Safety Evaluation of Diverging Diamond Interchanges in Missouri

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ABSTRACT

The Diverging Diamond Interchange (DDI) has gained in popularity since its first implementation in the United States in 2009. The operational benefits and lower costs of retrofitting a conventional diamond with a DDI have contributed to their increased use. Existing research on DDIs has focused primarily on the assessment of operational benefits. Unfortunately, formal safety evaluations of DDIs are lacking. This study aims to fill the knowledge gap by conducting a safety evaluation of DDIs using three types of before-after evaluation methods: Naïve, Empirical Bayes (EB), and Comparison Group (CG). Three evaluation methods were used since the methods involved different trade-offs, such as data required, complexity, and regression-to-the-mean. All three methods showed that a DDI replacing a conventional diamond decreased crash frequency for all severities. The highest crash reduction was observed for fatal and injury (FI) crashes – 63.2% (Naïve), 62.6% (EB), and 59.3% (CG). Property damage only crashes were reduced by 33.9% (Naïve), 35.1% (EB), and 44.8% (CG). Total crash frequency also decreased by 41.7% (Naïve), 40.8% (EB), and 47.9% (CG). A collision diagram analysis revealed that the DDI, as compared to a diamond, traded high severity for lower severity crashes. While 34.3% of ramp terminal-related FI crashes in a diamond occurred due to the left turn angle crashes with oncoming traffic, the DDI eliminated this crash type. One potential concern for the DDI is the possibility of wrong-way crashes, but only 4.8% of all fatal and injury crashes occurring at the ramp terminal of a DDI were wrong-way crashes. In summary, the DDI offers significant crash reduction benefits over conventional diamond interchanges.

INTRODUCTION

Recently in the US, the diverging diamond interchange (DDI) has become a popular alternative to other forms of interchange designs. Since the first DDI installation in Springfield, Missouri, in 2009, there have been more than 30 locations across the US where DDIs have been installed. Three factors have contributed to this rapid adoption of the DDI in the US. First, the operational benefits of the DDI, including lower overall delay and higher left turn movement capacity *(1, 2)* compared to a conventional diamond, have made it an attractive alternative. Second, the lower costs of retrofitting an existing diamond interchange with a DDI have also played an important role in its adoption. For example, a cost comparison between the DDI and the Tight Urban Diamond Interchange (TUDI) in Kansas City, Missouri, showed the DDI cost approximately 50% less *(3, 4)*. Third, fewer conflict points compared to a conventional diamond along with positive safety results from limited safety evaluations *(2)* have provided further encouragement about the merits of the design.

The main impetus behind the initial research on DDI was to evaluate its operational benefits as compared to other designs. While the seminal study of Chlewicki *(5)* illustrated the delay savings resulting from a DDI, the follow-up studies by Bared et al *(1)* and Edara et al *(2)* further confirmed its operational benefits, specifically the doubling of left turn movement capacity. Several subsequent studies have agreed with these early studies on the operational benefits of DDIs *(6, 7)*. Because the motivation behind the initial research into the DDI was improving operational benefits, there has been a gap in the existing knowledge pertaining to the safety performance of the DDI. A preliminary assessment of the safety of an intersection or interchange design can be obtained using conflict points. Figure 1 shows the conflict points for both a DDI and a conventional diamond interchange. The DDI has 18 conflict points (2 crossing, 8 merging, and 8 diverging) while the conventional diamond interchange has 30 conflict points (10 crossing, 10 merging, and 10 diverging) *(3, 6, 8)*. Fewer conflict points across all conflict types reduce the exposure of traffic to crashes. Importantly, 8 out of 10 crossing conflict points are eliminated by the DDI design. Crossing conflicts typically result in right angle collisions that have a higher potential for injuries *(3)*.

FIGURE 1 Conflict Points at DDI and TUDI Interchanges *(8)*

Typically, empirical safety evaluations of new alternative designs are not possible until a few years after they are introduced into practice due to the lack of sufficient crash data. One study *(7)* reviewed crash data for a one-year period after the first DDI was constructed in Springfield, Missouri. The study concluded that the DDI was operating safely based on a comparison of before and after crash frequencies. But the small sample size did not allow for a rigorous statistical safety evaluation.

Due to the crossover of traffic at the two ramp terminals in a DDI, there was some initial apprehension about the potential for wrong-way crashes *(5)*. Some of these concerns were alleviated through human factor studies conducted by the Federal Highway Administration (FHWA). Using driver simulator studies, FHWA showed that wrong-way maneuvers were minimal and not statistically different from those at a conventional diamond interchange *(9)*. There are no empirical studies using real-world crash data either confirming or denying the higher frequency of wrong-way crashes at a DDI. There are also no empirical studies analyzing differences in the types and frequencies of crashes occurring at a DDI and a conventional diamond.

The current study aims to fill the knowledge gap in the safety of the DDI. Data from six sites in Missouri were used to conduct a before-after evaluation of the DDI. Missouri was the first state to have built a DDI and has the largest number of DDIs built or under construction (15 as of July 2014). Thus, Missouri offers a rich dataset for conducting a safety evaluation of DDIs. The safety evaluation consisted of three types of observational before-after evaluation methods: Naïve, Empirical Bayes (EB), and Comparison Group (CG). Collision diagram analysis was also conducted to determine differences in crash types between a DDI and a conventional diamond.

This study makes a few key contributions to the body of literature on DDI performance. First, this is the first study to conduct a system-wide safety evaluation using multiple DDI sites. Second, this study offers the first extensive safety evaluation of DDI using three before-after analysis methods. Third, crash modification factors (CMF) for total, fatal and injury, and property damage only crashes for a DDI were developed for the first time in this study. The CMF values provide the expected reduction in crashes achieved by a DDI as compared to a conventional diamond interchange. Fourth, an extensive review of the collision diagrams was conducted to derive trends in the types of crashes before and after a DDI were installed at the study sites.

