AN EVALUATION OF OPERATIONAL EFFICIENCY BETWEEN SINGLE POINT URBAN INTERCHANGE WITH FRONTAGE ROAD AND TIGHT DIAMOND INTERCHANGE

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ABSTRACT
Signalized interchanges have been playing an important role in roadway system, particularly in urban areas. Among the various interchange configurations, the Single Point Urban Interchange (SPUI) and the Tight Diamond Interchange (TDI) are most commonly used in current practice. Though a number of studies have proved that in general SPUIs outperform TDIs in operational efficiency, however, none of them attempted to compare the operation efficiency of a special SPUI configuration, SPUI with Frontage Road (SPUI-F) with TDI. With this motivation, this paper proposed an evaluation towards SPUI-F and TDI. The research was based on a real case of Reno, Nevada. Layout of both interchanges were modeled in VISSIM. Three MOEs (average delay, average speed and average queue length) were selected to perform the operational efficiency. The results indicated that the TDI is more efficient in comparison to the SPUI-F. Research findings could provide guidelines for the selection of interchange configurations.

BACKGROUND

The Tight Diamond Interchange (TDI) and the Single Point Urban Interchange (SPUI) are two common types of Diamond Interchange (DI) (*1*), which is one of the most popular signalized interchange design configurations. They differed a lot in geometry overview. Normally, the span length of a SPUI bridge ranges from 160ft to 280ft (*2*); while for the TDI, the distance between two signalized intersections is usually between 200ft to 400ft with a bridge span of 140ft to 180ft (*2*). Apart from the geometry differences, the operational strategies for these two interchanges are also different. For SPUI, the dual left turn operation strategy has been widely employed; for TDI, the TTI-four phase strategy (*3, 4, 5, 6*) has been commonly accepted. To date, a number of research have been conducted to compare the operational efficiency between two types of interchanges; most of the existing studies revealed that the SPUI outperforms TDI in term of operational efficiency. In practice, due to the restrictions of local road geometry and land use, some variations of diamond interchange were proposed. One of the variations is the Single Point Urban Interchange with frontage road (SPUI-F). Though some of the research (*7*) indicated that the TDI would performance better than the SPUI-F, there lacks solid evidences to assess the performance of SPUI-F.

Therefore, this paper evaluated the performance of a real SPUI-F in Reno, Nevada (i.e., the I-580/Plumb Ln interchange). It used to be a traditional TDI; in 2003, the Nevada Department of Transportation (NDOT) rebuilt it as a SPUI-F. With the evaluation results, this research aims to provide general guidelines regarding the selection of SPUI-F and TDI. The remainder of this paper is organized as follows: a comprehensive literature review was provided to summarize the previous works towards the operational efficiency and safety evaluation of TDI and SPUI. The methodology part designed the candidate signal timing plans and traffic volume scenarios. Then, VISSIM simulation was employed for performance evaluation. Finally, evaluation results, including the average delay, average speed and average queue length were presented.

CASE STUDY

To evaluate the operational efficiency of both interchanges, a real site was employed by this research as the basis of the evaluation road network. The case study site is the I-580/Plumb Lane interchange which is located in Reno, Nevada.

Originally, this interchange was a TDI operated by two separate signal controllers. Over the years, the traffic volume was totally changed and it was later changed to a SPUI-F with the same lane configuration. However, no concrete evidence indicated that the SPUI-F outperformed the TDI in operation, no comprehensive evaluation indicated the preference of the SPUI-F compared to TDI. The SPUI-F is composed of the two frontage roads and two ramps, which is consistent with a typical SPUI design. However, the lane configuration is different from a typical SPUI. The details of the lane configurations and the road curvature geometry of both interchanges are shown in Figure 1.

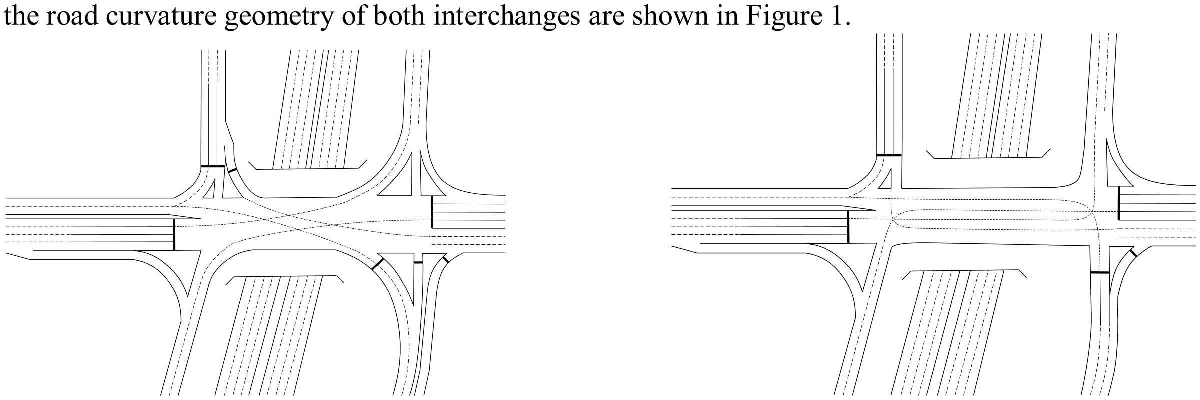

FIGURE 1 Configuration of the Current and Previous I-580/Plumb Ln SPUI Interchange

