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Article

Evaluating Pedestrian Service of the New Super Diverging Diamond Interchange on Three Case Study Sites in Denver, Colorado

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Abstract: Ensuring safe and comfortable conditions for pedestrians necessitates specific strategies at intersections and service interchanges where traffic and pedestrians interact in complex ways with other modes of transportation. This study aims to investigate pedestrian performance at the new Super Diverging Diamond Interchange (Super DDI) using real-world locations (i.e., I-225 and Mississippi Ave, I-25 and 120th Ave, and I-25 and Hampden Ave in Denver, Colorado). Three alternative designs, typical DDI, and two versions of Super DDI were considered to make a reasonable comparison with the existing Conventional Diamond Interchange (CDI). A comprehensive series of simulation models (192 scenarios with 960 runs) were tested using VISSIM and Synchro to analyze pedestrian operation (travel time, number of stops, and waiting time) in various traffic and pedestrian distributions. As one of the primary contributions in this paper, pedestrian safety was evaluated based on a surrogate performance measure called design flag, introduced by the new National Cooperative Highway Research Program (NCHRP-948) guideline. The results indicated that the proposed new Super DDI designs are relatively safe when compared with CDI and DDI. For example, a pedestrian analysis of one of the most popular alternative interchanges, DDI, showed potential for unsafe pedestrian conditions in all aspects.

Keywords: alternative interchanges; DDI; Super DDI; pedestrian performance; VISSIM; design flags

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1. Introduction

1.1. Background

In a modern sense, walking has been emphasized not only as a sustainable option economically and environmentally but also for improving society's public health. With the continuous increase in automobile transportation in the United States, pedestrians have become more vulnerable to traffic crashes, especially in urban areas. According to the National Highway Traffic Safety Administration (NHTSA), there were 6283 pedestrians killed and 75,000 injured in traffic crashes in 2018, accounting for nearly 17 percent of all traffic fatalities throughout the nation [1]. It was also found that a pedestrian was killed every 84 min on average in a traffic crash. Despite the lower percentage, these numbers indicate the magnitude of risk faced by pedestrians considering the low walking levels relative to other modes of travel. The risk seems to be more frequent in intersections and service interchanges (where a freeway meets an arterial). For example, approximately 60 percent of pedestrian crashes occurred at intersections in Montreal [2], while the rate in a few places within the U.S. is as high as 76 percent [3]. Therefore, traffic agencies have begun to emphasize raising pedestrian awareness by providing safety tips, educational material, and other resources.

Roadway junctions (i.e., intersections and interchanges) can be considered as the bottleneck node where pedestrian–vehicle conflicts could be critical due to the complicated traffic flow. Throughout the decades, a series of unconventional intersection and interchange designs were introduced to better deal with traffic operation and safety, including median U-turn intersections [4,5], superstreet intersections [5–8], uninterrupted flow intersections [9], offset diamond interchanges [10], special width approach lanes [11], dynamic reversible lane control [12], displaced left-turn intersections [13,14], exit-lanes for left-turn intersections [15–17], tandem intersections [18,19], and continuous flow intersection [20]. Pedestrians often face challenges at grade-separated highway interchanges because of the angle and speed of on- and off-ramps, which lead drivers to concentrate primarily on other motor vehicles, leaving sufficient attention to pedestrians. Moreover, major portions of the existing Conventional Diamond Interchanges (CDI) in the U.S. were 60–70 years old. The pedestrian performance was not taken into consideration with much importance during their design and construction. In response to the significant traffic growth over the last two decades, alternative interchanges are gaining attention from transportation agencies who seek to improve the performance of old and failing service interchanges. As one of the best accomplishments, the Diverging Diamond Interchange (DDI) became popular, and since then more than 90 DDIs have been deployed throughout the U.S. [21]. Although DDI has the potential to offer good traffic operation and superior safety [22,23], controversy still remains regarding its friendliness to pedestrians. DDI might not be an ideal design in terms of pedestrian safety, since there are free-flow movements. Alternative intersections and interchanges sometimes include altering traffic lanes from their traditional paths, which may create confusion and risk concerns for other road users such as pedestrians and bicyclists. All these facts caused the National Cooperative Highway Research Program (NCHRP) to launch a new project entitled NCHRP 07-25 regarding pedestrian and bicyclist performance at alternative intersections and interchanges which was recently published under the National Academies Press [24].

In 2019, the Super Diverging Diamond Interchange (Super DDI) was proposed by Molan et al. (2019), and it was claimed as a new alternative design with the potential to mitigate the concerns of the DDI, especially in terms of pedestrian performance [25,26]. This paper introduces the two forms of Super DDI and evaluates its pedestrian performance by expanding the previous work. It is worth mentioning that the main goal of this research is to improve the performance of failing service interchanges in the mountain-plains region by introducing a new alternative design [27].

1.2. Objective

The primary objective of this study is to facilitate the existing research on novel Super DDI by assessing pedestrian performance exclusively in two versions of the proposed design, thereby comparing the existing designs using real-world locations. The operational performance of pedestrians investigated in this study include pedestrian travel time, the average number of stops, and waiting time, while the number of crossings, number of lanes crossed, and conflicting traffic volumes are considered to provide insight into safety implications. As one of the primary contributions in this paper, the performance of the pedestrians in various interchange designs was evaluated based on a surrogate performance measure called “design flag”, introduced by the new NCHRP guideline [24] to identify potential safety, accessibility, operational, and comfort issues for pedestrians. To the extent of the authors’ knowledge, this is the first study that utilizes the design flag assessment method to examine pedestrian safety in the interchanges.

The authors examined three alternative designs, DDI and two versions of Super DDI, to create a sensible difference with the existing CDI through the use of microsimulation modeling tools. Also, the construction costs associated with different alternative designs are maintained low by keeping each design within the existing right-of-way (ROW). Due to the comprehensive efforts needed for describing various elements of the new design, this paper concentrates primarily on pedestrian performance, while traffic operation and safety are documented in other existing manuscripts [28,29]. Therefore, this study addresses a notable and significant gap in the research. In the following paragraphs, a brief description of the Super DDI design with the proposed pedestrian paths is outlined to establish a clear understanding for readers.

1.3. Super DDI Design

The Super DDI, proposed by the second author of this manuscript, was developed from the idea of combining the features of the synchronized interchange with those of the DDI [25,26]. The geometry, traffic movement, and the position of signals with the corresponding phase diagram of Super DDI are provided in Figure 1. Super DDI is similar to the DDI layout. However, the better signal progression system and the absence of free-flowing vehicle–pedestrian conflicts apparently make Super DDI more advantageous than DDI in some cases. Super DDI allows traffic in both directions to operate completely separate from each other. Specifically, a perfect progression for through traffic can be achieved since it utilizes half-signals affecting only one direction of the arterial instead of full-signals affecting both directions of the arterial. The two versions of the Super DDI design are demonstrated in Figures 2 and 3. As illustrated from version 1, there are two left-turn lanes on each side of the arterial for turning onto the on-ramp while one left-turn lane for vehicles turning from the off-ramp onto the arterial. As for version 2, it has one lane for left-turns onto the on-ramp from the arterial and two lanes for turning off of the off-ramp. Version 1 would be appropriate for high left-turn volumes from the arterial, whereas version 2 would work better for high left-turn volumes from the freeway onto the arterial.

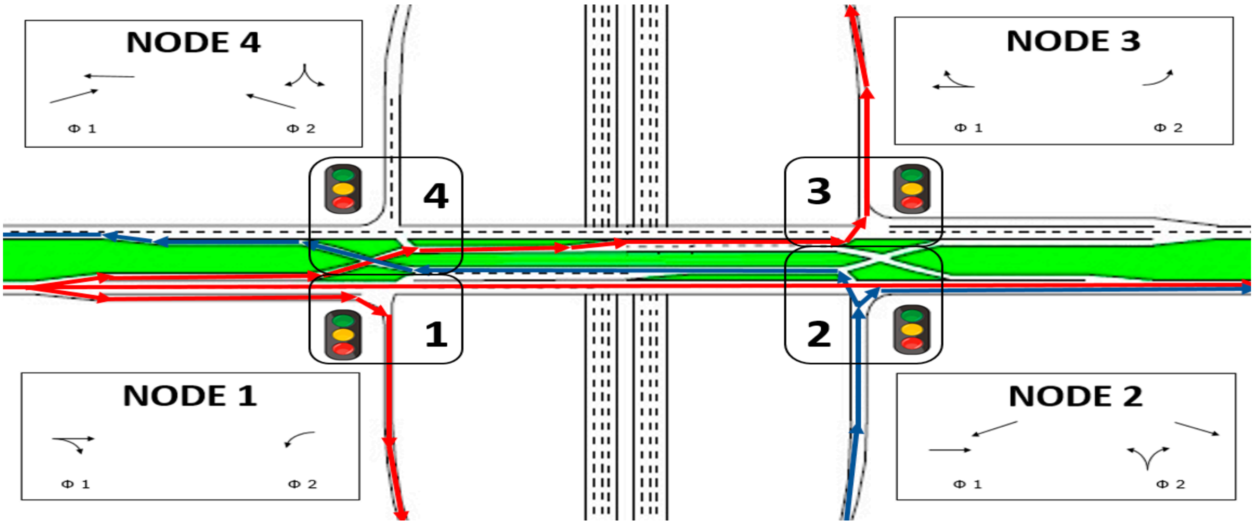


Figure 1. Traffic movement and signal phasing of Super DDI design [30].