METHODOLOGY AND RESULTS

Site Selection and Data

The before-after safety analysis of DDI designs implemented in Missouri was conducted using data from six DDI sites. Six additional sites were used as comparison sites for comparison group analysis. Although there were ten operational DDI sites in Missouri at the time of this research, four sites were recently opened to traffic and did not have enough crash data for the after-installation period. Table 1 contains the following characteristics of the six DDI locations: traffic volume, date open to traffic, the duration of before and after periods, and geometric characteristics.

The duration of before and after periods was determined by taking into account seasonality and construction effects. Initially, five years of crash data were processed for the before period, and the after period duration varied depending on the opening date of the DDI. The after period ranged from 1 year to 4 years for the six sites. In order to avoid the effect of construction activity, crashes that occurred during the construction period were not included in the after period data. Seasonality was also accounted for by matching the months included in the before period with that of the after period. All six DDI designs replaced conventional diamond interchanges. Pedestrian crossings were implemented in the median or roadside as listed in Table 1. The last two rows in Table 1 describe the traffic control for left turn movements from the crossroad to the entrance ramp, and the right turn movements from the exit ramp to the crossroad.

The data necessary for conducting the before-after analysis were obtained from several sources. Aerial photographs were used to measure distances and determine geometric characteristics. The Automated Road Analyzer (ARAN) viewer from the MoDOT Transportation Management System (TMS) database allowed for facilities to be viewed for different years and at specific log miles, which enabled the estimation of short distances such as lane widths and median widths. Computer Aided Design tools were used to measure horizontal curve distances and radii of ramps and freeway facilities. Traffic data was obtained from the MoDOT TMS database for different locations and years within the study period.

TABLE 1 DDI Site Characteristics

Crash data was collected for the entire interchange footprint for the study periods reported in Table 1. The footprint included the influence areas of all interchange components. For the freeway, crashes were included from the beginning of speed change lanes to end of speed change lanes in both directions of travel. For the crossroad, the influence area included 250 ft. (76 m) from the ramp terminals, and crashes were collected for the ramp terminals and the crossroad segment in between the terminals. Collision diagrams were also obtained for fatal and injury crashes during both before and after periods. The diagrams provided additional information regarding the circumstances and details of the type of crashes.

Crash Severity Analysis

The severity of crashes was studied during the before and after periods. The crash data was classified into four severity types: minor injury, disabling injury, fatal, and property damage only (PDO). The crash data was aggregated across all six sites by severity type, and the annual crash frequency was calculated and shown in Figure 2 ('All Facilities'). The percentage reductions in crash frequency for all facilities were 57.7% for FI, 26.4% for PDO, and 34.7% for TOT after DDI implementation. There were no fatal crashes at any of the six sites before the installation of DDI. There was one pedestrian fatality that occurred during the after period at one site, but the details of that crash were unknown since it was a hit and run that occurred late at night. Since the fatal crash occurred within the footprint of the DDI, it was still included in the safety evaluation in this study. Figure 2 also presents the aggregate crash frequency of all injury crashes denoted by FI (fatal and injury), Property Damage Only (PDO) crashes, and the total number of crashes denoted by TOT.

FIGURE 2 Crashes per Year by Severity during the Before and After Period

Crash Type Analysis

The crash report images for fatal and injury crashes occurring at ramp terminals were reviewed to identify any differences in the types of crashes occurring at a conventional diamond versus a DDI. Collision diagrams were created to visualize the frequency of various types of crashes. A collision diagram is a useful intersection safety tool, for example, for roundabout safety evaluations *(10)*.

The crash reports follow the statewide Missouri Uniform Crash Report (MUCR) format. The Missouri State Highway Patrol is the state depository for traffic crash reports with the responsibility of training their officers to complete the reports following the Statewide Traffic Accident Records System standards (STARS) *(11)*. All crashes within the footprint of the interchange were landed at the specific reported location of the crash for both periods separately. Although crashes occurring at all interchange facilities were reviewed, only the crashes occurring at the ramp terminals or related to the ramp terminals were analyzed using the collision diagrams. This focus on ramp terminals was due to the fact that the primary difference between the conventional diamond and a DDI is the configuration of ramp terminals and the interaction between traffic movements at the terminals.

The collision diagrams generated for the before and after period are shown in Figure 3. In generating Figure 3, crashes occurring over the same period before and after DDI were included for each site. Sites 1, 2, and 3 had the same duration of before and after periods (see Table 1). However, for sites 4, 5, and 6, the duration of after period was shorter than the before period. Thus, the duration of before period for sites 4, 5, and 6 was reduced to match the shorter after period. This adjustment in the duration allowed for a fair comparison of the before crashes (traditional diamond) with the after crashes (DDI), since they occurred over the same duration. It is important to note that this adjustment in duration was only done for collision diagram analysis, the crash frequency analysis previously discussed and the safety evaluation (Naïve, EB, CG) procedures used the actual durations listed in Table 1. For the collision diagram shown in Figure 3, the crashes were classified into 14 different types for the before and after periods. Although the total number of crash types was 14 in both periods, the types of crashes were different. The top two crash types in the before period at the conventional diamond ramp terminals were, 1) collision of left turn movements from inside the crossroad and the oncoming through movement, and 2) rear end collisions on the exit ramp at the intersection.

FIGURE 3 Before / After Collision Diagrams for Fatal and Injury Crashes

In the after period for the DDI design, the top two crash types were, 1) rear end collisions between right turning movements on the exit ramp at the intersection, and 2) rear end collisions on the outside crossroad approach leg to the ramp terminal (see Figure 3). It was also observed that some other types of crashes distributed across the different legs of the DDI ramp terminal increased, but all these crashes were of lower severity. For instance, sideswipes at the different merging and diverging locations, and the loss of control in the bays while making turning movements, increased with the DDI; however, none of these types of crashes resulted in any severe injuries. Thus, the DDI design traded a severe crash type, right angle left turn crash, with less severe rear end, sideswipe, and loss of control crash types. The wrong way crashes inside the crossroad between the two ramp terminals accounted for 4.8% of the crashes occurring at the DDI.

