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Modeling safety performance of the new super DDI design in terms of vehicular traffic and pedestrian

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ABSTRACT

Most existing interchanges in the United States were built more than 50 years ago based on old design policies. Many of these designs are not consistent with current traffic and pedestrian demands anymore. Therefore, this inconsistency has caused problems regarding operation and safety. This paper models safety performance of a new design called super diverging diamond interchange (super DDI) considering VISSIM simulation and surrogate safety assessment model (SSAM). Six other interchange designs were also considered for comparing to the new super DDI design. Overall, 252 simulation scenarios were modeled in VISSIM and then tested by SSAM. Also, the same number of tests were considered to evaluate pedestrian performance of the designs considered in this study. Based on results, super DDI showed a high potential either in terms of traffic safety and pedestrian safety. In comparison to other designs, super DDI had the minimum number of simulated conflicts as well as the lowest mean speed and time to collision (TTC) of simulated conflicts. This fact shows that super DDI could perform promising in reducing crash frequency and crash severity. Reviewing the geometry of the super DDI, lower traffic involving in each conflict point should be one of the main reasons for the promising traffic safety performance of the design. Regarding pedestrian performance, super DDI got the third rank of the lowest mean pedestrian travel times. There is no free-flowing conflict between vehicles and pedestrians in a super DDI. Therefore, pedestrian paths of the super DDI are predicted to be safer than the paths in a typical DDI design.

1. Introduction

Alternative interchange designs are attracting the attention of transportation agencies and designers more than ever. Most of the existing interchanges in the U.S were built in the 1950s and 1960s when traffic demand was much lower, and the type of vehicles and driving habits were different. Also, the knowledge of highway safety is more developed now, and this fact provides an appropriate situation to increase the efficiency of interchanges regarding operation and safety using alternative interchanges.

1.1. Objective

This manuscript seeks to evaluate the performance of an alternative design called super diverging diamond interchange (super DDI). In light of the primary purpose, specific objectives for this research can be mentioned as:

1) Determining traffic safety performance of the super DDI in comparison to conventional and other alternative interchanges, including the number of conflicting interactions between vehicles, severity of conflicting interactions, traffic volume involving in conflict points, and the number of vehicle stops;
2) Determining pedestrian safety performance of the super DDI in comparison to conventional and other alternative interchanges, including the ease and safety of pedestrian paths, travel time, waiting time, and locations of paths.

Safety, traffic operation, pedestrian performance and the construction cost are the main measure of evaluations (MOEs) for evaluating intersections and interchanges based on past studies (Chlewicki, 2003; Edara et al., 2005; Bared et al. (2005);; Eyler, 2005; Shin et al., 2008; Edara et al., 2015; Yeom et al., 2015; Mehrara Molan, 2017). Due to the large discussions needed in evaluating new designs, this paper focuses on the safety performance of super DDI regarding vehicular traffic and pedestrian, while traffic operation and the construction cost estimation

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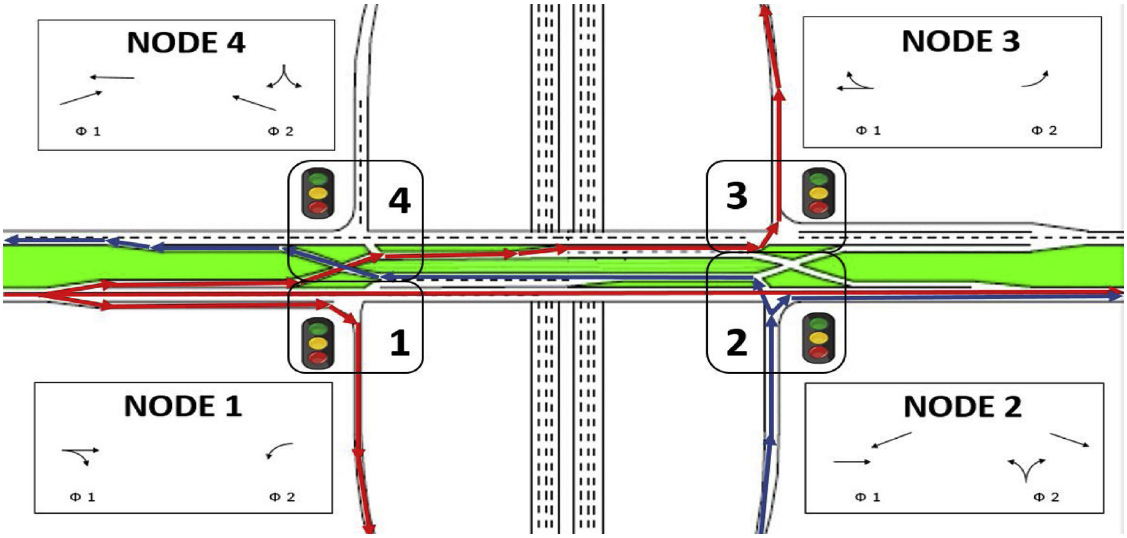

Fig. 1. Super DDI design.

are discussed in another work (Mehrara Molan et al., 2019).

1.2. Super DDI design

Interchanges can be divided into two categories of "service interchanges" (when freeways meet arterials or collectors), and "system interchanges" (when freeways meet freeways). Super DDI is a service interchange. There are typically big safety concerns regarding service interchanges because of vehicle-vehicle, and vehicle-pedestrian conflicting interactions on arterial. Fig. 1 shows a general view of the super DDI design. Eastbound (EB) vehicle routes are illustrated in red, while the blue line shows the vehicle direction from northbound (NB) ramp. Westbound (WB) and southbound (SB) approaches also follows similar patterns. The reason of calling the design as super DDI is because of its similarity to superstreet (also called synchronized, or RCUT) intersection and the diverging diamond interchange (DDI) designs. These designs are shown in Fig. 2. Based on the previous research (Edara et al., 2015; Yeom et al., 2015; Mehrara Molan, 2017; Hummer et al., 2010; Inman and Haas, 2012; Mehrara Molan and Hummer, 2017), both superstreet and DDI designs present a great performance regarding improving traffic safety. However, in terms of traffic operation, superstreet and DDI were not found very well in high left-turning traffic and high through traffic demands, respectively. Also, as the past studies have mentioned (Edara et al., 2015; Yeom et al., 2015; Mehrara Molan, 2017; Mehrara Molan and Hummer, 2018a), pedestrian performance of the DDI was not investigated very well due to having free-flowing (unsignalized) vehicle-pedestrian conflicts. Super DDI, as a design that combines the features of superstreet and DDI designs, showed a significant potential regarding traffic operation in the previous study (Mehrara Molan et al., 2019). Therefore, investigating a similar performance in terms of traffic safety, and pedestrian may introduce it as a promising alternative design to serve all roadway users well.