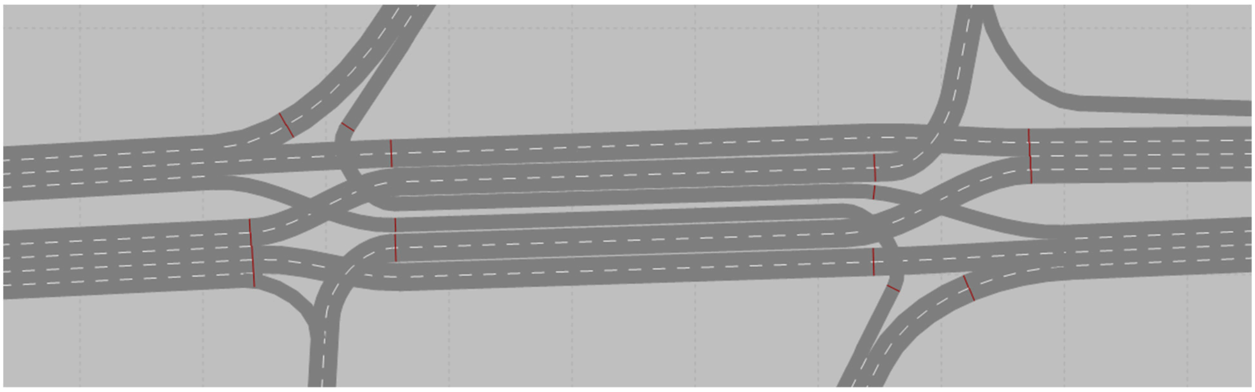


Figure 2. Super DDI Version 1 (Super DDI-1) [30].

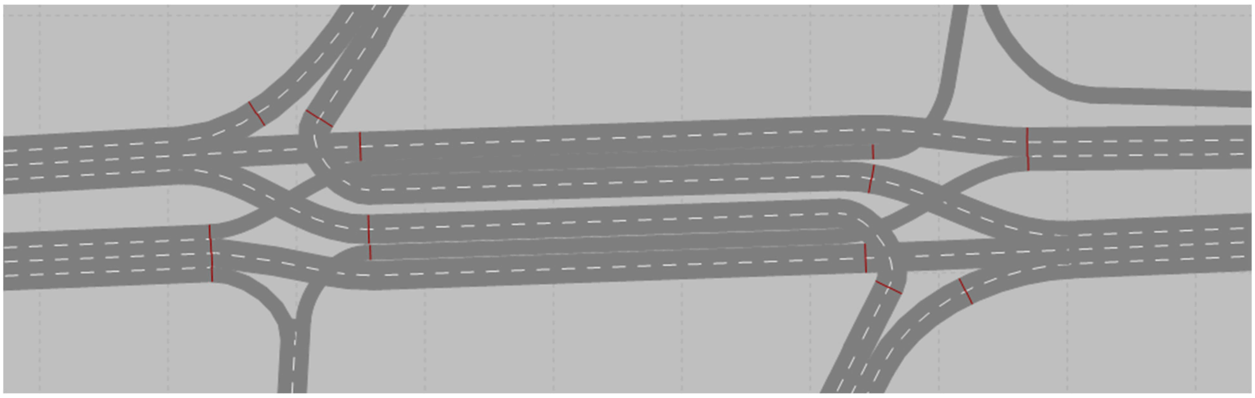


Figure 3. Super DDI version 2 (Super DDI-2) [30].

Figure 4 indicates two proposed alternative pedestrian routes for the Super DDI. Between the alternative paths, a side path (red line) would be the best option because of its simple pedestrian operation with better safety. However, similar to the typical middle pedestrian path in DDIs, the blue line (middle path) in Super DDI would have to cross four signals (for traveling in the north–south direction), resulting in longer travel times. The blue route would be appropriate if there was a shorter bridge width.

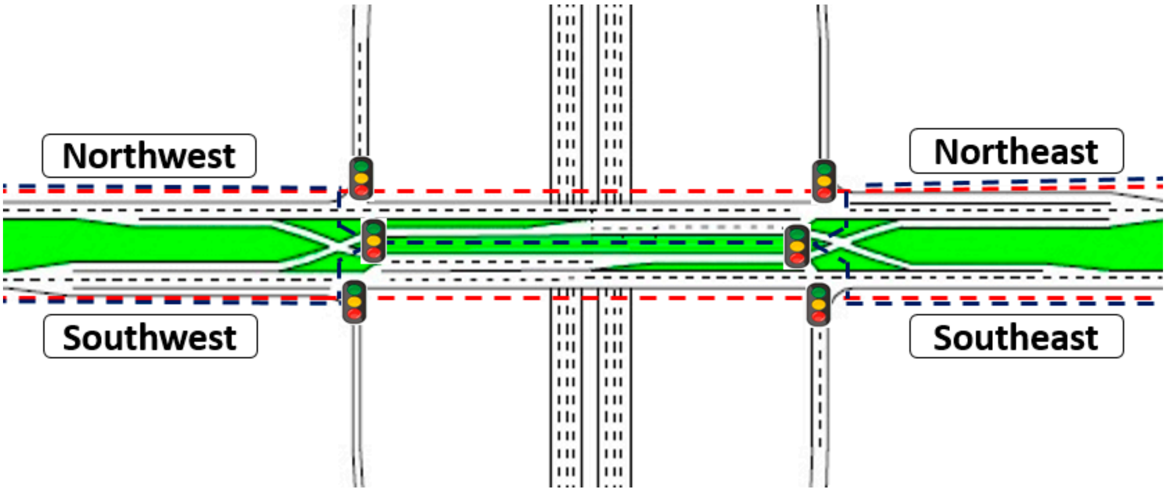


Figure 4. Proposed pedestrian paths in Super DDI design (red line = side path, blue line = middle path) [30].

2. Materials and Methods

Since field testing was not possible for analyzing the proposed design, due to the fact that it has not been built yet, simulation modeling using VISSIM (2020 version) and Synchro (version 11) was selected as the most applicable assessment tool for this. The VISSIM microsimulation package has been popular in different sectors of transportation engineering. More specifically, its applications include use in studies investigating user behavior [31,32] and studies related to the operation and safety of transportation infrastructures [25,26,33,34]. Synchro, a macroscopic simulation software, can analyze the performance of signalized intersections by optimizing signal times based on the *Highway Capacity Manual* [35]. The study first determined optimum signal timing and cycle length using Synchro. After that, signal data was incorporated into VISSIM models replicating each interchange design to evaluate the pedestrian performance.

2.1. Site Selection, Data Preparation, and Geometry Design

While investigating the most commonly failing and hazardous interchanges out of 62 service interchanges in the Denver metro area in Colorado, the research team identified three interchanges using the critical lane volume (CLV) method: I-225 and Mississippi Ave; I-25 and 120th Ave; and I-25 and Hampden Ave. Therefore, these interchanges were selected as promising alternatives for future retrofit to be substituted by either DDI or Super DDI. Two main reasons behind choosing these interchanges include (i) a relatively high volume-to-capacity (v/c) ratio (i.e., greater than 1), and (ii) ideal bridge width (ten traffic lanes on each site) for constructing either a DDI or a Super DDI.

There are two main sources named Denver Regional Council of Governments and the Colorado Department of Transportation (CDOT), which provide all the required traffic data associated with the selected interchange. Specifically, the data were collected for an hour during the AM, Noon, and PM peaks. The data contain all the necessary information regarding traffic proportions, turning movements, and pedestrian movements. However, the research team did not find any significant difference in pedestrian performance in the three different peaks and hence considered only PM peak hours for this research. The data collection was conducted on April 19, 2018 (4:30–5:30 PM) for I-225 and Mississippi Ave; August 4, 2017 (4:45–5:45 PM) for I-25 and 120th Ave; and June 22, 2010 (4:45–5:45 PM) for I-25 and Hampden Ave. Other non-traditional sources such as Google Maps and Google Earth Pro were used to map geometric features and obtain the posted speed limits for the network pertinent to this study. The obtained traffic volume was calculated for projections in the years 2020 and 2030, and those projections assumed an annual growth rate of 2%. These calculations simulated how the models are likely to function under current and future conditions.