Safety Effectiveness Evaluation

Safety effectiveness evaluations use quantitative estimates of how a treatment, project, or a group of projects affected crash frequencies or severities. The effectiveness estimate is useful for future decision-making and policy development *(12).* The observational before and after evaluation methods used in this study compared the anticipated safety of a site without the treatment in the after period to the actual safety of the entity with the treatment in the after period *(13)*. Three different methods were selected to evaluate the safety effectiveness of the DDI: Naive, Empirical Bayes (EB), and Comparison Group (CG). These methods were selected due to their different approach and use in previous safety research *(12, 14)*. An interchange was considered as the entire facility or project, by aggregating the various facilities within its footprint. This approach is commonly known as the "Project Level" analysis in the HSM *(12)*. The facilities within the interchange footprint include ramp terminals, ramp segments, speed-change lanes, and freeway segment.

The project level analysis was chosen instead of a site-specific analysis for two reasons. First, some data inconsistencies were found in the crash data. For example, crashes occurring at one of the two ramp terminals at an interchange were sometimes placed by the police at the midpoint between the two terminals on the crossroad. There were a few instances when a crash that occurred on an exit ramp was placed on the freeway mainline. Such "crash landing" issues were observed after reviewing a sample of crash reports. Without accurate information on the frequency of crashes occurring on each interchange facility, it was not possible to conduct a site-specific analysis. The second reason for choosing the project level analysis was the usefulness of the developed CMF values for DDI. When a DDI replaces an existing diamond interchange, the ramp terminals and crossroad undergo the most significant changes. However, other facilities such as ramp segments and speed-change lanes within the interchange also undergo some changes. Thus, choosing the interchange as the unit of analysis takes into account changes applied to all interchange facilities. State transportation agencies are often interested in knowing the safety effect of replacing a diamond interchange with a DDI more than the changes occurring at the facility level. A project-level analysis would provide an estimate of this safety effect. Although the analysis was performed for entire interchanges, the crash frequency prediction was still performed at the facility level when applying the EB and CG methods.

Naive Method

The main impetus behind the Naïve before-after evaluation method is that the change in safety from the before period to the after period is the result of all the changes that may have occurred at the site, including the effect of treatment. The treatment may not be the only change that occurs at a site and thus attributing the change in safety to the applied treatment alone may not be accurate. Instead, the Naïve method assumes that the change in safety is caused by all factors that may have changed from the before period to the after period *(13)*. The safety effectiveness is calculated using the expected number of crashes and the actual observed number of crashes for the after period as discussed by Hauer *(13).*

Empirical Bayes Method

The second before-after method, Empirical Bayes (EB), has been used in previous studies to evaluate the safety effectiveness of alternative intersection designs *(14)*. The EB method is also recommended by the Highway Safety Manual (HSM) *(12)* for conducting safety evaluations. The HSM discusses many safety effectiveness performance measures, such as percent reduction of crashes, shift in crash type and severity, and crash modification factors (CMF) *(12)*. For observational before-after studies, it is important to understand the underlying reasons for implementing a certain treatment. Sites chosen for implementing a DDI typically have either congestion or safety problems. Thus, a selection bias is introduced into the sample. To account for this bias and the resulting regression to the mean, the HSM recommends using the EB method.

The EB method utilizes safety performance functions (SPF) to estimate the average crash frequency for treated sites during the after period as though the treatment had not been applied *(12)*. This estimated average crash frequency is then compared with the actual crash frequency during the after period. The expected crash frequency is calculated as the weighted average of the observed crash frequency and the SPF-predicted crash frequency. The weights are determined using the overdispersion parameter of the SPF and are not dependent on the observed crash frequency. The comparison of expected crash frequency and observed crash frequency for the after period forms the basis for deriving safety effectiveness *(12)*.

Missouri is currently calibrating its interchange facilities according to the soon-to-be-released HSM freeway chapters *(16)*; thus, interchange calibration factors are not yet available. Due to the lack of calibration factors, a calibration factor of 1.0 was used for the interchange facilities. Despite this assumption, the results of EB can still provide a useful estimate of the safety effectiveness of DDI.

For project level analysis, the predicted crash frequency for the whole interchange was obtained by summing the predicted values for all interchange facilities. The expected interchange crash frequency was calculated using a weighted average of all the facilities of an interchange, taking into account correlations among the facilities as recommended by the HSM *(12)*. According to Hauer et al *(13, 15)*, there are two bounds of correlation: perfectly correlated and independent facilities. The weight adjustment factors for the two bounds of correlation were computed. For partial correlation conditions, Bonneson et al. *(16)* recommend averaging the expected crash estimate of the perfect correlation and independent conditions.

Comparison Group

A before and after comparison group method compares the after period crash frequency of treatment sites (DDI) with the crash frequency of a set of control (or comparison) sites. One comparison site was chosen for each treatment site. Each comparison site was carefully selected by matching the traffic, geometric characteristics, and crash frequency (during the before period) of the treatment site. The set of comparison sites is called the comparison group. The basic characteristics of all six sites in the comparison group are presented in Table 2.

The geometric features considered were the number of lanes, horizontal curves, left turn lanes on the crossroad, presence of median, and signal control. The geometric features and the AADTs of the comparison facilities were tracked over the study period to ensure that they did not vary significantly or witness high traffic volumes fluctuations over the years. The comparison group consisted of a yoked comparison, which is a special case where a single comparison site is matched to one treatment site based on similar conditions *(17)*.

The suitability of the comparison group was verified using the sample odds ratio test presented by Hauer *(13)*. This test compares crashes over a specified time period for the comparison and treatment groups during a period before the treatment was implemented. If the mean of the sequence of odds ratios is sufficiently close to 1.0 and the confidence interval includes the value of 1.0, then the candidate comparison group is considered a good candidate *(13,17)*.