1.3. Other interchanges involved in the analysis

Fig. 3 has illustrated the other interchange types considered in this research. A conventional diamond interchange was selected since it has the highest frequency among all interchanges in the U.S. The parclo B is a popular design which typically serves a higher capacity in comparison to other conventional designs. As already discussed, DDI is widespread all around the U.S. due to its very good performance, especially in terms of improving traffic safety in high left-turning traffic demands. To date, 89 DDIs has been established in the U.S. (DDI website, 2018). Synchronized, Milwaukee A and Milwaukee B interchanges were also chosen because of the potential identified regarding their performance as possible alternatives for the failing interchanges based on the previous studies (Eyler, 2005; Mehrara Molan, 2017).

2. Literature review

The first effort regarding alternative designs probably goes back to 1950s when jughandle intersections were constructed in New Jersey, NY. Median U-turn (MUT) design was invented in Michigan in the 1960s. Despite the high frequency of MUT intersections all across the U.S., MUT interchanges did not become popular, and the interchange design was mostly utilized only in Michigan.

The early 1990s might be considered as a turning point in alternative design studies due to inventing the first single-point interchange (SPI). Hundreds of SPIs were built in the U.S. to overcome the problems caused by the considerable traffic growth in the 1990s. Despite the good traffic operation of SPIs, they had a complex pattern for drivers to follow. This fact could make a safety threat causing wrong-way

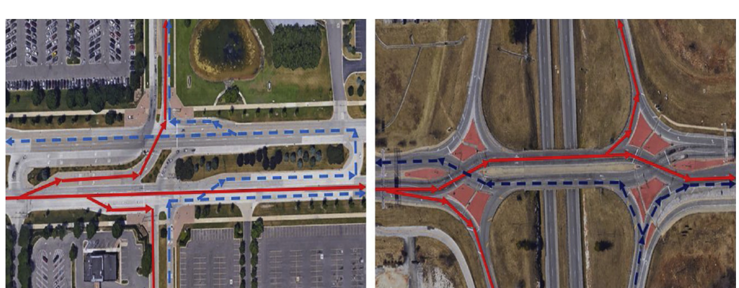

Fig. 2. Superstreet (left side: Big Beaver Rd and Lakeview Drive, Troy, MI) and DDI (right side:I-44@Kansas Expressway, KS) designs.

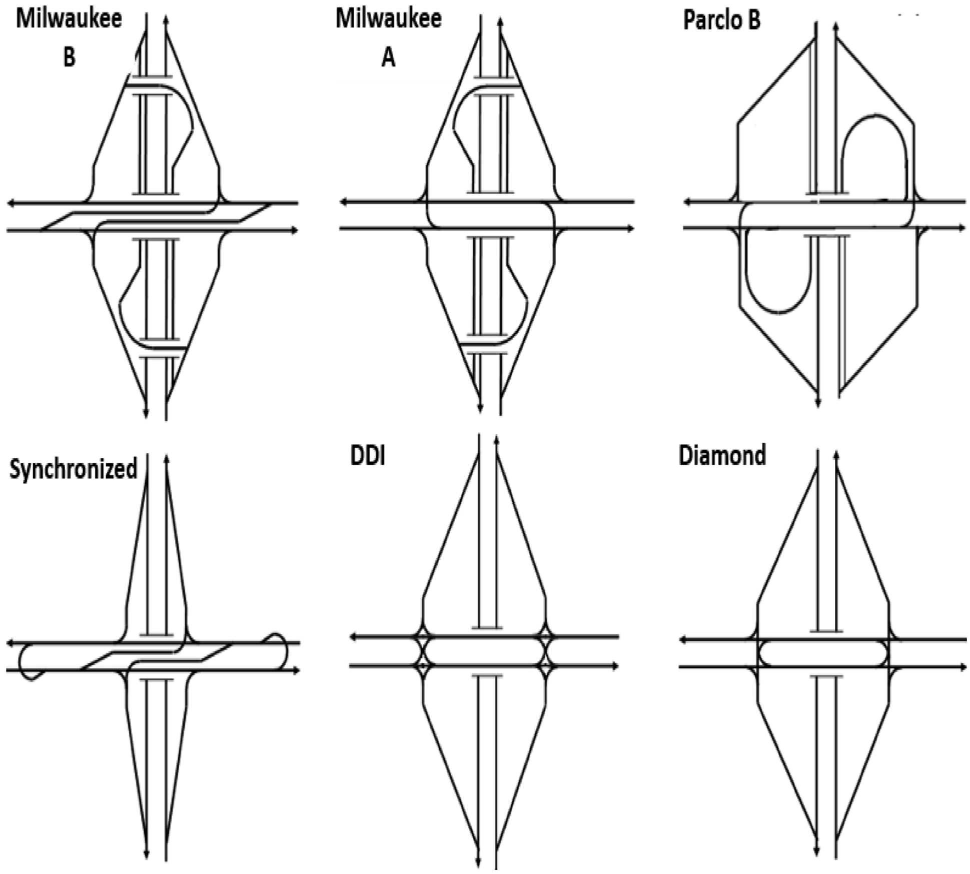

Fig. 3. Interchange types considered in this research (not to scale).

movements for the drivers who were unfamiliar with the design. Also, pedestrian paths had free-flowing conflicts with turning vehicular traffic.

Since the first publication on DDIs by Chlewicki (2003), many researchers (Edara et al., 2005; Bared et al. (2005); Edara et al., 2015; Yeom et al., 2015; Vaughan et al., 2013; Khan and Anderson, 2016) have been conducted various studies related to DDIs. DDIs could provide a good traffic operation in a lower construction cost than SPIs. Also, its safety performance was examined very well because of removing the number of conflict points. On the other hand, DDI's pedestrian performance was found almost similar to SPIs, and there were still free-flowing conflicts between vehicles and pedestrians.

Berry and Click (2011) did VISSIM simulation research on three unconventional interchange designs: the MUT interchange, a superstreet, and a design called "FRE" that requires all left turn vehicles to use U-turn crossovers downstream from the interchange. They found that all three designs have great operational potential. The FRE design is especially promising in places where agencies do not want to widen an existing narrow bridge of the arterial over the freeway.

Molan and Hummer (2017; 2018a,b) evaluated the performance of synchronized and Milwaukee B interchanges as two possible substitutes for failing interchanges. Both the designs showed potential, especially in terms of traffic safety and pedestrian safety. Synchronized could be a good alternative for the old diamond interchanges with high through traffic demands, while DDI was identified as a better option in high left-turning traffic cases. The performance of Milwaukee B interchange was evaluated as the best in comparison to other designs considered in the research; however, the construction cost was estimated higher because of having three bridges.

Mehrara Molan et al. (2019) proposed the super DDI design as a promising alternative service interchange to boost the performance of the typical DDIs. The traffic operation of the super DDI was found significantly better than a typical DDI. The mean vehicle travel time was estimated 16% lower in a super DDI than the typical DDI. On the other hand, the super DDI was estimated to be more expensive than the DDI (about 1.2 million dollars) in terms of construction costs.