Furthermore, for the purpose of this paper, it must be acknowledged that the effect of connected and autonomous vehicles (CAVs) on pedestrian performance could be considered for evaluating the performance in 2040 or 2045 (considering a design period of 20–25 years). However, since evaluating CAVs was out of the research scope, 2030 was considered the design year for predicting the future pedestrian operation of the interchanges. The truck composition used in the analysis was 5% based on the available field data. Table 1 shows the existing (2020) mean traffic volumes on each turning movement of the selected interchanges.

Table 1. Entry traffic volume (2020 PM) for the selected interchanges.

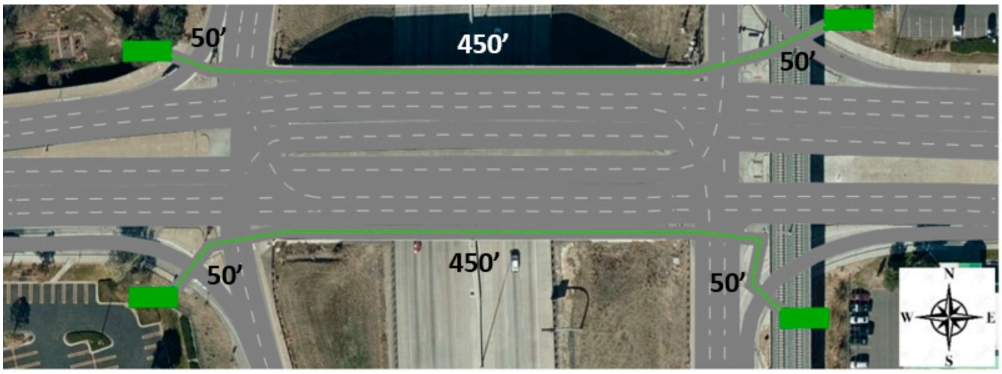
Location	**Arterial (EB)**			**Arterial (WB)**			**Ramp (NB)**		**Ramp (SB)**		**Total**
	LT	**T**	**RT**	**LT**	**T**	**RT**	**LT**	**RT**	**LT**	**RT**	
I-225 and Mississippi Ave	512	1930	453	446	1799	408	397	441	470	412	7268
I-25 and 120th Ave	710	1948	1097	919	1737	384	637	780	427	525	9164
I-25 and Hampden Ave	116	1776	1023	597	2044	679	1095	606	892	174	9002

Note: LT = left turn, T = through, RT = right turn.

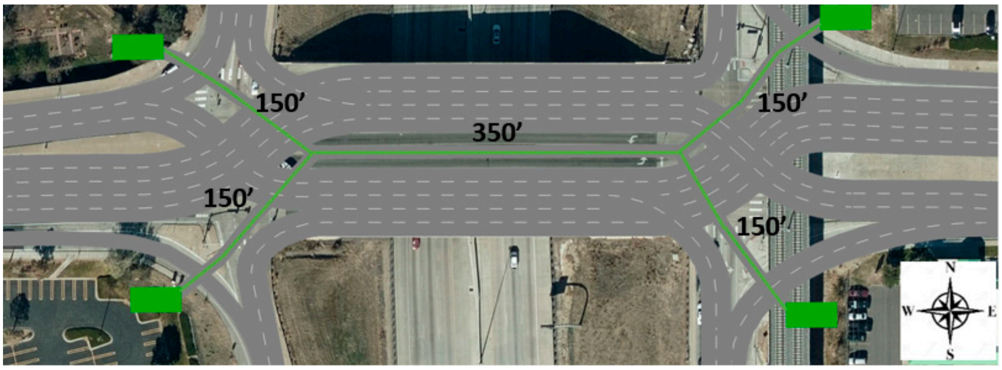
The pedestrian volume collected from the CDOT was very low. Therefore, the study considered various distributions of pedestrian volume, where 45 and 90 pedestrians per hour per route were selected to represent moderate and high demand, respectively. There are three reasons for choosing a relatively high pedestrian volume in the simulation. First, there is a lack of high pedestrian demands in US interchanges relative to those replicated in this paper, aside from some intersections in downtown areas where these would not be appropriate for this study. Second, relatively low demand in pedestrian flow would lead to instability in the results due to insufficient sample sizes. Third, different pedestrian demand levels up to a high level would help provide performance variation in various designs since pedestrians tend to travel in packs or bunches instead of in paths, creating an additional delay.

Between the two alternative pedestrian paths for the Super DDI design shown in Figure 4, the side path (red line) would offer smooth pedestrian operation and better safety as compared to the middle path (blue line). However, in the case of reducing the bridge width, the middle path (blue line) seems to be more appropriate. Comparing the facts and authors' judgements, the side path (red line) is considered the best option and is hence used for pedestrian analysis in this paper. Among the designs tested in the simulation models, both CDI and Super DDI had two pedestrian paths on the side with 10 feet width while DDI had the path in the middle of the bridge. The reason behind avoiding the side path for DDI was safety concerns since it would cross the left entrance to the on-ramp route and create conflict with free-flow traffic.

The geometric layout of the investigated interchanges with the corresponding pedestrian paths (in green lines) is shown in Figure 5 considering one of the case study sites as an example. The layout of other case study sites was identical and hence is not provided here to avoid redundancy. On the whole, Figure 5 demonstrates that it is possible to implement all of the designs within the original ROW limits. It was noted that the expansion of the bridge would not be required to deploy the alternative designs. Moreover, based on the DDI's FHWA manual [36], the crossover angle in both DDI and Super DDI designs was set at 45 degrees to reduce the wrong-way possibilities. As demonstrated in Figure 5, each interchange design consists of ten traffic lanes on the bridge.

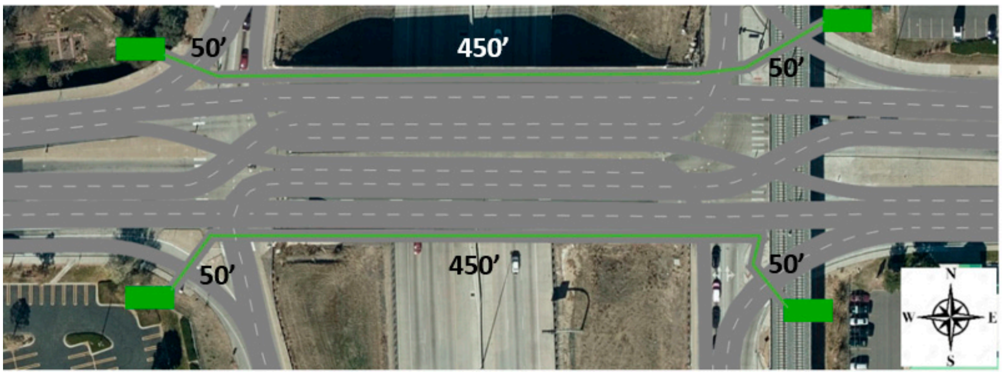


(**a**)



(**b**)

Figure 5. *Cont.*



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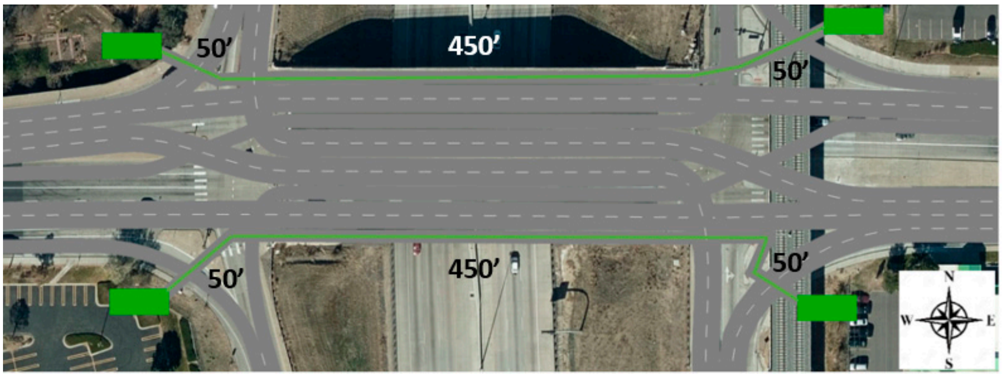


(**d**)

Figure 5. Geometric layout of interchanges selected for study at I-225 and Mississippi Ave (green line shows pedestrian path). (**a**) Existing CDI; (**b**) Possible DDI configuration; (**c**) Possible Super DDI-1 configuration; (**d**) Possible Super DDI-2 configuration.

