6)$$

RESULTS

Calibration of Ramp Terminal SPFs

After reviewing the crash reports for all facilities and correcting the crash locations, the calibration of D4 ramp terminal SPFs was performed. The calibration factors were developed for two severity levels: fatal and injury (FI) and property damage only (PDO). The calibration factors for signalized with two lanes were 1.087 for FI and 2.360 for PDO crashes; for signalized with four lanes were 0.853 for FI and 1.830 for PDO crashes; and for stop controlled were 1.290 for FI and 2.298 for PDO crashes.

The results of the calibration showed that the crash frequency at ramp terminals of a diamond interchange are generally higher in Missouri in comparison to the data used to develop the SPFs (i.e., Washington, Maine, and California) (5).

Safety Effectiveness Evaluation

The observed and the expected crashes obtained from the two safety evaluation methods are presented in Table 2. Results in the table are shown by crash severity for each DDI site, two rows for the two ramp terminals at each site. The sum totals of crashes occurring at 'all facilities' combined are shown in the last row. Thus, a total of 414 crashes consisting of 76 fatal and injury and 338 PDO crashes occurred at twenty DDI ramp terminals (i.e., 10 DDI sites) included in this study. Some DDI sites had significantly higher number of crashes than others (e.g., ramp terminals 1 to 6). This was partly because they were in operation for a longer time period.

If the observed crashes in the after period are less than the expected crashes, it means that the DDI had a positive safety benefit and helped to reduce the number of crashes. While the observed crashes were lower than the expected crashes for several DDI sites for the two methods, a few sites or methods indicated an opposite trend. The expected crashes for 'all facilities' combined were higher than the observed crashes for FI, PDO, and total (TOT) crashes, for both methods.

TABLE 2 Observed and Expected Crashes in the After Period

DDI Location	N.	FI ¹			PDO ²			TOT ³		
		Observed	Expected ⁴		Observed	Expected		Observed	Expected	
			CG ⁵	EB ⁶		CG	EB		CG	EB
RT-13/I-44	1	10	51	22	52	59	65	62	107	87
Springfield, MO	2	9	72	29	32	102	103	41	170	132
I-270/Dorsett Rd.	3	5	25	21	32	62	81	37	92	102

Maryland Heights, MO	4	9	46	34	47	121	166	56	178	201
James R. Exp./National Av.	5	6	38	18	44	29	36	50	60	54
Springfield, MO	6	12	67	26	43	61	67	55	118	93
US-65/MO-248	7	2	6	5	1	3	9	3	7	14
Branson, MO	8	1	7	7	9	9	22	10	16	29
I-435/Front St.	9	1	5	5	5	10	23	6	16	28
Kansas City, MO	10	0	2	5	4	7	17	4	10	22
Chestnut Exp./Route 65	11	2	7	5	6	10	15	8	17	20
Springfield, MO	12	8	10	7	17	7	14	25	15	21
US-60/Kansas Expy.	13	1	1	2	10	1	4	11	2	6
Springfield, MO	14	4	3	4	9	4	13	13	7	17
US-67/Columbia St.	15	1	4	3	5	5	9	6	9	11
Farmington, MO	16	0	5	4	8	14	23	8	21	26
I-70/Woods Chapel Rd.	17	3	1	2	10	3	9	13	4	11
Blue Springs, MO	18	1	1	1	3	1	4	4	3	5
I-70/Stadium Blvd.	19	0	1	3	1	1	5	1	2	8
Columbia, MO	20	1	3	5	0	1	6	1	3	12
All Facilities		76	356	207	338	510	692	414	856	899

Notes: ¹ FI denotes fatal and injury; ² PDO denotes property damage only; ³ TOT denotes total crashes;

⁴ The expected crash values were rounded (up) to facilitate comparison with observed crash values;

⁵ CG denotes Comparison Group method; ⁶ EB denotes Empirical Bayes method;

Each DDI location was divided by ramp terminal, numbered from 1-20.