3. Methodology

3.1. Simulation environment

As the first step in this study, geometric characteristics of interchanges were modeled in VISSIM (version 7). VISSIM, which was manufactured in Germany in the 1970s as the first time, is a microscopic simulation package for modeling different traffic patterns with detailed geometric configurations and drivers' behavioral characteristics encountered in the transportation system (Liu et al., 2012). Geometric features of interchanges were considered using real-world data collected from 30 existing interchanges. Fig. 4 shows the details regarding the geometric data gathered from existing interchanges, while a summary of the data has been presented in Table 1.

All the designs had the same number of traffic lanes. This research considered two through traffic lanes and one exclusive lane for each left/right turning traffic. Also, the maximum longitudinal grades on ramps and loops were selected 2% and 3.5%, respectively, based on Green Book (A Policy on Geometric Design of Highways and Streets, 2011). Traffic signal data was obtained using Synchro (version 8) to consider the optimized signal operation in each simulation test. Then, the optimized data was used in VISSIM for modeling the traffic signals. Synchro is a macroscopic software for implementing the performance of signalized/unsignalized intersections and roundabouts based on Highway Capacity Manual's 6th edition [2010]. As it is common in the U.S., the vehicle speed of 70 mph and 35 mph were chosen on the freeway and arterial, respectively. Two horizontal curves with radii

No.	Address	Interchange	Radius-Right Turn of OnRamp	Radius-Right Turn of OffRamp	Ave Length of OnRamps	Ave Length of OffRamps	Radius-Loop	Distance btw Nodes
1	Haggerty Connector and 12 Mile Rd	Parclo A	60	30	2300	2400	260	1400
2	I-275 and Ann Arbor Rd	Parclo A	60	60	1800	1800	260	1300
3	I-275 and Ford Rd	Parclo A	60	60	1800	1900	270	1400
4	I-275 and Eureka Rd	Parclo A	55	55	2400	2400	260	1600
5	Haggerty Rd and Detroit Industrial Expy	Parclo A	45	30	1800	1800	200	1000
6	I-275 and 6 Mile Rd	Parclo A	50	50	1500	2600	280	1500
7	Belleville Rd and Detroit Industrial Expy	Parclo A	50	30	2000	2000	230	1250
8	I-96 and Novi Rd	Parclo A	35	50	2300	2600	225	1250
9	I-96 and Novi Rd	Parclo A	35	50	2300	2600	280	1250
10	I-96 and Fowlerville Rd	Parclo B	50	No Ramp	1700	No Ramp	230	1200
11	I-75 and 14 Mile Rd	Parclo B	50	50	1700	1200	240	1200
12	I-96 and Kensington Rd	Parclo B	30	No Ramp	1200	No Ramp	240	1350
13	I-96 and Milford Rd	Parclo AB	50	50	1800	2000	280	1300
14	I-275 and 7 Mile Rd	Parclo AB	45	25	1600	2200	260	1500
15	I-96 and Latson Rd	Diamond	40	40	2200	2200	No Loop	1500
16	I-275 and Ecorse Rd	Diamond	50	50	1900	2150	No Loop	1600
17	US-23 and US-12	Diamond	50	50	1500	2000	No Loop	1400
18	I-275 and Sibley Rd	Diamond	45	45	2100	2100	No Loop	1650
19	I-94 and Van Dyke Rd	Diamond	35	30	1000	1200	No Loop	300
20	I-94 and Candieux Rd	Diamond	30	25	800	1200	No Loop	300
21	M-10 Fwy and Forest Ave	Diamond	20	20	800	800	No Loop	250
22	M-10 Fwy and Linwood Rd	Diamond	20	20	1000	1000	No Loop	250
23	I-75 and University Dr	DDI	Free-flow Right Turn	Free-flow Right Turn	1200	2800	No Loop	1300
24	I-44 and Kansas Expressway	DDI	Free-flow Right Turn	Free-flow Right Turn	1000	1000	No Loop	600
25	US-60 and National Ave	DDI	Free-flow Right Turn	Free-flow Right Turn	1300	1400	No Loop	700
26	I-15 and American Fork	DDI	Free-flow Right Turn	Free-flow Right Turn	1200	1800	No Loop	800
27	I-15 and Timpanogos Hwy	DDI	Free-flow Right Turn	Free-flow Right Turn	2600	1800	No Loop	700
28	I-590 and South Winton Road	DDI	Free-flow Right Turn	Free-flow Right Turn	1700	1300	No Loop	600
29	US-129 and Middlesettlements Rd	DDI	Free-flow Right Turn	Free-flow Right Turn	800	1200	No Loop	700
30	I-846 and 27th St	Milwaukee A	Free-flow Right Turn	Free-flow Right Turn	1800	1700	230	600

Fig. 4. Geometric data collected from 30 service interchanges (all the measurements are in ft).

Table 1
Collected geometric data of existing service interchanges.

Parameter	Right turn radius of ramps (ft)	Length of ramps (ft)	Loop radius (ft)	Distance between ramp terminals, (ft)		
				Parclo	Diamond	DDI
Average	42	1750	250	1300	900	750
Median	48	1800	260	1300	850	700
Minimum	20	800	200	1000	250	600
Maximum	70	2800	280	1600	1650	1300
Selected	40	2000	250	1200	600	600

equal to 1400 ft and 700 ft were considered on direct ramps to provide an appropriate speed transition considering the maximum superelevation of 6 percent (as recommended in Michigan). On loop ramps, vehicles had the constant speed of 25 mph which is the proper speed for a 250-ft radius based on the Green Book (A Policy on Geometric Design of Highways and Streets, 2011).

In addition to the information provided in Table 1, the angle at the crossovers is another important design component for the super DDI and DDI designs. According to the DDI guidebook (2014), the angle at the super DDI and DDI crossovers was set at 45° with a radius of 91 m (300 ft) for the horizontal curves leading into and out of the crossovers. This angle was recommended by the DDI guideline to minimize the potential for wrong-way movements.

The clearance time of the pedestrian signal was selected after reviewing 25 signalized intersections in Detroit, Michigan. Based on the collected data, the average clearance times of 10.3, 13.7, 17.2, and 18.7 s were found for two-lane, three-lane, four-lane, and five-lane crosswalks, respectively. Therefore, the research considered a 7-sec clearance time in one-lane crossings while a 3.5-sec were added for an extra lane. The pedestrian speed was categorized into two groups: (1) walking pedestrians with 91% of the volume and a mean speed of 5 fps, and (2) running pedestrians with 9% of the volume and a mean speed of 9.6 fps. The speed values were assumed based on a data collection done by a previous study (Hummer et al., 2014). Other studies (Ishaque and Noland, 2009; Oskarbski et al., 2016) had also estimated the speeds of walking pedestrians in a range of 3.6–5.8 fps.