2.2. Simulation Scenarios

In VISSIM, the geometry of each design was constructed using background maps inherent to the programs. The simulated models were further enhanced by integrating traffic volumes with their routing decisions. The geometry was also examined through Google Street View to replicate actual field conditions. In order to characterize vehicle speed, the custom cumulative probability functions were established using available field speed data while the posted speed was considered as the 85th percentile. Areas indicating a need for reduced speed were placed where vehicles made any turns (e.g., right turns on and off of the freeway) to precisely reproduce driving behavior.

Due to the very low presence of pedestrians, the study considered eight arbitrary distributions of pedestrian volume, as shown in Table 2. There were four pedestrian origin points, each having one possible route summed up in a total of four routes (from southeast to southwest and vice versa, from northeast to northwest and vice versa). Note that no pedestrians passed over the arterial. In other words, they only traversed the bridge.

Table 2. Distribution of pedestrian volume.

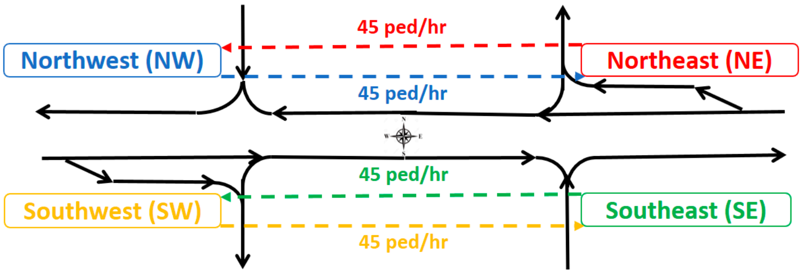
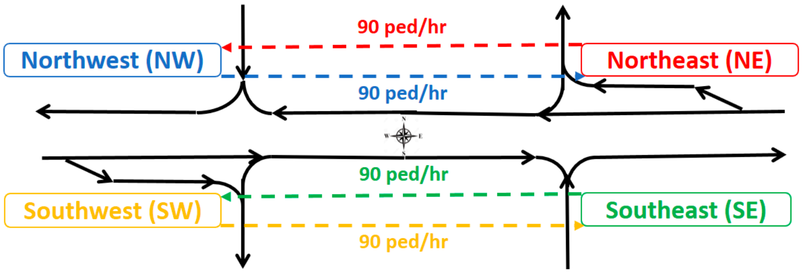
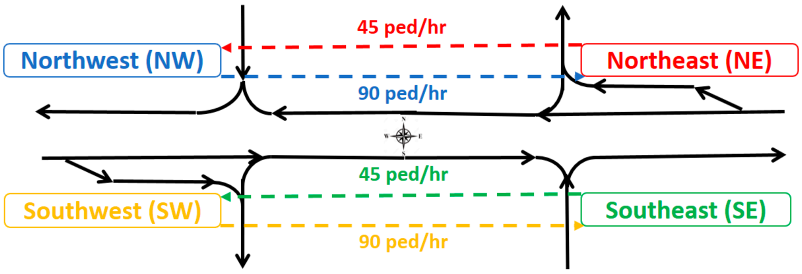
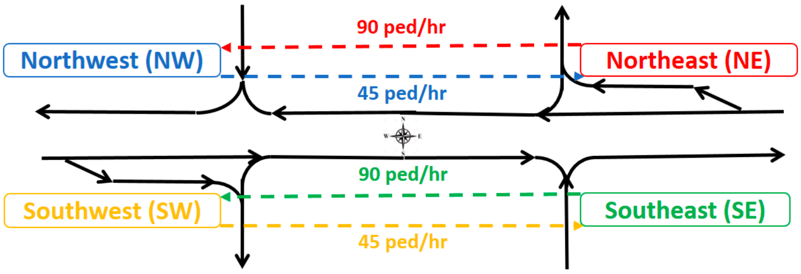
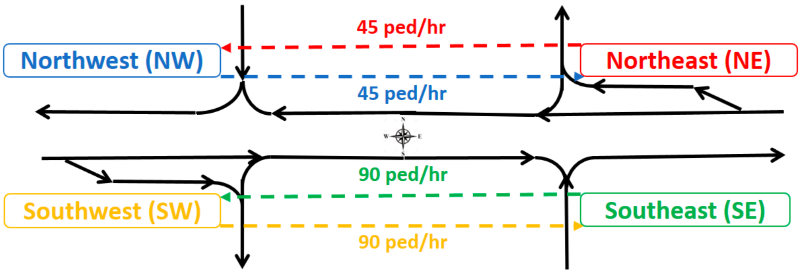
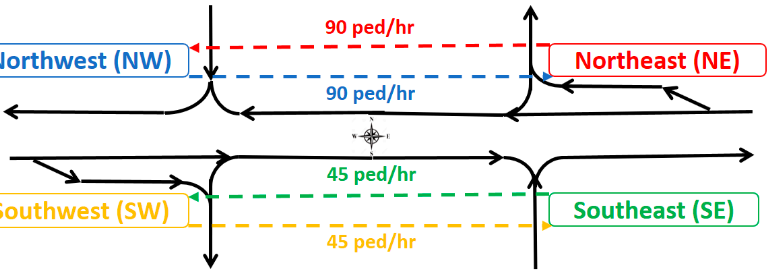
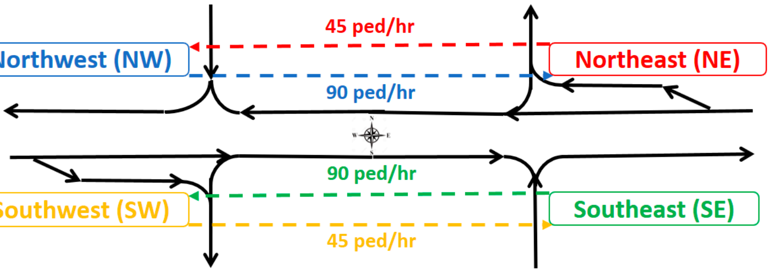
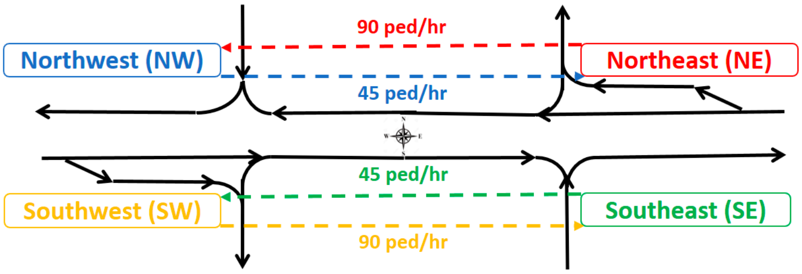
Pedestrian Volume Distribution	Description of the Scenario
1. All 45	
2. All 90	
3. E 45–W 90	
4. E 90–W 45	
5. N 45–S 90	

Table 2. *Cont.*

Pedestrian Volume Distribution	Description of the Scenario
6. N 90–S 45	
7. NE and SW 45–NW and SE 90	
8. NE and SW 90–NW and SE 45	

Each design was tested considering eight distributions of pedestrian volume as shown in Table 2. Based on this information, new alternatives were developed, and microsimulation models replicated conditions for current (the year 2020) and projected (the year 2030) traffic volumes, with each design encompassing sixteen different scenarios, comprising a total of 192 scenarios (three locations * four designs * sixteen traffic distributions = 192 tests). The total length for each microsimulation model was set at 4500 s (75 min) with 900 s (15 min) as warm-up time. This study used three performance indices, i.e., travel time, waiting time (on red intervals), and the number of stops to evaluate pedestrian operation directly extracted from the VISSIM output. Although the study tried to examine vehicle–pedestrian conflicts using VISSIM trajectory files through Surrogate Safety Assessment Model (SSAM), it was possible because of its limitation in precisely simulating vehicle-pedestrian interactions [37].

To incorporate the impact of simulation seeds in various VISSIM scenarios, each test was run five times with their average being selected as the representative outcome of each scenario. Also, a factorial analysis method was employed to make sure that many more than just two samples were added to any comparison made within the analysis. To address this, a two-way analysis of variance (ANOVA) with post hoc tests at a 95% confidence level (p-value = 0.05) was applied to determine the notable differences between the pedestrian performance of the interchanges utilizing the R statistical program.