The CG safety effectiveness is calculated using both observed crash data and predicted values. In the first step, SPFs are used to determine the predicted crashes for both before and after periods, and for treated and comparison sites. An adjustment factor by severity, for each period, is then calculated for each pair of treatment and comparison sites by dividing the total number of predicted crashes for the treatment site and the total number of predicted crashes for the comparison site. Each treated site is compared to all the comparison sites, thus there are adjustment factors for each pair of treatment and comparison site. The expected crashes for comparison and treatment sites are then calculated using the adjustment factors and observed crashes. The safety effectiveness values for each site and for the entire treatment group are computed using the expected and observed crashes. The HSM provides the necessary equations and an illustrative example for computing the adjustment factors, expected crashes, and the safety for the CG method *(12)*.

Results of Safety Effectiveness Evaluation

Naïve Method

The odds ratio and safety effectiveness were computed for three types of crashes – fatal and injury only crashes (FI), property damage only crashes (PDO), and total crashes (TOT). The safety effectiveness results showed a 41.7% (2.9%) reduction in total crash frequency after DDI implementation. The value in the parenthesis denotes the standard error of the estimated safety effectiveness. The FI crash frequency experienced the greatest reduction of 63.2% (4.1%), while the PDO crash frequency decreased by 33.9% (3.7%). All reductions were statistically significant at the 95% confidence level.

As previously discussed, the Naïve method can only estimate the cumulative effect of all changes that have occurred at the treatment sites during the study period. It is however, not possible to ascertain the individual effects of the safety treatment using the Naïve method. Variability of traffic, road user behavior, weather, and many other factors could change over time *(13)*. Nevertheless, the Naïve method still serves as a good starting point for the safety analysis due to its statistical accuracy, and it has been frequently used in safety evaluations as it provides a precise upper bound *(13)*.

Empirical Bayes Method

The project-level EB method was applied to conduct the safety evaluation. The safety effectiveness values were calculated for the three correlations previously discussed: independent, fully correlated, and partially correlated. The results for the three crash types are shown in Table 3. In Table 3, the observed crashes, the EB expected crashes, and the safety effectiveness values for each site are reported in different rows. The standard error values are also reported in parenthesis next to each safety effectiveness value. The right-most column provides the results for the entire treatment group (combination of all six sites).

Since the actual correlation among the interchange facilities is not known, the safety effectiveness values obtained assuming partial correlation can be used for determining the crash modification factors for the DDI *(16)*. The safety effectiveness values for partial correlation are highlighted in red bold text in Table 3. For the entire treatment group ('All Sites' column in Table 3), the percentage reduction in crashes was the greatest for FI crashes, at 62.6% compared to the 35.1% for PDO and 40.8% for TOT crashes. These findings are consistent with the results of the crash severity analysis and the Naïve method. The left turn angle crashes that were predominant in the traditional diamond design (before period) were completely eliminated in the DDI design (after period), which accounts for the reduction in severe crashes.

The EB results for individual sites (see Table 3) showed that the DDI was effective at decreasing the FI crashes at all six sites, although the reduction at the sixth site was not statistically significant at the 95% confidence level. The PDO crashes also decreased at all six sites with the reductions statistically significant at all but sites 3 and 6. The TOT crashes also decreased at all six sites and the reductions were statistically significant at all but site 6. The lack of statistical significance of the EB results for site 6 was due to two reasons. First, the duration of the after period for site 6 was the smallest among all six sites at

10 months. Second, the observed crash frequencies per year before DDI (10 FI, 24 PDO, 34 TOT) and after DDI (9 FI, 24 PDO, 32 TOT) were not considerably different.

Comparison Group Method

For computing the sample odds ratio, a time frame of five years was chosen (2004 to 2009) before any DDI in the treatment group was implemented. The mean, standard error, and the 95% confidence interval of the sample odds ratio were computed. The mean value for FI, PDO, and TOT crashes were 0.97 (0.31 standard error), 1.01 (0.20), and 1.00 (0.22), respectively, all close to 1.0. All 95% confidence intervals also included 1.0. Based on the sample odds ratio results and confidence intervals, the comparison group was deemed to be suitable for comparison with the treatment group following the FHWA guidelines for developing crash modification factors *(17)*.

The safety effectiveness was then calculated using the comparison group method previously discussed. The CG method produced safety effectiveness values (and standard errors) of 59.3% (4.8%) reduction in FI crashes, 44.8% (3.3%) reduction in PDO crashes, and 47.9% (2.7%) reduction in TOT crashes, all significant at the 95% confidence level.

TABLE 3 Project-level EB Results

The safety effectiveness results obtained from the Naïve, EB, and CG methods are compared in Table 4. The safety effectiveness values for each category (FI, PDO, TOT) are shown in different rows for the three methods. Again, the standard error values are reported in parenthesis next to each safety effectiveness value. The overall safety effectiveness values for the entire treatment group are also shown in the right-most column.

TABLE 4 Safety Effectiveness Results by Site for the Three Methods

The Naïve results for individual sites shown in Table 4 revealed that the DDI was effective at decreasing FI crashes at all six sites, PDO crashes at five out of six sites (one site witnessed an increase that was not statistically significant), and total crashes at all six sites. The variation in the safety effectiveness values for FI crashes across the sites was not high. However, PDO and TOT crashes showed higher variation across the six sites. The EB results for individual sites were previously discussed. The CG results for individual sites, shown in Table 4, indicated statistically significant reductions in FI crashes for sites 1, 2, and 3 only. Site 6 actually showed an increase in FI crashes, although it was not statistically significant. For the CG method, statistically significant reduction in PDO and TOT crashes were observed for the first five sites. Again, site 6 showed increases in PDO and TOT crashes that were statistically significant. In addition to the short duration of the after period and the lack of considerable variation in the observed crash frequency before and after DDI for site 6, one additional reason may have contributed to the CG results for site 6. The comparison site used for site 6 witnessed higher crash reductions for FI and TOT crashes. For comparison site 6, the observed crash frequencies per year in the before period were: 12 FI, 31 PDO, 42 TOT and in the after period were: 2 FI, 34 PDO, 36 TOT crashes.