Two proposed pedestrian paths across the super DDI are presented in Fig. 5. The authors believe that the side path (red line) would be the best option in terms of pedestrian operation and safety; however, the middle path (blue line) seems to be better when there is any restriction for designing the side paths such as a desire to reduce the bridge width. This research only considered the side path alternative for the pedestrian analysis. All the designs tested in the study had two pedestrian paths that were 1600 ft long and 10 ft wide on the side except the DDI, which had the path in the middle of the bridge. In fact, the choice between a side path and a middle path is very dependent on the context; however, the authors considered the middle path for DDI due to safety concerns with crossing the left entrance to the on-ramp in side paths of DDIs.

Traffic volumes were chosen considering a v/c (volume/capacity) ratio equal to one for traffic signals of the diamond interchange based on CLV (critical lane volume) calculation. CLV is a typical method for gaining an initial estimation of the traffic operation at signalized intersections. The v/c = 1 represents a high traffic demand, when traffic volume is equal to the capacity. The pedestrian volume was considered as 360 pedestrians per hour for four routes (from southeast to southwest and vice versa, from northeast to the northwest and vice versa). Thus, each route included 90 pedestrians per hour, and no pedestrians crossed the arterial (they only crossed the bridge).

3.2. Simulation models

The safety evaluation was conducted using Surrogate Safety

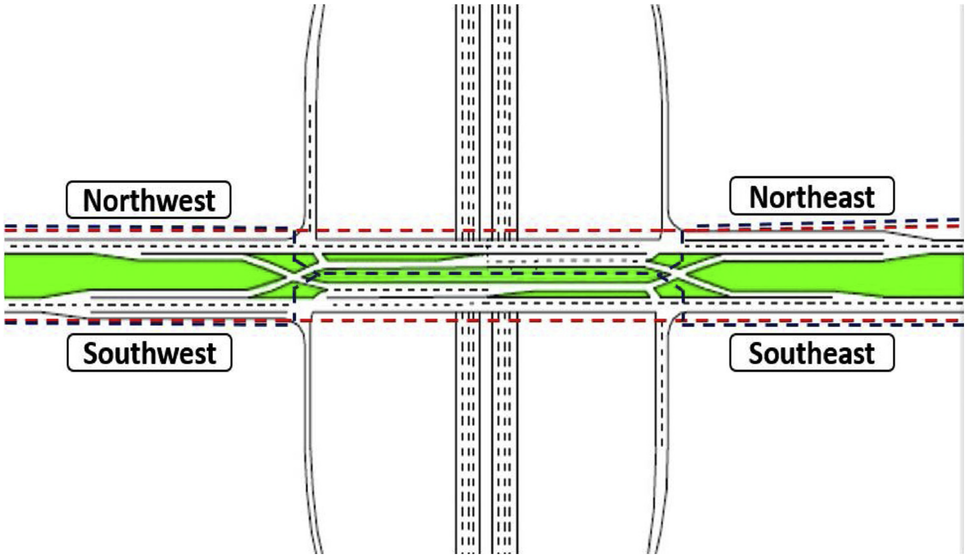

Fig. 5. Two proposed pedestrian paths for super DDI design (red line = side path, blue line = middle path). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
The simulation scenarios defined for the safety analysis.

Truck Percentage	Turning Volume Ratios	Traffic Distribution	
		EB/WB	NB/SB
4 %	Left turn = Through = Right turn (High Turning Condition)	EB = WB (Equal traffic on EB and WB)	NB = SB (Equal traffic on NB and SB)
8 %	Left turn = 0.66 Through = Right turn (Moderate Turning Condition)	EB = 0.5 WB (higher traffic on WB)	NB = 0.5 SB (higher traffic on SB)
	Left turn = 0.25 Through = Right turn (Low Turning Condition)		0.5 NB = SB (higher traffic on NB)

Table 3
The mean entry traffic volume considered on each traffic lane in simulation modeling.

Route	Turning Traffic					
	Arterial			On-Ramp		Total
	Left Turn	Through[a]	Right Turn	Left Turn	Right Turn	
High Turning	428	428	428	428	428	5136
Moderate Turning	375	563	375	375	375	5252
Low Turning	333	667	333	333	333	5332
Average	379	553	379	379	379	5244

[a] There are two lanes for the through traffic in each approach.

Assessment Model (SSAM) which provides the frequency and speed of narrowly averted vehicle-to-vehicle collisions in traffic considering a time to collision (TTC) threshold. According to the recommendations provided in previous studies (Fan et al., 2012; Huang et al., 2013; Shahdah et al., 2014), a 1.5-sec threshold was selected for the TTC to investigate the conflicting interactions on SSAM. However, another TTC threshold (equal to 1.0 s) was also considered for the new super DDI, DDI, and the conventional diamond to compare their results considering two TTC threshold values. The maximum post-encroachment time (PET) was considered equal to 5 s as well. No analysis was conducted for vehicle-pedestrian conflicts because SSAM is not able to precisely simulate vehicle-pedestrian interactions. Based on the best knowledge of the authors, there is also no other software package able to model the conflicts between vehicles and pedestrians. Therefore, VISSIM had the main role in analyzing the pedestrian performance in terms of travel time, waiting time (on red intervals), and the number of stops.

3.3. Simulation tests

Table 2 illustrates the traffic conditions considered in the research. Based on a data collection done on 37 existing service interchanges, 4% and 8% were found as 50th and 85th percentiles for the truck volume ratio, respectively. Similar truck ratios were also found in another study in Michigan (Eamon and Siavashi, 2018). Three turning volume ratios were selected to include the possible turning conditions in interchanges

Table 4
Average travel times under various traffic turning cases based on VISSIM.

Sites	VISSIM (sec)		Probe Data (sec)		Overall Mean Difference (sec)
	AM Peak Hour	PM Peak Hour	AM Peak Hour	PM Peak Hour	
I-94 Fwy@16 Mile Rd	27.1	34.2	24.9	32.4	2.0
M-10 Fwy@Linwood Rd	24.8	27.0	22.8	25.2	1.9
Telegraph Rd@Ecorse Rd	30.6	32.2	28.2	28.4	3.1
Overall	27.5	31.1	25.3	28.6	2.3

Fig. 6. VISSIM model of the interchange I-94@16 mile Rd in Michigan.

Table 5
Average number of simulated conflicts under various traffic turning cases based on SSAM (TTC threshold = 1.5 s).

Design	Overall	High Turning	Moderate Turning	Low Turning
DDI	468	392	447	586
Diamond	3340	2839	3632	3728
Milwaukee A	1518	1091	1368	2097
Milwaukee B	477	465	499	469
Parclo B	1552	1508	1622	1524
Super DDI*	240	292	212	219
Synchronized	1738	2087	1605	1520

* No insignificant diff ;erence was found between any of the designs and the super DDI at the 0.05 level.