The safety effectiveness values computed using the two methods are presented in Table 3. The values in each cell indicate percentage change (+ indicating a reduction after DDI) and its standard error expressed in parenthesis. The combined safety effectiveness across 'all facilities' are shown in the last row of Table 3. The safety effectiveness values for individual DDI sites were predominantly positive indicating a reduction in crashes after DDI. However, as noted earlier, a few sites had a negative safety effectiveness value indicating an increase in total crashes after DDI ('TOT' column in Table 3). Two ramp terminals witnessed a statistically significant increase in total crashes at the 95% confidence level with the CG method. These terminals were the ramp terminal on N.13 (i.e., US-60/Kansas Expy. interchange) and ramp terminal N.17 (i.e., I-70/Woods Chapel Rd.). Only one year of after DDI period data was available for these two sites. It is possible that the short duration of after period data may have contributed to the negative safety effectiveness values witnessed at these sites. For PDO and TOT crashes, negative safety effectiveness values were not statistically significant with the EB method. For FI crashes, all negative safety effectiveness value reported in Table 3 were not statistically significant for both methods.

In computing the combined 'all facilities' safety effectiveness values, the EB and CG methods considered both the crash trends and their variability at individual DDI sites. Therefore, extreme, albeit not-significant, trends witnessed at a few sites do not bias the aggregated estimate. The safety effectiveness values can be converted to crash modification factors. Although the combined safety effectiveness values are reported for the CG and EB methods in Table 3, this study recommends using the statistically rigorous EB method to generate CMFs for the ramp terminals of a DDI. The advantages of EB over CG method were discussed earlier in the methodology section. The EB results showed a reduction of 63.4% (4.7%) in FI crashes, 51.2% (3.3%) in PDO crashes, and 54.0% (2.7%) in TOT crashes (see Table 3), all estimates being significant at the 95% confidence level. Thus, the CMFs for DDI ramp terminals are as follows: **0.366 for FI crashes, 0.488 for PDO crashes, and 0.460 for TOT crashes.**

TABLE 3 DDI Ramp Terminal Site Specific Safety Effectiveness

DDI Location	N.	FI ¹		PDO ²		TOT ³	
		CG ⁴	EB ⁵	CG	EB	CG	EB
RT-13/I-44 Springfield, MO	1	80.5(7.5)	54.7(15.8)	13.1(17.8) ⁶	19.9(15.3) ⁶	42.2(10.2)	28.7(11.7)
	2	87.5(4.9)	68.8(11.2)	69.1(6.9)	69.1(6.6)	76.1(4.6)	69.1(5.6)
I-270/Dorsett Rd. Maryland Heights, MO	3	80.4(10.6)	76.5(11.1)	48.9(11.5)	60.6(8.4)	60.0(8.3)	63.9(7.0)
	4	80.5(7.9)	73.8(9.6)	61.4(6.9)	71.8(4.8)	68.7(5.1)	72.1(4.3)
James R. Exp./Nat. Av. Springfield, MO	5	84.5(7.4)	67.1(14.3)	-51.2(36.1) ⁶	-22.7(26.6) ⁶	17.1(16.8) ⁶	7.6(17.8) ⁶
	6	82.0(6.2)	54.1(14.6)	29.8(14.4)	36.1(12.4)	53.8(8.1)	41.1(9.6)
US-65/MO-248 Branson, MO	7	64.7(27.7)	58.0(29.7)	67.9(33.4)	88.9(10.9)	58.3(25.7)	78.2(12.8)
	8	85.8(15)	85.6(14.1)	3.8(36.9) ⁶	59.8(14.6)	38.3(21.9)	65.9(11.6)
I-435/Front St. Kansas City, MO	9	79.5(21.7)	79.8(19.8)	50.5(23.5)	78.0(10.1)	62.1(16.4)	78.4(9.1)
	10	100.0(0.1)	100.0(0.1)	39.9(32.1) ⁶	76.7(12.0)	60.0(21.2)	82.2(9.1)
Chestnut Exp./Route 65 Springfield, MO	11	72.7(23.1)	59.5(28.7)	40.6(28.6) ⁶	59.0(18.0)	53.8(19.3)	59.1(15.7)
	12	17.1(39.2) ⁶	-15.0(45.3) ⁶	-133.2(78.6) ⁶	-21.4(36.4) ⁶	-67.6(45.9) ⁶	-19.3(29.9) ⁶
US-60/Kansas Expy. Springfield, MO	13	-3.7(112.5) ⁶	35.5(62.8) ⁶	-882.8(410.0)	-150.2(90.7) ⁶	-486.9(222.1)	-98.3(66.9) ⁶
	14	-35.4(78.3) ⁶	-5.6(54.6) ⁶	-122.4(83.6) ⁶	33.2(23.8) ⁶	-87.3(59) ⁶	24.7(22.3) ⁶
US-67/Columbia St. Farmington, MO	15	73.7(29.9)	61.4(34.9)	2.1(53.5) ⁶	42.1(28.6) ⁶	32.2(33.3) ⁶	46.6(24.1)
	16	100.0(0.1)	100.0(0.8)	41.5(23.9)	65.0(13.5)	61.3(15.5)	69.8(11.5)
I-70/Woods Chapel Rd. Blue Springs, MO	17	-181.5(209.5) ⁶	-30.4(77.2) ⁶	-276.1(141.8)	-9.6(38.1) ⁶	-220.5(107.3)	-13.8(33.9) ⁶
	18	32.6(74.9) ⁶	-13.4(110.4) ⁶	-115.4(139.8) ⁶	28.2(42.3) ⁶	-51.1(84.5) ⁶	21.0(40.4) ⁶
I-70/Stadium Blvd. Columbia, MO	19	100.0(0.1)	100.0(0.1)	4.8(100.3) ⁶	79.4(20.1)	54.0(47.6) ⁶	86.8(13.0)
	20	64.2(37.6)	81.2(18.5)	100.0(0.1)	100.0(0.1)	69.6(31.2)	91.4(8.6)
All Facilities		73.3(3.6)	63.4(4.7)	21.0(5.6)	51.2(3.3)	42.7(3.6)	54.0(2.7)