In summary, all three before-after evaluation methods for all sites combined showed that the DDI was effective at improving safety, especially for reducing FI crashes. The results for individual sites also demonstrated that FI, PDO, and TOT crashes decreased at most sites after DDI implementation.

CONCLUSIONS

In this paper, the safety evaluation of Diverging Diamond Interchanges in Missouri was conducted. Missouri was ideal for such a study because it was the first state to implement DDIs in the US, thus significant after treatment data was available. This study used crash data from six sites in Missouri to conduct a comprehensive before-after evaluation of the DDI. The safety evaluation consisted of three types of observational before-after evaluation methods: Naïve, Empirical Bayes (EB), and Comparison

Group (CG). Collision diagram analysis was also conducted to determine the differences in crash types at a DDI and a conventional diamond.

The collision diagram analysis revealed that right angle crashes were predominant in the before period at the ramp terminals of a conventional diamond. Specifically, 34.3% of ramp terminal-related fatal and injury crashes occurred due to collisions between the crossing left turn from inside the crossroad and the oncoming through traffic. Due to the crossover design, the DDI completely eliminated this crash type from occurring. One of the potential concerns of a DDI is the possibility of wrong-way crashes. This study found that only 4.8% of all fatal and injury crashes occurring at the ramp terminal of a DDI were wrong-way crashes. The review of remaining crash types found that the DDI exchanged high severity crash types, such as those occurring at a conventional diamond, for lower severity crash types.

All three before-after safety evaluation methods produced consistent results. The DDI design replacing a conventional diamond decreased crash frequency for all severities. The most significant crash reduction was observed for fatal and injury crashes – 63.2% (Naïve), 62.6% (EB) and, 59.3% (CG). Property damage only crashes reduced by 33.9% (Naïve), 35.1% (EB), and 44.8% (CG). The total crash frequency also decreased by 41.7% (Naïve), 47.9% (EB), and 52.9% (CG). The safety effectiveness results for the six sites also demonstrated that FI, PDO, and TOT crashes decreased at most sites after DDI implementation. This study documented the safety benefits of DDI, which complements the existing knowledge on the operational benefits of DDI. In future research, data from DDIs in different states may be jointly analyzed to develop a nation-level crash modification factor for the DDI.

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TABLE 1 DDI Site Characteristics

Site Location		RT-13 an d I-44 Springfield, MO	I-270 and Dorsett Rd Maryland Heights, MO	James River Exp. and National Av. Springfield, MO	US 65 and MO248 Branson, MO	I-435 and Front Street Kansas City, MO	Chestnut Exp. and Route 65 Springfield, MO
Opening Date		6/21/2009	10/17/2010	7/12/2010	11/20/2011	11/6/2011	11/10/2012
Periods (Months)	Before	51	35	38	44	44	40
	After	51	35	38	22	22	10
Crossroad	Speed (mph)[1]	40	35	40	35	40	40
	AADT[2]	27082	29275	26891	19842	16087	24513
	Lanes[3]	4	6	6	3	4	4
Freeway	Speed (mph)[1]	60	60	60	65	65	60
	AADT[2]	47734	151923	68179	32604	75276	62207
	Lanes	4	8	4	4	6	6
Configuration Type		Overpass	Underpass	Overpass	Overpass	Underpass	Underpass
Pedestrian Accommodation		Median	Roadside	Median	Median	Median	Roadside
Ramp Terminal Spacing (ft.)		530	480	630	740	420	370
Dist. to Adjacent Street (ft.)		320/685	265/635	530/580	580/1795	530/1955	160/475

Notes:
[1] Posted speed limit
[2] AADT of 2013 for reference purpose only
[3] Lanes between ramp terminals

TABLE 2 Comparison Group Sites Description

Site Location		US 60 and US 160 Springfield, Greene, MO	IS 170 and Page Av. Overland, St. Louis, MO	US 65 and Division St. Springfield, Greene, MO	US65 and Branson Hills Pkwy. Branson, Taney, MO	IS 435 and 23rd Trfy. Kansas City, Jackson, MO	US 65 and Battlefield Rd. Springfield, Greene, MO
Crossroad	Speed (mph)[1]	50	40	45	35	45	40
	AADT[2]	18461	34358	11178	16767	22497	22725
	Lanes[3]	5	6	4	5	6	4
Freeway	Speed (mph)[1]	70	60	60	60	65	60
	AADT[2]	23902	120770	58988	29562	79635	65260
	Lanes	4	6	6	4	6	6
Configuration Type		Overpass	Underpass	Overpass	Overpass	Underpass	Overpass
Spacing Ramp Terminals (ft.)		680	400	440	680	310	475
Distance to Public Road (ft.)		290/1000	530/550	220/440	430/430	890/225	575/800
Left Turn Signal IN[4]		PO/PO	PO/PO	PP/PP	PP/PP	PO/PO	PP/PP
Exit Ramp Right Turn Signal[5]		Y/Y	Y/Y	Y/Y	Y/Y	Y/Y	SC/SC

Notes:
[1] Posted speed limit
[2] AADT of 2013 for reference purpose only
[3] Lanes between ramp terminals
[4] IN = Left turns on crossroad segment between ramp terminals, PP = Protective Permissive, PO = Protected Only
[5] Y = Yield, SC = Signal Control