Table 6
Average speed, TTC, PET, and PET variance of conflicting interactions per run based on SSAM (TTC threshold = 1.5 s).

Design	Speed (mph)	TTC (sec)	PET (sec)
DDI	5.71	0.72	1.28
Diamond	4.96	0.89	0.90
Milwaukee A	8.35	0.68	0.66
Milwaukee B	10.78	0.58	0.48
Parclo B	9.76	0.75	0.75
Super DDI	4.54	1.06	1.30
Synchronized	4.61	0.93	1.10

during peak hour time. To cover balanced and unbalanced traffic situations, six different traffic distributions were considered in the study as shown in Table 2.

Overall, the pedestrian and safety experiments each included 252 simulation runs (seven designs*two truck volume ratios*three turning volume ratios*six traffic distributions = 252 tests). Each VISSIM simulation test was run two times to include the effect of different simulation seeds in the analysis. Also, a factorial analysis was considered using ANOVA (analysis of variance) method to ensure that many more than two samples contributed to any comparison made in the analysis. "ANOVA is a collection of statistical models and their associated estimation procedures used to analyze the differences among group means in a sample" (Diez et al., 2015). Based on Table 2, the three entry traffic volumes were examined approximately 5140, 5250, and 5330 vehicles per hour in the network, respectively. Table 3 shows the average entry traffic volume considered for each lane in each approach.

This research considered a similar methodology as considered in the previous study related to traffic operation analysis of the super DDI (Mehrara Molan et al., 2019). However, in comparison to the previous study, the DDI V/C = 1 demand level was ignored for the safety and pedestrian evaluations, and the results in these two parts are based on a demand level of V/C = 1 at a diamond interchange. Based on the experiences from another similar research (Mehrara Molan, 2017), some of the designs cannot complete the scenarios with a high range of traffic due to the lack of capacity and this issue could affect the results of safety and pedestrian analyses.

Table 7
Type of simulated conflicts found under various traffic turning cases based on SSAM (TTC threshold = 1.5 s, and 1.0 s).

Design	TTC Threshold	High Turning			Moderate Turning			Low Turning		
		Cross-ing	Rear End	Lane Change	Cross-ing	Rear End	Lane Change	Cross-ing	Rear End	Lane Change
Diamond	1.5 sec	29	2283	526	32	3061	538	29	3079	619
DDI	1.5 sec	0	324	70	1	362	84	1	464	121
Super DDI	1.5 sec	2	253	37	0	183	29	1	189	30
Diamond	1.0 sec	23	1872	395	26	2410	485	21	2401	433
DDI	1.0 sec	1	237	62	1	270	96	2	367	110
Super DDI	1.0 sec	2	177	42	1	123	30	1	125	25

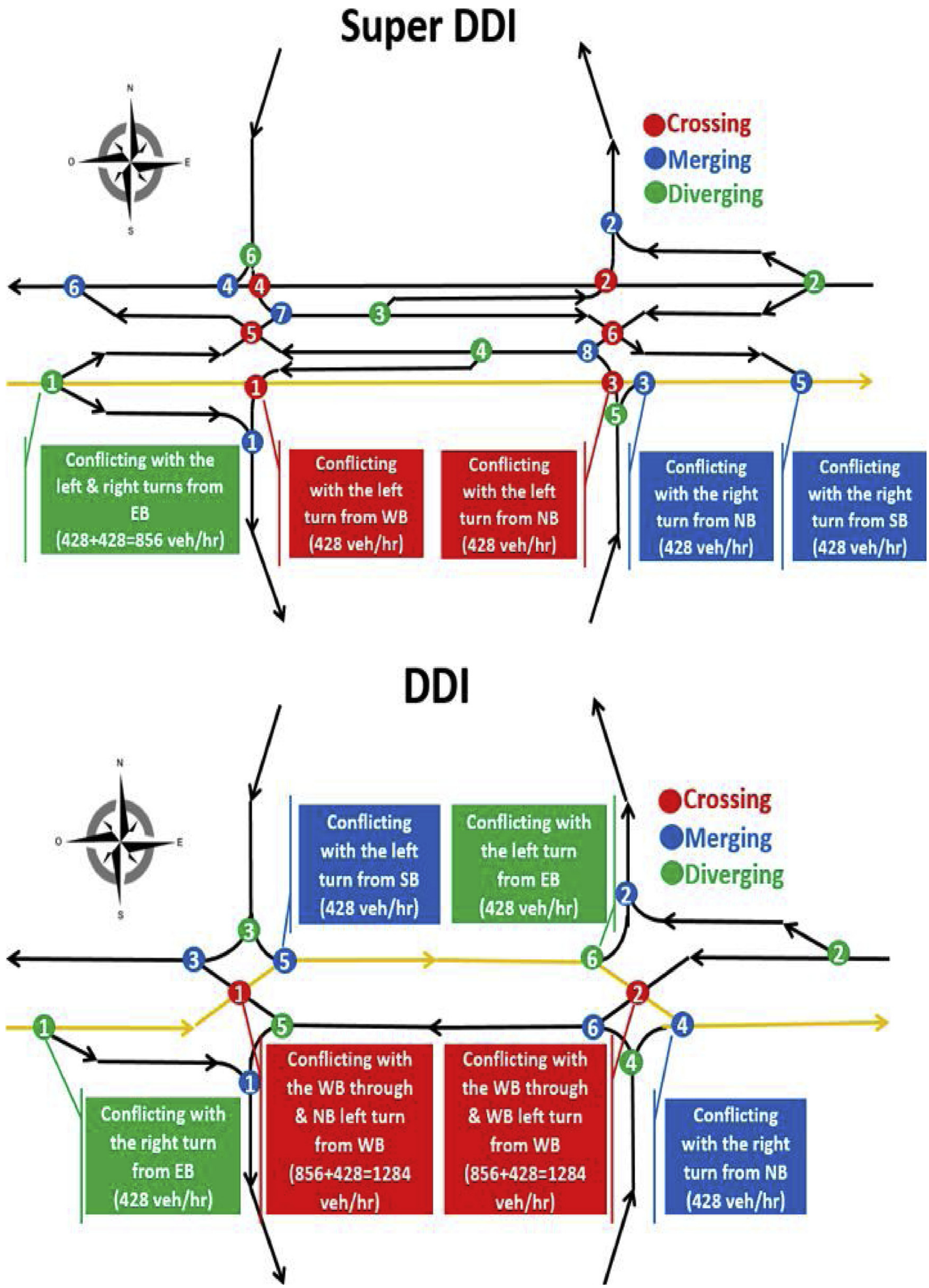

Fig. 7. Type and number of the conflicts points in super DDI and DDI (the brown lines show through traffic routes in each design).