2.3. Traffic Signal Design

Undoubtedly, signal timing and phasing are essential parts of analyzing pedestrian operation. Therefore, all the signals employed in the simulation models were developed using Synchro to confirm the accurate signal timing as well as phasing. In Synchro, 180 and

40 s were considered as the maximum and minimum cycle lengths, respectively. Also, all traffic signals were set at the same or multiple of the maximum cycle length to generate a signal progression system. Turning vehicles were allowed to right-turn on red (RTOR) in the simulation yielding to pedestrians in permissive (shared) green intervals. Note that yellow and all-red intervals were set at 4 and 2 s, respectively based on the *Manual on Uniform Traffic Control Devices* (MUTCD) [38] for traffic signals.

Since the field signal data for the selected locations were not available, the study considered a 7-s clearance time at one-lane crossings and added 3.5 s for any additional lane based on the previous studies [26,33]. Note that all the minimum green times were satisfied during the signal design. Pedestrians at the on-ramp and off-ramp crossings at the CDI and DDI had four free-flowing conflicts with the vehicle movements, and hence pedestrians had to yield before crossing in those cases. As for the Super DDI design, there were signals at every pedestrian crossing except for the free-flowing right-turn vehicles entering the on-ramp. Table 3 provides the cycle lengths with the red interval for pedestrians used for each model that was determined with guidance from Synchro.

Table 3. Average signal cycle length with the corresponding red interval of pedestrians.

Interchange Type	**Traffic Volume Year**	**I-225 and Mississippi Ave**		**I-25 and 120th Ave**		**I-25 and Hampden Ave**	
		CL (sec)	**R (sec)**	**CL (sec)**	**R (sec)**	**CL (s)**	**R (sec)**
CDI	2020	90	28	150	47	160	42
	2030	180	47	150	47	180	46
DDI	2020	60	36	140	76	90	51
	2030	80	46	150	81	150	81
Super DDI-1	2020	60	25	75	35	75	32
	2030	75	30	75	35	75	32
Super DDI-2	2020	60	27	75	35	75	30
	2030	75	30	75	35	75	30

Note: CL = average cycle length of the scenarios, and R = average red interval of pedestrians (clearance time of pedestrians is included).

2.4. User Behavior

Reviewing the previous studies, it was found that the walking pace imitates a normal distribution with 70–80% of the observation data near the average. The current research applied pedestrian speeds according to field data collection from a previous study on pedestrian performance at superstreet intersections [39]. Based on that study, pedestrian speeds were categorized into two groups: (i) 91% as walking pedestrians with a mean speed of 5 fps, and (ii) the remaining 9% as running pedestrians with a mean speed of 9.6 fps. The prime concern for vehicles and pedestrians on the free-flow crossings was designed in such a way that drivers had to stop when pedestrians could notice a minimum gap of 3 s or more to start off a crossing.

The distribution of vehicle speed was defined as 65 kmph (40 mph) (posted speed limit) for passenger cars and 57 kmph (35 mph) for trucks on the arterials, and these were set as the 85th percentile of the corresponding vehicle speeds. As for the ramps, the mean vehicle speed of 57 kmph (35 mph) was set at I-225 and Mississippi Ave, while 73 kmph (45 mph) was set at the other two locations. Based on data collected in previous studies [40,41], the turning speeds of vehicles were set at 33 kmph (20 mph) on approaches and 25 kmph (15 mph) on the center of turns.

2.5. Calibration and Validation

It is very important to calibrate and validate all the simulation models in order to properly replicate the field conditions. For this purpose, the GEH statistics were determined where the simulated traffic volumes of at least five runs were compared to the real-world hourly traffic. Table 4 shows the GEH values for various scenarios at the selected locations.

As illustrated, the calculated GEH statistics matched with the satisfied values (less than 5), which confirmed successful model calibration. After calibrating the base design (i.e., CDI interchange) in VISSIM, the resulting driver behavior information was incorporated into the other interchange designs. More information is provided in [28,29] regarding the GEH estimated in this study.

Table 4. GEH statistics.

Scenario		Mean GEH Statistics Considering all Turning Movements	<5?
I-225 and Mississippi Ave	2020 PM	2.01	Yes
I-25 and 120th Ave	2020 PM	3.40	Yes
I-25 and Hampden Ave	2020 PM	3.46	Yes

2.6. Design Flags

As another measure of effectiveness (MOE), this study performed a design flag assessment proposed by the new NCHRP guide on pedestrian and bicyclist safety [24]. These design flags were not only unique to evaluating the performance measures of the alternative designs, but they were also applicable to designing safe pedestrian and bicycle facilities for each alternative, whether traditional or alternative intersections and interchanges (AIIs) design. The analysis included two types of design flags: (i) red flags, indicating design elements directly related to a safety concern for pedestrians or bicyclists; and (ii) yellow flags, indicating design elements negatively affecting user comfort (i.e., experiencing stress while walking or cycling). Although the study tested only the side pedestrian paths (i.e., north–south direction) in the simulation models, all possible pedestrian paths (north, south, east, and west) were considered to conduct design flags.

3. Results and Discussions

The following paragraphs summarize the performance of pedestrians in two versions of Super DDI in comparison to existing CDI and DDI designs. The analysis also demonstrates the impact of pedestrians on traffic operations. As the last part of the evaluation in this research, pedestrian safety was analyzed based on the new design flags method.

3.1. Overall Pedestrian Performance

3.1.1. Travel Time, Number of Stops, and Waiting Time

The overall pedestrian performance in each design is provided in Table 5. The table also includes the pairwise comparisons of the performance measures indicating whether the mean differences were statistically significant at the 0.05 level based on ANOVA. Pedestrian travel time and the average number of stops were obtained from VISSIM. The number of stops should be considered one of the main factors when examining pedestrian safety concerns. Pedestrians tended to commit more violations as the number of stops increased. To elaborate on this matter, the waiting time was estimated by multiplying the number of stops by half of the red interval (shown in Table 3) for pedestrians. Note that the number of stops determined from the simulation output was due to red lights since pedestrians had the right-of-way for crossing at any other conflict point with vehicles. Therefore, this parameter was used to identify the probability of facing a red interval in this study. The purpose of applying a half red interval was to consider an average stop length for the pedestrians assuming random arrivals [26,33]. For example, the waiting time was estimated equal to 8 s for CDI at I-225 and Mississippi Ave, multiplying 0.40 (the number of stops) by 18.75 (half of the average red interval = $0.5 \times (28 \times 47)/2$).

Table 5. Average pedestrian performance and ANOVA with post hoc tests per interchange design based on VISSIM.

Average Performance									
Interchange Type	**I-225 and Mississippi Ave**			**I-25 and 120th Ave**			**I-25 and Hampden Ave**		
	Travel Time (s)	**Stops (no)**	**Waiting Time (s)**	**Travel Time (s)**	**Stops (no)**	**Waiting Time (s)**	**Travel Time (s)**	**Stops (no)**	**Waiting Time (s)**
CDI	124	0.4	8	140	0.42	10	145	0.86	19
DDI	145	0.54	11	200	0.62	24	180	0.57	19
Super DDI-1	128	0.5	7	150	0.48	8	155	0.54	9
Super DDI-2	130	0.48	7	150	0.49	9	151	0.54	8

ANOVA Tests										
Interchange Type	Compares With	Mean Difference								
		I-225 and Mississippi Ave			I-25 and 120th Ave			I-25 and Hampden Ave		
		Travel Time (s)	Stops (no)	Waiting Time (s)	Travel Time (s)	Stops (no)	Waiting Time (s)	Travel Time (s)	Stops (no)	Waiting Time (s)
CDI	DDI	−20.78	−0.14	−3.51	−59.48	−0.2	−14.59	−35.09	0.29	**0.12**
	Super DDI-1	−4.23	−0.1	**0.73**	−9.13	−0.06	1.48	−10.1	0.32	10.48
	Super DDI-2	−5.85	−0.08	**0.76**	−9.55	−0.07	1.28	−5.35	0.32	11.01
DDI	CDI	20.78	0.14	3.51	59.48	0.2	14.59	35.09	−0.29	**−0.12**
	Super DDI-1	16.55	0.04	4.24	50.34	0.14	16.07	24.99	**0.03**	10.36
	Super DDI-2	14.93	0.06	4.27	49.93	0.13	15.87	29.74	**0.03**	10.89
Super DDI-1	CDI	4.23	0.1	−0.73	9.13	0.06	−1.48	10.1	−0.32	−10.48
	DDI	−16.55	−0.04	−4.24	−50.34	−0.14	−16.07	−24.99	**−0.03**	−10.36
	Super DDI-2	**−1.62**	**0.02**	**0.03**	**−0.42**	**−0.01**	**−0.21**	4.75	**0**	**0.53**
Super DDI-2	CDI	5.85	0.08	−0.76	9.55	0.07	−1.28	5.35	−0.32	−11.01
	DDI	−14.93	−0.06	−4.27	−49.93	−0.13	−15.87	−29.74	**−0.03**	−10.89
	Super DDI-1	**1.62**	**−0.02**	**−0.03**	**0.42**	**0.01**	**0.21**	−4.75	**0**	**−0.53**

Note: Each value describes the average sum of all indicated scenarios. Figures in bold represent the insignificant differences at the 0.05 level.