TABLE 3 Project-level EB Results

Severity	Correlation	Parameter	RT-13 and I-44 Springfield, MO (Site 1)	I-270 and Dorsett Rd Maryland Heights, MO (Site 2)	James River Exp. and National Av. Springfield, MO (Site 3)	US 65 and MO248 Branson, MO (Site 4)	I-435 and Front Street Kansas City, MO (Site 5)	Chestnut Exp. and Route 65 Springfield, MO (Site 6)	**All Sites**
FI		Observed Crashes	29	29	22	6	11	7	104
	I[1]	EB Expected Crashes[4]	74	82	61	15	27	9	269
		SE (St.E.)[5]	61.0(8.1)	64.8(7.2)	63.9(8.5)	60.8(16.3)	59.6(12.4)	20.3(30.4)[6]	61.4(4.2)
	C[2]	EB Expected Crashes	83	88	64	16	26	9	286
		SE (St.E.)	65.1(7.5)	67.0(6.8)	65.4(8.4)	63.4(15.4)	57.5(13.3)	18.2(31.4)[6]	63.7(4.1)
	P[3]	EB Expected Crashes	79	85	62	16	27	9	277
		SE (St.E.)	**63.2(7.8)**	**65.9(7.0)**	**64.7(8.4)**	**62.1(15.8)**	**58.6(12.8)**	**19.3(30.9)[6]**	**62.6(4.1)**
PDO		Observed Crashes	116	188	114	17	52	19	506
	I	EB Expected Crashes	164	302	119	37	98	18	739
		SE (St.E.)	29.3(9.0)	37.8(5.6)	4.4(12.5)[6]	53.9(11.7)	47.2(7.7)	-3.0(24.1)[6]	31.6(3.8)
	C	EB Expected Crashes	198	326	126	41	106	20	818
		SE (St.E.)	41.5(7.7)	42.4(5.2)	9.7(12.3)[6]	58.4(10.7)	51.1(7.1)	3.0(22.8)[6]	38.2(3.5)
	P	EB Expected Crashes	181	314	123	39	102	19	779
		SE (St.E.)	**36.0(8.3)**	**40.2(5.4)**	**7.1(12.4)[8]**	**56.3(11.2)**	**49.2(7.4)**	**0.1(23.5)[6]**	**35.1(3.7)**
TOT		Observed Crashes	145	217	136	23	63	26	610
	I	EB Expected Crashes	233	383	163	52	126	27	984
		SE (St.E.)	37.9(6.6)	43.3(4.6)	16.6(9.1)[6]	55.8(9.6)	49.9(6.6)	4.7(19.1)[6]	38.1(3.0)
	C	EB Expected Crashes	274	412	172	57	132	28	1076
		SE (St.E.)	47.2(5.8)	47.4(4.3)	20.8(9.0)	59.7(8.9)	52.3(6.3)	7.8(18.6)[6]	43.4(2.8)
	P	EB Expected Crashes	254	398	167	55	129	28	1030
		SE (St.E.)	**42.9(6.2)**	**45.4(4.5)**	**18.8(9.0)**	**57.8(9.2)**	**51.1(6.4)**	**6.2(18.8)[6]**	**40.8(2.9)**

Notes: [1] I denotes independent correlation
[2] C denotes full correlated
[3] P denotes partial correlation
[4] The expected crash values are rounded (up) to facilitate comparison with observed crash values
[5] SE denotes Safety Effectiveness (%). ST.E denotes Standard Error (%). Negative SE values represent an increase in crashes.
[6] Not significant at the 95% confidence level

TABLE 4 Safety Effectiveness Results by Site for the Three Methods

Severity	Method	RT-13 and I-44 Springfield, MO (Site 1)	I-270 and Dorsett Rd. Maryland Heights, MO (Site 2)	James River Exp. and National Av. Springfield, MO (Site 3)	US 65 and MO248 Branson, MO (Site 4)	I-435 and Front Street Kansas City, MO (Site 5)	Chestnut Exp. And Route 65 Springfield, MO (Site 6)	**All Sites**
FI	Naïve	63.3 (7.9)	69.5 (6.4)	64.5 (8.7)	60.0 (17.3)	59.3 (13.2)	15.1 (34.4) [1]	**63.2 (4.1)**
	EB	63.2 (7.8)	65.9 (7.0)	64.7 (8.4)	62.1 (15.8)	58.6 (12.8)	19.3 (30.9) [1]	**62.6 (4.1)**
	CG	69.8 (6.8)	70.8 (6.4)	69.0 (7.9)	36.1 (29.8) [1]	20.3 (27.3) [1]	-204.5 (143.2) [1]	**59.3 (4.8)**
PDO	Naïve	23.7 (9.4)	44.2 (5.1)	-3.6 (13.8) [1]	51.5 (13.0)	54.6 (6.9)	3.7 (24.3) [1]	**33.9 (3.7)**
	EB	36.0 (8.3)	40.2 (5.4)	7.1 (12.4) [1]	56.3 (11.2)	49.2 (7.4)	0.1 (23.5) [1]	**35.1 (3.7)**
	CG	57.7 (5.5)	57.3 (4.1)	32.3 (9.4)	39.3 (17.0)	26.9 (11.7)	-191.7 (82.4)	**44.8 (3.3)**
TOT	Naïve	37.0 (6.7)	49.7 (4.2)	20.5 (9.1)	53.6 (10.6)	55.4 (6.2)	6.2 (20.3) [1]	**41.7 (2.9)**
	EB	42.9 (6.2)	45.4 (4.5)	18.8 (9.0)	57.8 (9.2)	51.1 (6.4)	6.2 (18.8) [1]	**40.8 (2.9)**
	CG	60.2 (4.4)	59.4 (3.6)	43.9 (6.7)	38.8 (14.7)	25.1 (10.9)	-191.6 (70.5)	**47.9 (2.7)**

Notes: Standard error values are shown in the parenthesis next to the safety effectiveness
Negative values represent the percentage increase in crashes
[1] Not significant at the 95% confidence level