3.4. Validation

Calibration and validation are two of the important tasks in any simulation study. As described in the methodology section, this study mainly focused on calibration by collecting real-data and considering valid references to build a realistic simulation environment for the evaluation. Validation was considered as a secondary goal in this study. Validation could not be done for the new super DDI since it is a proposed design which is not built yet. Also, VISSIM's car following model was not changed since this research did not target any specific location as a case study. Note that the car following model could be different case by case due to the differences in driving behavior and regulations in various locations.

According to Essa and Sayed (2015), the outcomes of SSAM models

Table 8
A comparison between super DDI and DDI regarding the traffic volume conflicting in their vehicle routes in this study.

			Conflict Points Facing [b]	Traffic Volume (veh/hr) Involving in Conflict Points [a]											
				High Turning Condition				Moderate Turning Condition				Low Turning Condition			
				Crossing	Merging	Diverging	Total	Crossing	Merging	Diverging	Total	Crossing	Merging	Diverging	Total
Super DDI	Arterial (EB Approach)	Left Turn	1 5 7 3 2 2	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI
		Through	1 1 3 3 5	856	856	856	2568	750	750	750	2250	666	666	666	1998
		Right Turn	1 1	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI
	On-Ramp (NB Approach)	Left Turn	5 3 8 4 5 6	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI
		Right Turn	5 3 5	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI	The same as DDI
DDI	Arterial (EB Approach)	Left Turn	1 1 5 6 2	1284	856	1712	3852	1501	750	1876	4127	1667	666	2000	4333
		Through	1 1 5 6 2 4	2568	856	856	4280	3002	750	750	4502	3334	666	666	4666
		Right Turn	1 1	0	428	1284	1712	0	375	1501	1876	0	333	1667	2000
	On-Ramp (NB Approach)	Left Turn	4 6 5 1 3	1284	1712	856	3852	1501	1876	750	4127	1667	2000	666	4333
		Right Turn	4 4	0	1284	428	1712	0	1501	375	1876	0	1667	333	2000

[a] Traffic volumes were extracted considering Table 3.
[b] This column shows the conflict point facing EB arterial and NB ramp., while the similar conflict points would exist on WB and SB routes.

Table 9
The average number of vehicle stops per hour in interchange designs based on VISSIM.

Design	Overall	High Turning	Moderate Turning	Low Turning
DDI	0.55	0.49	0.52	0.75
Diamond	0.84	0.86	0.85	0.77
Milwaukee A	0.38	0.37	0.38	0.38
Milwaukee B	0.57	0.58	0.59	0.55
Parclo B	0.62	0.64	0.63	0.60
Super DDI	0.46	0.47	0.45	0.46
Synchronized	0.73	0.80	0.71	0.69

was evaluated valid if the delay (or travel time) extracted from VISSIM is accurate. Essa and Sayed (2015) considered a two-step calibration on VISSIM to find the relationship between simulated conflicts of SSAM and real conflicts observed in a field study. The first step was done on calibrating the delay time of VISSIM while the second part was focused on driver behavior. Based on results, the effect of the first step was more significant in terms of SSAM validation. In other words, a calibrated VISSIM environment would also result in accurate outcomes for SSAM analysis. Therefore, our study also conducted a validation for the travel time performance comparing travel time between VISSIM and vehicle probe data in three existing interchanges in Michigan. Table 4 presents the validation results gained in this study.

As shown in Table 4, the mean difference between the measured and simulated travel times was 2.3 s (higher for VISSIM) which demonstrated an insignificant difference at the 0.05 level in ANOVA for all the comparisons. The traffic condition of each interchange was evaluated in afternoon (PM) and morning (AM) peak hours considering ten repetitions in VISSIM. Vehicles' speeds were chosen in the same range as the existing speed limit at the site. Because of the inconsistency between the dates of signal timing and the traffic counts, Synchro was utilized to provide the signal data needed in VISSIM. The rest of the variables were selected as described in the methodology section. Note that destination and origin locations of the travel distances in VISSIM were chosen the same as the locations used to get the real-travel times. Fig. 6 shows an example regarding the origin and destination points in one of the interchanges considered for the validation part.

4. Discussions

The following paragraphs describe the results found in this research. Note that the main focus of the discussion is on elaborating the new super DDI's results since the other designs were already discussed in past studies (Mehrara Molan, 2017; Mehrara Molan and Hummer, 2017) with similar methodology.

4.1. Vehicular traffic safety

Table 5 shows the rate of simulated conflicts observed with SSAM, while the average of speed, PET, and the TTC of simulated conflicts have been illustrated in Table 6.

The results revealed superior performance by the super DDI on this measure. In fact, the super DDI seemed to be one of the safest designs either from the viewpoint of the frequency or the severity of conflicts. The total number of conflicting interactions in the super DDI was almost half of a DDI. Based on ANOVA, the number of simulated conflicts was found to be significantly lower for the new super DDI in comparison to other designs considered at the 0.05 level. Regarding the severity of conflicts, the super DDI had the lowest speed of conflicting vehicles as well as the highest value of TTC and PET. Results show that the low-conflict pattern was maintained for the super DDI for all turning traffic tested.

SSAM also identifies the type of simulated conflicts considering the conflict angle between vehicles. SSAM identifies any conflict with an angle sharper than 30° as a rear-end conflict, while the angles between 85 and 180° would be considered as a crossing conflict. The conflicts with an angle between 30 and 85° would be identified as lane change conflicts (SSAM, 2017). Table 7 makes a comparison between the new super DDI, DDI, and the conventional diamond in terms of type of conflicts. Also, Table 7 included the results found considering a TTC threshold of 1.0 s to make sure that we found similar outcomes with a different TTC threshold. TTC = 1.0 s also shows the number of conflicting interactions which have higher potential to make a crash. Based on Table 7, the results were similar for the TTC threshold of 1.5 s and 1.0 s.

To investigate the reasons of the superior performance of the super DDI, Fig. 7 shows the type and the number of conflict points for the super DDI and DDI, and also shows an example of the traffic volume involved on through traffic routes when there is a high turning volume. Table 8 also makes a comparison between these two designs in terms of the traffic volume involved in conflict points for different vehicle route. Based on Fig. 7, super DDI has 20 conflict points (six crossing, eight merging, and six diverging points) which is six more than a DDI. This rate of conflict points is the highest frequency among all interchanges considered in this study. According to Molan and Hummer (2018b), there are 18 and 12 conflict points on the conventional diamond and Milwaukee B interchanges, respectively, while parclo B, DDI, Milwaukee A, and synchronized interchanges have 14 conflict points in their geometry. However, this high rate of conflict points is the main reason for the great safety performance of the super DDI in comparison to the other designs. In other words, the big conflict points (crossing #1 and #2) of the DDI are divided and distributed in smaller conflict points (crossing #1 through #6) in a super DDI design. For example, in the crossing point #1 on DDI, the EB traffic volume, which consists of EB left turn and the EB through traffic, are conflicting with NB left turn (from on-ramp) and the WB through traffic. On the other hand, the EB through and left turn traffic demands are facing only the WB left turn, and NB left turn, respectively, to pass the first node of their routes. This advantage was possible for the super DDI because the through traffic routes do not cross each other. Also, there are two more merging conflict points in the super DDI. In the DDI, left turns from freeway face

Table 10
Average pedestrian performance per run for each interchange designs based on VISSIM.