Based on the results shown in Table 5, on average, the CDI appeared to be the best design in terms of travel time and the number of stops by a close margin over the Super DDI, while both Super DDI designs outperformed the other designs in minimizing pedestrian waiting times, indicating that pedestrians were less prone to jaywalking or violation-related activities. On the other hand, DDI had the worst performance in terms of all MOEs.

Regarding pedestrian travel time shown in Table 5, the CDI was found to perform best, and it provided faster routes for pedestrians. The reason for the higher travel time performance of the conventional diamond design was the existence of only one signalized crossing for each route in the geometry, while the other crossing was a free-flow with the right-of-way for pedestrians based on the existing design. Moreover, pedestrians of CDI were experiencing protected green light simultaneously with the green light of off-ramps (since no through traffic was designated on the off-ramps). Based on the ANOVA analysis shown in Table 5, the pedestrian performance was significantly better in CDI compared to other designs in terms of travel time and number of stops except for the stop evaluation at I-25 and Hampden Ave. As a possible reason for the greater number of stops of CDI at the I-25 and Hamden Ave, the signal cycle length (shown in Table 3) was considerably longer compared to the other interchanges, and the pedestrians also experienced lower ratios of the green interval over cycle length (g/c) due to the presence of relatively high turning traffic from the off-ramp. For example, the NB left-turn demand from the off-ramp was over 1000 vehicles per hour at this location based on Table 1. Although the simulation outcomes showed a relatively good performance of CDI, the results could be different in the real-world scenario. For instance, vehicles often do not yield to pedestrians on free-flowing entrance ramps regardless of pedestrian right-of-way in that situation. Also, there is always a possibility of limited through traffic on the off-ramps, resulting in conflict with pedestrians.

Compared to DDI, both Super DDI designs performed significantly better based on the ANOVA results shown in Table 5. The only exception was found in the stop evaluation at I-25 and Hampden Ave, where the mean differences were insignificant. After reviewing the results, it can be concluded that Super DDI should be a more promising design for improving pedestrian performance than DDI. The possible reasons behind the relatively worse performance of DDI include longer pedestrian paths, more stops (due to facing more traffic signals), higher clearance time due to crossing longer crosswalks (especially in crossing the through traffic in the crossovers), and lower g/c ratios.

3.1.2. Pedestrian Conflicts

Based on the previous studies [2,42], the type, frequency, and size (length) of conflict points with vehicles have notable impacts on pedestrian safety. The volume of conflicting traffic is another contributing parameter to pedestrian safety. The conflicts between pedestrians and vehicles are demonstrated in Table 6. Note that only one pedestrian path (i.e., southwest to southeast) was considered to estimate the conflicting traffic volume using Table 1. The results indicate that DDI had the highest number of crossing lanes with the highest conflicting volume. This is due to the fact that DDI has through arterial lanes that cross and re-cross each other, resulting in more and longer conflicting points with a significantly higher total conflicting volume experienced by the pedestrians. Table 6 also shows that the Super DDI eliminated all the free-flow crossings and reduced the number of crossing lanes by 40% as compared to DDI. On the other hand, the conflicting traffic volume in Super DDI was found to be reduced by approximately 70%, 50%, and 55% at the three locations, respectively, when compared to DDI.

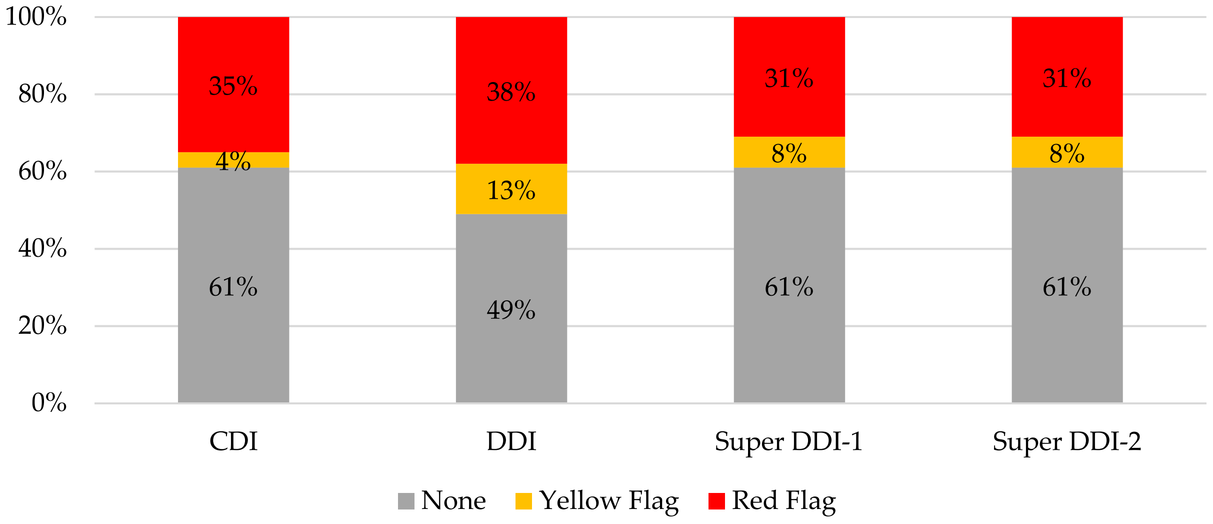
Table 6. The comparison of vehicle-pedestrian vonflicts per rach design for the selected locations.

Location	**Route**	**Design**	**Free-Flow Crossing**			**Permissive Crossing**			**Protected Crossing**			**Total Crossing**		
			N [a]	**L** [b]	**V** [c]	**N**	**L**	**V**	**N**	**L**	**V**	**N**	**L**	**V**
I-225 and Mississippi Ave	Southwest to Southeast (one-way)	CDI	0	0	0	2	2	894	2	5	843	4	7	1737
		DDI	2	2	894	0	0	0	2	8	4441	4	10	5335
		Super DDI-1	0	0	0	1	1	453	3	5	1284	4	6	1737
		Super DDI-2	0	0	0	1	1	453	3	5	1284	4	6	1737
I-25 and 120th Ave	Southwest to Southeast (one-way)	CDI	0	0	0	2	2	1877	2	5	1556	4	7	3433
		DDI	2	2	1877	0	0	0	2	8	5030	4	10	6907
		Super DDI-1	0	0	0	1	1	1097	3	5	2336	4	6	3433
		Super DDI-2	0	0	0	1	1	1097	3	5	2336	4	6	3433
I-25 and Hampden Ave	Southwest to Southeast (one-way)	CDI	0	0	0	2	2	1629	2	5	1692	4	7	3321
		DDI	2	2	1629	0	0	0	2	8	5780	4	10	7409
		Super DDI-1	0	0	0	1	1	1023	3	5	2298	4	6	3321
		Super DDI-2	0	0	0	1	1	1023	3	5	2298	4	6	3321

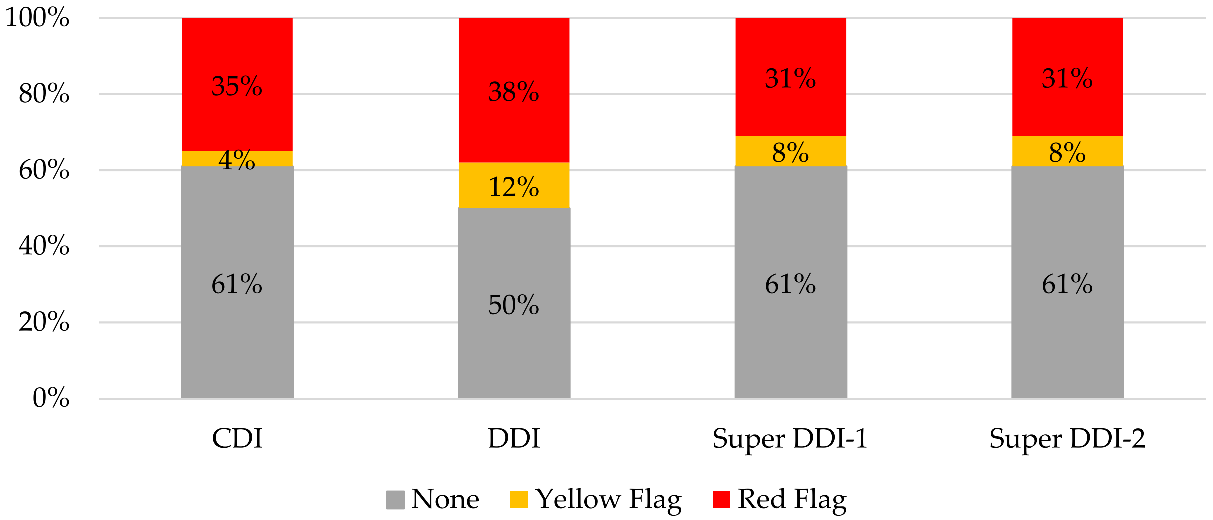
Note: [a] number of Crossings, [b] number of lanes crossed, [c] conflicting traffic volume (veh/hr)—calculated using Table 1.