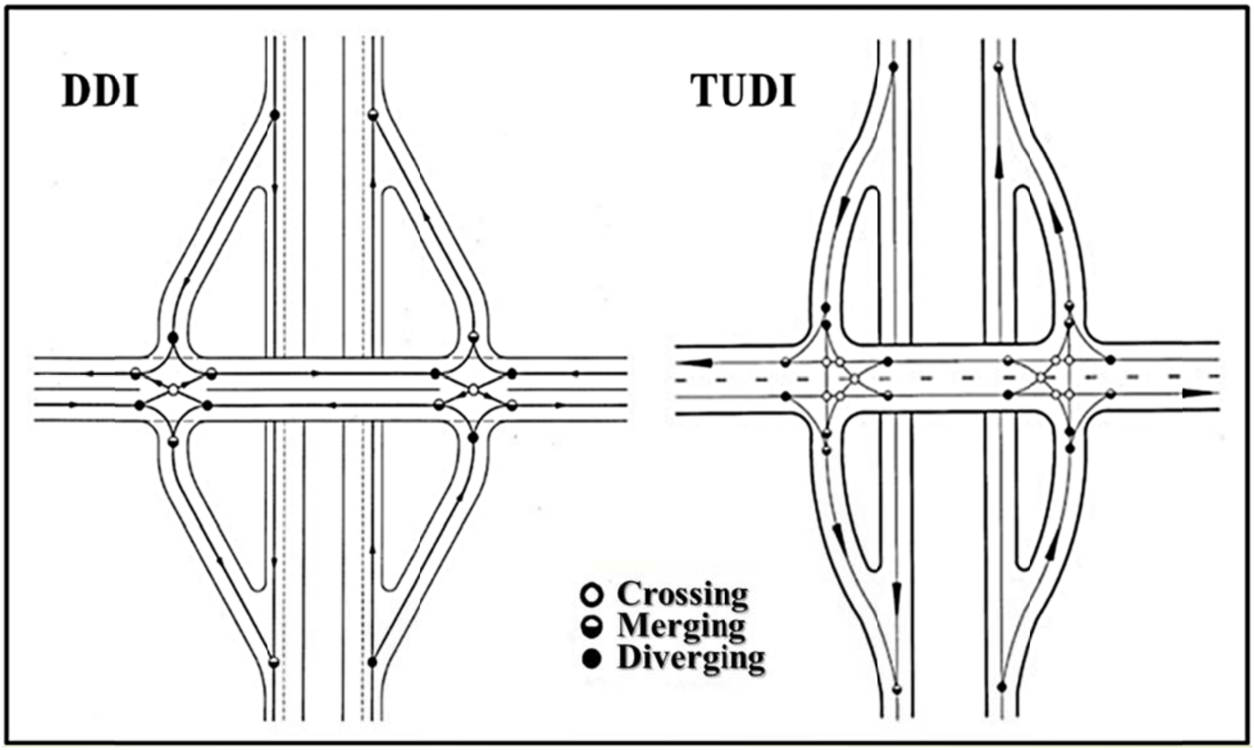


FIGURE 1 Conflict Points at DDI and TUDI Interchanges ***(8)***

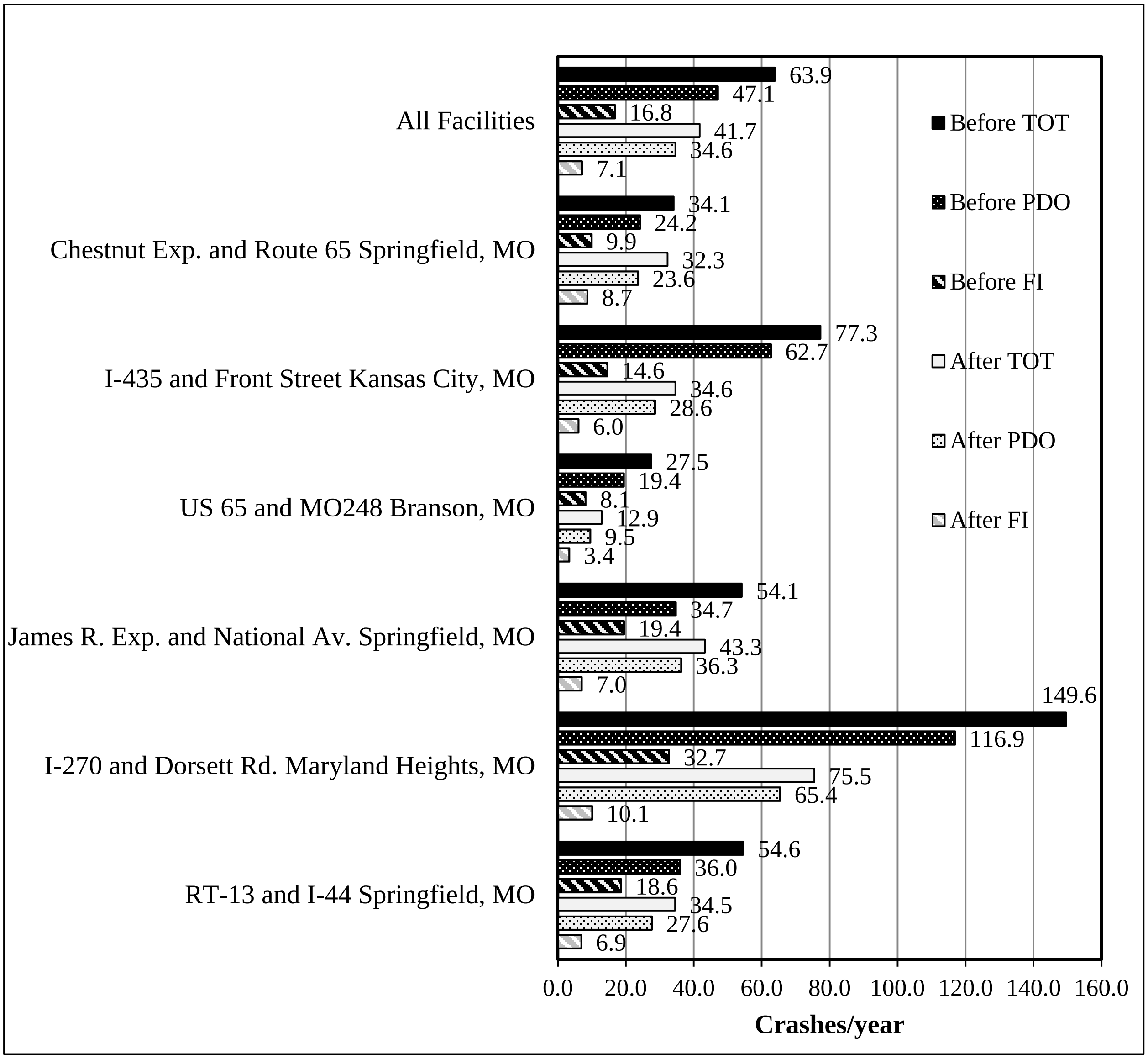
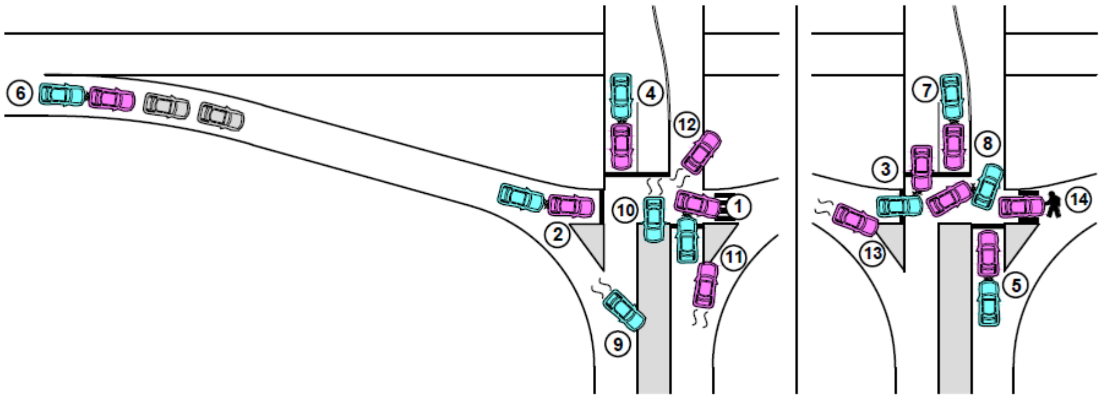