Design	Overall		High Turning		Moderate Turning		Low Turning	
	Travel Time (sec)	Stops (no)	Travel Time (sec)	Stops (no)	Travel Time (sec)	Stops (no)	Travel Time (sec)	Stops (no)
DDI	386	2.05	380	2.13	386	1.96	391	2.07
Diamond	346	0.68	348	0.71	346	0.66	344	0.65
Milwaukee A	342	0.93	343	1.03	342	0.89	342	0.87
Milwaukee B	**355**	1.25	**357**	1.29	**356**	1.32	**353**	1.13
Parclo B	348	1.34	**352**	1.20	348	1.10	345	1.09
Super DDI	**356**	1.25	**358**	1.30	**356**	1.30	**355**	1.15
Synchronized	364	1.34	371	1.27	364	1.15	360	1.02

Note: Bold represents the insignificant differences in mean pedestrian travel time (sec) between super DDI and the other designs at the 0.05 level.

Table 11
The estimated waiting time of pedestrians, on average per delayed pedestrian.

Parameters	Overall			High Turning			Moderate Turning			Low Turning		
	CL [a] (sec)	R [b] (sec)	Waiting Time (sec)	CL (sec)	R (sec)	Waiting Time (sec)	CL (sec)	R (sec)	Waiting Time (sec)	CL (sec)	R (sec)	Waiting Time (sec)
DDI	75	43	44	61	36	38	76	42	41	89	49	51
Diamond	120	36	12	120	39	14	120	36	12	120	33	11
Milwaukee A	67	31	14	62	32	16	66	31	14	73	30	13
Milwaukee B	57	28	18	53	30	19	57	28	18	62	27	15
Parclo B	70	32	21	67	34	20	70	32	18	74	31	17
Super DDI	57	28	21	53	30	19	57	28	18	62	27	15
Synchronized	68	28	19	65	30	19	67	27	16	71	26	13

[a] Average cycle length of scenarios.
[b] Average red interval of pedestrians (clearance time of pedestrians is included).

Table 12
The comparison of vehicle-pedestrian conflicts per pedestrian route in each interchange.

Parameters	Free-Flow Crossing			Permissive Crossing			Protected Crossing			Total		
	N[a]	L[b]	V[c]	N	L	V	N	L	V	N	L	V
DDI	2	2	758	0	0	0	2	5	2970	4	7	3728
Diamond	0	0	0	1	1	379	1	2	758	2	3	1137
Milwaukee A	1	2	758	0	0	0	1	2	758	2	4	1516
Milwaukee B	0	0	0	1	1	379	1	2	758	2	3	1137
Parclo B	0	0	0	1	1	379	1	2	758	2	3	1137
Super DDI	0	0	0	1	1	379	1	2	758	2	3	1137
Synchronized	0	0	0	1	1	379	1	2	758	2	3	1137

[a] Number of crossings.
[b] Total Length (number of lanes).
[c] Average Conflicting Traffic Volume (veh/hr)-Estimated using average values of Table 3.

both the EB left turn and through traffic in the merging point #5; however, in a super DDI, they would face the EB left turn and through traffic separately in two steps in merging points #7 and #5.

Table 8 supports the discussion done in the previous paragraph. There is no difference between the traffic volume involving in conflict points of DDI and super DDI designs, except in through traffic routes, where the super DDI should be safer due to having less traffic volume involved with its conflict points. This superior performance would be more considerable as the through traffic demands increases (in moderate and low turning conditions).

As another indicator of safety, the number of vehicle stops was extracted from VISSIM and presented in Table 9. The number of stops can be considered as an important factor for evaluating the driver comfort, and it is likely that drivers get frustrated and commit more violations when faced with a high number of stops. The super DDI had the second lowest number of stops on average after the Milwaukee A.

4.2. Pedestrian safety

The pedestrian performance of the super DDI was presented in Table 10.

Both the pedestrian travel time and the number of stops were seen lower for the super DDI than for a typical DDI. According to an ANOVA conducted at the level of 0.05, the results for the super DDI were similar to the Milwaukee B, parclo B, and synchronized interchanges, but were not as good as the diamond or the Milwaukee A. Note that the good results in these MOEs for the Milwaukee A were due to the fact that the pedestrians had the right-of-way in the simulation over vehicles on the free-flowing entrance ramps; in actuality, vehicles usually do not yield to pedestrians in that situation. Also, in the diamond interchange, pedestrians were receiving protected green light simultaneously with the green light of off-ramps (since no through traffic was defined on the off-ramps). Therefore, the pedestrian performance was observed very well in the diamond interchange; however, the results should be different in the cases with through traffic on the off-ramps.

Table 11 shows estimates of the waiting times of pedestrians by multiplying the number of stops by half of the red time. Note that the number of stops is used as a parameter for the probability of facing a red interval in this study since pedestrians had the right-of-way for crossing at any other conflict point with vehicles, so all the stops were because of red lights. The purpose of using half the red interval was to consider an average stop length for the pedestrians assuming random arrivals. For example, the waiting time was estimated equal to 44 s for the DDI multiplying 2.05 (the number of stops) by 21.5 (half of the red interval). On this measure, the super DDI was superior to the DDI, with a 26-sec saving on average. The super DDI again performed similarly to the Milwaukee B, parclo B, and synchronized interchanges on this measure, with the diamond as the best design.

The types of conflicts between pedestrians and vehicles per pedestrian route are described in Table 12 for the designs tested. Note that the average conflicting traffic volume (with pedestrian paths) was estimated using Table 3. Table 12 shows that the super DDI removes all the free-flow crossings and reduces the lengths of conflict areas by over 200% and reduces the volume of conflicts by over 300% in comparison to a traditional DDI.

To elaborate on the results of Table 12, Fig. 8 has illustrated a comparison between super DDI and DDI from the viewpoint of vehicle-pedestrian conflicts in the pedestrian route from southwest to southeast.