3.2. Design Flags Assessment

As the last part of the evaluation in this research, design flags were assessed for all possible pedestrian crossing movements. According to the NCHRP-948 guideline, 13 out of 20 flags were investigated for pedestrian safety, which summed up a total of 52 potential flags (13 flags multiplied by four pedestrian flows) for each design [24]. Figure 6 summarizes design flags including potential flag severity (yellow vs. red flag) per each design alternative for the three specified locations. The analysis indicates that DDI resulted in the highest percentage flagged attributing to 50–54%, whereas CDI and Super DDI had fewer design flags compared to DDI ranging from 38–40%. Super DDI was found as the best alternative design for having the lowest number of red flags, which was about 10% and 20% lower than that of the CDI and DDI, respectively. Although CDI had the lowest percentage of yellow flags (4–6%), the Super DDI design outperformed the conventional diamond because of the reduction in flag severity. As a summary of the above analysis performed in this research, Super DDI is the most promising alternative design for improving pedestrian performance.

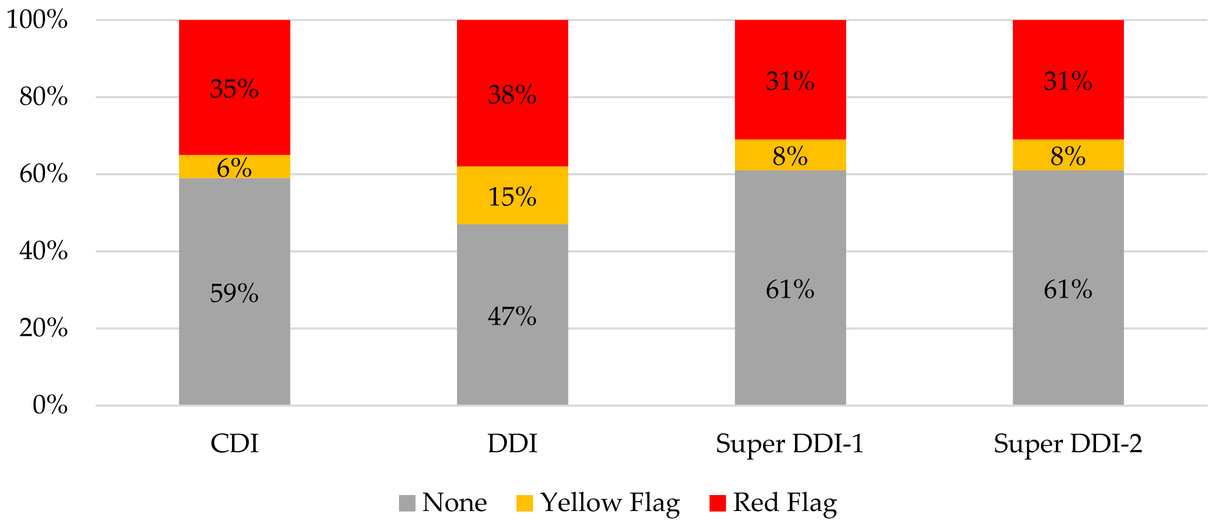


(**a**)



(**b**)

Figure 6. *Cont.*



(**c**)

Figure 6. Summary of design flags for pedestrian assessment. (**a**) I-225 and Mississippi Ave; (**b**) I-25 and 120th Ave; (**c**) I-25 and Hampden Ave.

4. Conclusions

Based on the results, the conventional diamond showed the best pedestrian operation in terms of travel time and the number of stops by a relatively small margin over the Super DDI. On the other hand, both Super DDI designs outperformed the other designs in minimizing pedestrian waiting times, indicating that pedestrians were less prone to jaywalking or violation-related activities. DDI demonstrated the worst performance in terms of all MOEs due to its longer pedestrian paths with higher clearance time of the crosswalk and lower g/c ratios. While analyzing vehicle–pedestrian conflicts, Super DDI appeared to offer relatively good pedestrian safety compared to other designs by eliminating all the free-flow crossings and reducing the number of crossing lanes and the conflicting traffic volume. From the assessment of design flag analysis, the Super DDI design is predicted to be safer for pedestrians compared to other designs due to its lowest number of red flags and the potential reduction in flag severity.

Despite the comprehensive simulation series and the analysis conducted in this paper, future studies could further evaluate the Super DDI's pedestrian and bicycle facilities. A driving simulator laboratory could analyze driver behavior and driver expectation and reaction to pedestrians in the new Super DDI. Adaptive signal timing control can effectively improve traffic as well as pedestrian efficiency [43–45], and it is the trend of signal control in the future. Continuing research will explore a cost–benefit analysis in locations with smaller bridge sizes and more advanced simulation analysis by incorporating connected and autonomous vehicle (CAV) applications. The findings from this study are anticipated to help highway agencies to take necessary actions and decide on management strategies for implementing appropriate alternative interchanges.

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References

1. National Highway Traffic Safety Administration (NHTSA). *Traffic Safety Facts: Pedestrians*; 2020. Available online: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812850 (accessed on 7 June 2022).
2. Brosseau, M.; Zangenehpour, S.; Saunier, N.; Miranda-Moreno, L. The impact of waiting time and other factors on dangerous pedestrian crossings and violations at signalized intersections: A case study in Montreal. *Transp. Res. Part F Traffic Psychol. Behav.* **2013**, *21*, 159–172. [CrossRef]
3. Pulugurtha, S.S.; Sambhara, V.R. Pedestrian crash estimation models for signalized intersections. *Accid. Anal. Prev.* **2011**, *43*, 439–446. [CrossRef]
4. Liu, P.; Lu, J.J.; Chen, H. Safety effects of the separation distances between driveway exits and downstream u-turn locations. *Accid. Anal. Prev.* **2008**, *40*, 760–767. [CrossRef] [PubMed]
5. Hummer, J.E. Unconventional left-turn alternatives for urban and suburban arterials—Part one. *ITE J. (Inst. Transp. Eng.)* **1998**, *68*, 26–29.
6. Holzem, A.M.; Hummer, J.E.; Cunningham, C.M.; O'Brien, S.W.; Schroeder, B.J.; Salamati, K. Pedestrian and bicyclist accommodations and crossings on superstreets. *Transp. Res. Rec.* **2015**, *2486*, 37–44. [CrossRef]
7. Mehrara Molan, A. Evaluation of Milwaukee B and Synchronized As New Service Interchange Designs. Ph.D. Thesis, Wayne State University, Detroit, MI, USA, January 2017. Available online: http://digitalcommons.wayne.edu/oa_dissertations/1845 (accessed on 11 December 2022).
8. Molan, A.M.; Hummer, J.E. Safety analysis of the new synchronized and milwaukee B interchanges in comparison to existing designs. *Accid. Anal. Prev.* **2017**, *109*, 29–35. [CrossRef] [PubMed]
9. Liu, Y.; Luo, Z. A Bi-Level Model for Planning Signalized and Uninterrupted Flow Intersections in an Evacuation Network. *Comp-Aid. Civ. Infrastr. Eng.* **2012**, *27*, 731–747. [CrossRef]
10. Molan, A.M.; Hummer, J.E. Improving Traffic Operations at Service Interchanges using the New Offset Diamond Design. *Transp. Res. Rec.* **2020**, *2674*, 522–536. [CrossRef]
11. Zhao, J.; Liu, Y.; Wang, T. Increasing Signalized Intersection Capacity with Unconventional Use of Special Width Approach Lanes. *Comp.-Aid. Civ. Infrastr. Eng.* **2016**, *31*, 794–810. [CrossRef]
12. Zhao, J.; Liu, Y.; Yang, X. Operation of signalized diamond interchanges with frontage roads using dynamic reversible lane control. *Transp. Res. Part C: Emerg. Technol.* **2015**, *51*, 196–209. [CrossRef]
13. Jagannathan, R.; Bared, J.G. Design and Operational Performance of Crossover Displaced Left-Turn Intersections. *Transp. Res. Rec.* **2004**, *1881*, 1–10. [CrossRef]
14. Suh, W.; Hunter, M.P. Signal design for displaced left-turn intersection using Monte Carlo method. *KSCE J. Civ. Eng.* **2014**, *18*, 1140–1149. [CrossRef]
15. Zhao, J.; Ma, W.; Zhang, H.M.; Yang, X. Increasing the capacity of signalized intersections with dynamic use of exit lanes for left-turn traffic. *Transp. Res. Rec.* **2013**, *2355*, 49–59. [CrossRef]
16. Wu, J.; Liu, P.; Tian, Z.Z.; Xu, C. Operational analysis of the contraflow left-turn lane design at signalized intersections in China. *Transp. Res. Part C: Emerg. Technol.* **2016**, *69*, 228–241. [CrossRef]
17. Zhao, J.; Liu, Y. Safety evaluation of intersections with dynamic use of exit-lanes for left-turn using field data. *Accid. Anal. Prev.* **2017**, *102*, 31–40. [CrossRef] [PubMed]
18. Xuan, Y.; Daganzo, C.F.; Cassidy, M.J. Increasing the capacity of signalized intersections with separate left turn phases. *Transp. Res. Part B: Methodol.* **2011**, *45*, 769–781. [CrossRef]
19. Yan, C.; Jiang, H.; Xie, S. Capacity optimization of an isolated intersection under the phase swap sorting strategy. *Transp. Res. Part B: Methodol.* **2014**, *60*, 85–106. [CrossRef]
20. Mier, F.D.; Romo, B.H. Continuous Flow Intersection. U.S. Patent Number 5,049,000, 1991. Available online: https://patents.google.com/patent/US5049000A/en (accessed on 11 December 2022).
21. ATS/American. Diverging Diamond Interchange. Available online: https://divergingdiamond.com (accessed on 7 September 2020).
22. Vaughan, C.; Cunningham, C.; Schroeder, B.; Hummer, J. Empirical Study and Assessment of Operational Performance of Double Crossover Diamond Interchanges. In Proceedings of the Transportation Research Board 92nd Annual Meeting, Washington, DC, USA, 13–17 January 2013; Available online: https://trid.trb.org/view/1242894 (accessed on 11 December 2022).
23. Bared, J.G.; Edara, P.K.; Jagannathan, R. Design and Operational Performance of Double Crossover Intersection and Diverging Diamond Interchange. *Transp. Res. Rec.* **2005**, *1912*, 31–38. [CrossRef]