FIGURE 2 Crashes per Year by Severity during the Before and After Period

BEFORE PERIOD

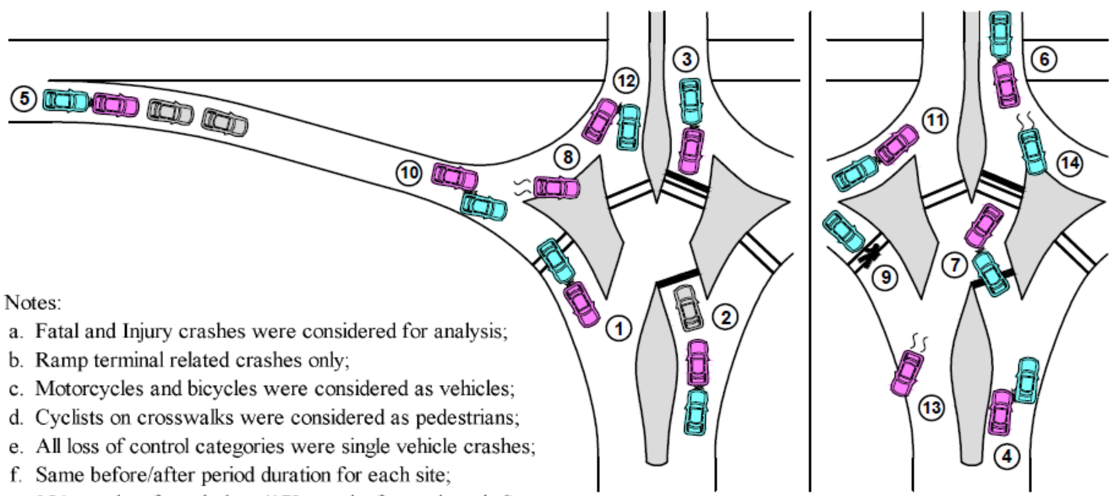
Conventional Diamond Interchange (D4 Ramp Terminals)



BEFORE			
	Crash Type	#	%
1	Crossing left turn inside crossroad leg	57	34.3
2	Rear end at exit ramp	51	30.7
3	Crossing left turn at exit ramp	14	8.4
4	Rear end inside crossroad through lane	14	8.4
5	Rear end outside crossroad	8	4.8
6	Rear end due to queuing from ramp terminal	8	4.8
7	Rear end inside crossroad left turn lane	5	3.0
8	Sideswipe exit ramp left turn	2	1.2
9	Run off exit ramp right turn	2	1.2
10	Loss of control left turn lane inside crossroad	1	0.6
11	Loss of control outside crossroad bay	1	0.6
12	Run off exit ramp left turn	1	0.6
13	Loss of control exit ramp bay	1	0.6
14	Pedestrian on crosswalk	1	0.6

AFTER PERIOD

Diverging Diamond Interchange (DDI)



AFTER			
	Crash type	#	%
1	Rear end at exit ramp right turn	23	37.1
2	Rear end outside crossroad	6	9.7
3	Rear end inside crossroad	5	8.1
4	Sideswipe on crossroad	4	6.5
5	Rear end due to queuing from ramp terminal	4	6.5
6	Wrong direction inside crossroad	3	4.8
7	Crossing at ramp terminal	3	4.8
8	Loss of control left turn at exit ramp bay	3	4.8
9	Pedestrian on crosswalk	2	3.2
10	Sideswipe on exit ramp	2	3.2
11	Rear end exit ramp left turn	2	3.2
12	Sideswipe exit ramp left turn and inside crossroad	2	3.2
13	Run off ramp terminal	2	3.2
14	Loss of control left turn inside crossroad bay	1	1.6

Notes:

a. Fatal and Injury crashes were considered for analysis;
b. Ramp terminal related crashes only;
c. Motorcycles and bicycles were considered as vehicles;
d. Cyclists on crosswalks were considered as pedestrians;
e. All loss of control categories were single vehicle crashes;
f. Same before/after period duration for each site;
g. 356 months of crash data (178 months for each period).

FIGURE 3 Before / After Collision Diagrams for Fatal and Injury Crashes