4.3. Limitations

The previous paragraphs summarized the safety assessment done in this study. Despite the comprehensive simulation series and the analysis conducted in this study, more studies should be done in the future to evaluate the super DDI's safety performance. To address a limitation in the existing evaluation, drivers' behavior could be modeled using driving simulation laboratory to include the effect of drivers' confusion

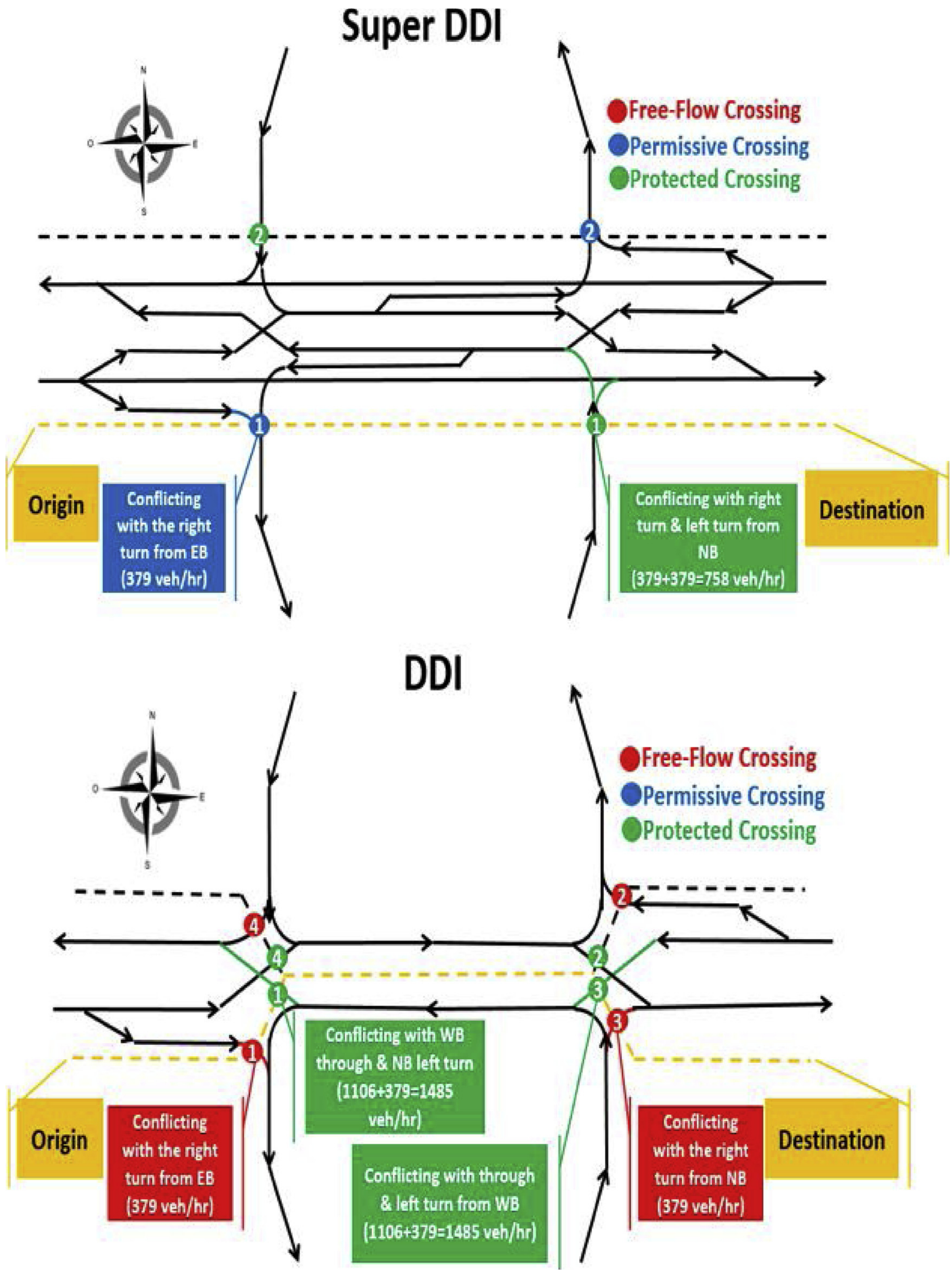

Fig. 8. A comparison between super DDI and DDI from the viewpoint of vehicle-pedestrian conflicts in the pedestrian route from southwest to southeast.

on safety of the new super DDI. Note that the wrong-way movement is one of the main threats that might result in severe crashes in unconventional designs. Also, a case study is recommended to evaluate super DDI's safety considering a calibrated car following model based on drivers' behavior in a specific location.

5. Conclusions

This study evaluated safety performance of the new super DDI design in terms of vehicular traffic and pedestrians. From a general point of view, the super DDI performed very well in safety-related measures. The percentage of simulated conflicts in the super DDI was found the minimum in comparison to other interchanges considered. The super DDI was also predicted to have a low rate of severe conflicts due to its low conflicting speed (between vehicles) and higher time to collision (TTC) based on surrogate safety assessment model (SSAM).

Regarding the pedestrian travel time, the super DDI was not as good as the Milwaukee A interchange, but the performance was better than the typical DDI. The pedestrian travel time in the super DDI was found to be about 3% more than a Milwaukee A which had the lowest travel time among all the interchanges tested; however, the super DDI is predicted to be one of the safest alternatives in terms of pedestrian safety. There is no free-flowing conflict between pedestrians and vehicles for the pedestrian paths proposed in this study for the super DDI design. Note that providing safe paths for pedestrians is one of the main requirements in any transportation project based on the recent policies. The results should be helpful to highway agencies making choices on interchange design and trying to serve all roadway users well.

This paper showed a high potential for the new super DDI in improving safety of vehicular traffic and pedestrians, while the other study (Mehrara Molan et al., 2019) also found a promising performance in terms of traffic operation for the design. Future research is needed to model driver behavior using a driving simulator laboratory. It is highly recommended to research on estimating an appropriate angle at the super DDI crossovers. This study considered a 45-degrees angle as recommended in DDI guideline (2014); however, an angle less than 45 ° may also be safe in terms of minimizing wrong-way movements. The reason is that the through traffic directions are not crossing each other at the super DDI crossovers, while the through traffic could make a wrong-way movement at the DDI crossovers due to shifting their routes to the left side on the bridge. Another recommended study related to the super DDI design might be investigating the effect of adjacent driveways (land uses and streets) on safety. Also, a case study is suggested to be done considering calibrated car following model to estimate the super DDI's safety performance in a location with specific driving behavior and regulations. Bicycle performance of the design could be a measure of effectiveness (MOE) in this study; however, the authors decided to consider the bicycle analysis in a further study. Note that the comparison regarding bicycle performance is predicted to be similar to the pedestrian performance done in this research since both MOEs follow the same features and method of analysis based on Highway Capacity Manual (Highway Capacity Manual (HCM, 2010). An on-going research is conducting the initial analyzes toward the possibility of constructing the first super DDI interchange in Colorado (Mehrara Molan and Ksaibati, 2018). As a perspective of the future works, before-after studies are essential to be done considering real-world crash data.

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