24. National Cooperative Highway Research Program (NCHRP). *Guide for Pedestrian and Bicyclist Safety at Alternative and Other Intersections and Interchanges*; National Academies Press: Washington, DC, USA, 2021; Available online: https://www.trb.org/Main/Blurbs/181781.aspx (accessed on 11 December 2022).
25. Molan, A.M.; Hummer, J.E.; Ksaibati, K. Introducing the Super DDI as a Promising Alternative Service Interchange. *Transp. Res. Rec.* **2019**, *2673*, 586–597. [CrossRef]
26. Mehrara Molan, A.; Hummer, J.E.; Ksaibati, K. Modeling safety performance of the new super DDI design in terms of vehicular traffic and pedestrian. *Accid. Anal. Prev.* **2019**, *127*, 198–209. [CrossRef] [PubMed]
27. Mehrara Molan, A.; Ksaibati, K. *Proposing the Super DDI Design to Improve the Performance of Failing Service Interchanges in Mountain-Plains Region*. Project #MPC-573; Mountain-Plains Consortium (MPC). 2018. Available online: https://www.mountain-plains.org/research/details.php?id=471 (accessed on 11 December 2022).
28. Haq, M.T.; Molan, A.M.; Ksaibati, K. Evaluating the Operational Efficiency of Two Versions of Super DDI Design: A Case Study in Denver, Colorado. *Transp. Res. Rec.* **2022**, *2076*, 747–762. [CrossRef]
29. Haq, M.T.; Molan, A.M.; Ksaibati, K. Surrogate safety assessment of super DDI design: A case study in Denver, Colorado. *J. Transp. Saf. Secur.* **2021**. [CrossRef]
30. Haq, M.T.; Molan, A.M.; Ksaibati, K. Proposing the Super DDI Design To Improve the Performance of Failing Service Interchanges in Denver Metro, Colorado. Final Report, MPC-573; Mountain Plains Consortium; 2022. Available online: https://rosap.ntl.bts.gov/view/dot/62820 (accessed on 11 December 2022).
31. Wang, L.; Ye, S.; Tang, M. Simulation research on crossing behavior of the pedestrians and vehicles at the Pedestrian crossing based on simulation software VISSIM. *Proc. Int. Conf. Comp. Net. Commun. Eng.* 2013. Available online: https://www.researchgate.net/publication/266646383_Simulation_research_on_crossing_behavior_of_the_pedestrians_and_vehicles_at_the_Pedestrian_crossing_bsed_on_simulation_software_VISSIM(accessed on 11 December 2022).
32. Haq, M.T.; Farid, A.; Ksaibati, K. Estimating Passing Sight Distances for Overtaking Truck Platoons—Calibration and Validation Using VISSIM. *Int. J. Transp. Sci. Technol.* **2021**, *11*, 255–267. [CrossRef]
33. Molan, A.M.; Hummer, J.E. Simulation modeling of pedestrian performance in the new synchronized and milwaukee B interchanges versus existing designs. *Transp. Res. Rec.* **2018**, *2672*, 151–160. [CrossRef]
34. Haq, M.T.; Zlatkovic, M.; Ksaibati, K. Benefit-cost assessment of truck climbing lanes: A case study of I-80 in Wyoming. *Transp. Lett.* **2022**, *2676*, 747–762. [CrossRef]
35. HCM. Highway Capacity Manual. National Research Council (NRC), U.S. 2010. Available online: https://www.trb.org/Publications/Blurbs/164718.aspx (accessed on 11 December 2022).
36. Schroeder, B.; Cunningham, C.; Ray, B.; Daleiden, A.; Jenior, P.; Knudsen, J. Diverging Diamond Interchange Information Guide. Report FHWA-SA-14-067. 2014. Available online: https://www.trb.org/Main/Blurbs/181562.aspx (accessed on 12 December 2022).
37. Wu, J.; Radwan, E.; Abou-Senna, H. Determination if VISSIM and SSAM could estimate pedestrian-vehicle conflicts at signalized intersections. *J. Transp. Saf. Secur.* **2018**, *10*, 572–585. [CrossRef]
38. Federal Highway Administration (FHWA). Manual on Uniform Traffic Control Device (MUTCD). U.S. Department of Transportation; 2009. Available online: https://mutcd.fhwa.dot.gov/ (accessed on 11 December 2022).
39. Hummer, J.E.; Holzem, A.M.; Rouphail, N.M.; Cunningham, C.M.; O'brien, S.W.; Schroeder, B.J.; Salamati, K.; Foyle, R.S. Pedestrian and Bicycle Accomodations on Superstreets. Final Report, FHWA/NC/2012-13. 2014. Available online: https://rosap.ntl.bts.gov/view/dot/26967 (accessed on 11 December 2022).
40. Wallwork, M. Walking In Real Intersection Design Course. 2004.
41. Fitzpatrick, K.; Schneider IV, W.H.; Park, E.S. Predicting speeds in an urban right-turn lane. *J. Transp. Eng.* **2006**, *132*, 199–204. [CrossRef]
42. Oskarbski, J.; Guminska, L.; Miszewski, M.; Oskarbska, I. Analysis of Signalized Intersections in the Context of Pedestrian Traffic. *Transp. Res. Procedia.* **2016**, *14*, 2138–2147. [CrossRef]
43. Dobrota, N.; Stevanovic, A.; Mitrovic, N. Development of assessment tool and overview of adaptive traffic control deployments in the U.S. *Transp. Res. Rec.* **2020**, *2674*, 464–480. [CrossRef]
44. Dobrota, N.; Stevanovic, A.; Mitrovic, N. Modifying signal retiming procedures and policies by utilizing high-fidelity modeling with medium-resolution traffic data. *Transp. Res. Rec.* **2022**, *2676*, 660–684. [CrossRef]
45. Gavric, S.; Sarazhinsky, D.; Stevanovic, A.; Dobrota, N. Development and Evaluation of Non-Traditional Pedestrian Timing Treatments for Coordinated Signalized Intersections. *Transp. Res. Rec.* **2022**. [CrossRef]