Notes: ¹ FI denotes fatal and injury; ² PDO denotes property damage only; ³ TOT denotes total crashes;

⁴ CG denotes Comparison Group method; ⁵ EB denotes Empirical Bayes method;

⁶ Not significant at the 95% confidence level;

Safety Effectiveness % (Standard Error %); Negative safety effectiveness values denote an increase in crashes.

CONCLUSIONS

The safety performance of novel alternative designs can be a motivating factor for their selection by transportation agencies facing the challenge of identifying creative solutions to address congestion and safety concerns at interchanges and intersections. Although the DDI design has been increasingly adopted by several states within the last five years, safety performance of the design is still not well documented. This paper takes a step forward in this direction and quantifies the safety of a ramp terminal of a DDI as compared to a conventional diamond interchange. Using data from twenty DDI ramp terminals in Missouri, this study was the first attempt at developing a crash modification factor for DDI ramp terminal facilities. This site-specific safety analysis of ramp terminals complements the project-level safety analysis and interchange-level CMFs developed in Claros et al. (2).

Conducting a site-specific safety evaluation can be challenging. The primary challenge faced in this research was the proper identification of crashes that can be attributed to the ramp terminal. A methodology was developed to review crash reports and generate consistent crash assignment to the ramp terminal facilities. The methodology involved an extensive review of crash reports including police officer narratives and collision diagrams. A total of 8,400 crash reports were reviewed.

The safety evaluation consisted of two types of observational before-after evaluation methods: Comparison Group (CG) and Empirical Bayes (EB). The two before-after safety evaluation methods produced consistent results. The DDI design replacing a conventional diamond decreased ramp terminal-related crashes for all severities. The most significant crash reduction was observed for fatal and injury crashes -73.3% (CG) and 63.4% (EB). Property damage only crashes reduced by 21.0% (CG), and

51.2% (EB). The total crash frequency also decreased by 42.7% (CG) and 54.0% (EB). The safety effectiveness results for the twenty terminals also demonstrated that FI, PDO, and TOT crashes decreased at most sites after DDI implementation.

The EB CMF values for the site-specific DDI ramp terminal of 0.366 for FI crashes, 0.488 for PDO crashes, and 0.460 for TOT crashes were all smaller than the project-level DDI CMF values of 0.374 for FI crashes, 0.649 for PDO crashes, and 0.592 for TOT crashes (2). This finding indicates that the ramp terminals in a DDI design experience higher reduction in crashes (as compared to a traditional diamond) than some other interchange facilities such as ramp segments or speed-change lanes.

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