Currently, the SPUI-F is operated by various cycle lengths ranging from 110 to 170 seconds. Since the actual traffic volume is not evenly distributed. The free mode is currently used. Another issue that needs to be taken into consideration is that the SPUI-F is not available for right turn on red for the southbound frontage road because of the existing two exclusive lanes for right turn vehicles. With this design, the right turn vehicles conflict with westbound through traffic. Besides, there is a frontage road design for the through movement, the SPUI-F could not use three phase operations. An additional phase was required to avoid the conflicts between ramps phases.

ANALYSIS METHODOLOGY

Evaluation Method

To derive reasonable comparison results for the two interchanges, different traffic volume scenarios were designed for the simulation test. In this research, seven scenario groups were developed. Under each scenario group, five cases were designed for sensitivity analysis, including the default volume case and the adjustments of the default volume case with criteria of add 15% volume, add 30% volume, deduct 15% volume and deduct 30% volume. The TDI geometry was designed based on the same outline of the SPUI-F but with different interior geometry. Same lane configurations were applied to both interchanges. During the simulations, the road network and the geometry were kept unchanged.

This research used the PTV VISSIM microscopic simulation software for sensitive analysis. Real-time simulation and output MOEs were easily extracted through this software. Three MOEs were selected to perform the results of the simulation: average delay, average queue length, and average speed. Among them, the average delay was of significant importance since it correlates with level of service and could immediate reflect the operational efficiency. The average speed can support the results from the average delay. The average queue length could also reveal the operational efficiency and confirm the conclusion from the average delay.

Volume Scenarios Design

The designed volume for this evaluation would not only reflect the current conditions but also offer scenarios to emphasize different conditions. Thus, the base volume was designed based on the existing volume. In this research, PM peak hour volume was selected as the default volume for base scenario. Besides the base scenario, six scenario groups were employed in the analysis as follows: heavy left turn movement scenario group, two approaches heavy left turn movement scenario group, heavy through movement scenario group, and two approaches heavy through movement scenario group, heavy ramp scenario group, and two approaches heavy ramp scenario group.

Scenario groups introduction:

- Base Scenario: Derived from the PM peak hour existing volume with some of the numbers round up to the nearest 10 number.
- Scenario 1 (one approach heavy left turn scenario): Designed for evaluation of heavy left turn conditions. For this scenario, the eastbound left turn movement was increased.
- Scenario 2 (two approaches heavy left turn scenario): Based on the previous scenario, the left turn volume of westbound was also changed. It aims to test the both directions.
- Scenario 3 (one approach heavy through scenario): Designed for evaluating one heavy through movement.
- Scenario 4 (two approaches heavy through scenario): The aim of the scenario is similar to the previous one but both opposite approaches were tested.
- Scenario 5 (one approach heavy ramp scenario): Focused on how the ramp volume variations influence the evaluation results.
- Scenario 6 (two approaches heavy ramps scenario): Tested the double side of the ramp volume variations on the evaluation results.

For each scenario group, besides the default volume, the remaining four case volumes were changed by the fixed percentage of the default case. Table 1 illustrated the base scenario group.

TABLE 1 Base Scenario Group

		SBT	SBL	SBR	EBT	EBL	EBR	NBT	NBL	NBR	WBT	WBL	WBR	TOTAL
BASE SCENARIO	-30% Volume	77	28	420	175	560	490	21	336	140	210	196	42	2695
	-15% Volume	94	34	510	213	680	595	25	408	170	255	238	51	3273
	Default Case	110	40	600	250	800	700	30	480	200	300	280	60	3850
	+15% Volume	127	46	690	288	920	805	35	552	230	345	322	69	4429
	+30% Volume	143	52	780	325	1040	910	39	624	260	390	364	78	5005

Signal Operation Setting

Feasible timing plans and reasonable engineering adjustments were also adopted alongside those cases to VISSIM.

Basic timing information, phase splits, and sequences were adjusted for each case. This study did not consider pedestrian constraints for the sake of fully testing the operational efficiency. Parameters like vehicle extension time (passage time), minimum green, yellow, and red clearance were determined separately for two interchanges without further changes when applied to different cases.

In this research, TDI and SPUI-F were also applied to different operational strategies. Three phase operations could not be applied to SPUI-F since the existence of the two frontage roads. Thus, four phase control was needed to split the ramp operations. For TDI, since in this case, there was not enough queue storage in the middle for vehicles, the TTI four-phase was therefore applied to this interchange to ensure a non-stop traffic between the two adjacent intersections.

MODEL CALIBRATION AND VALIDATION

The maximum vehicle queue length was selected for model validation. Multiple simulations were employed in the calibration to minimize the fluctuation of the maximum queue length. In this section, the accuracy of the maximum queue length was evaluated. Ten simulations with different random seeds were taken into consideration. In the calibration process, the one-hour simulation was evenly divided into 12 intervals (5 min intervals). For each simulation run, the maximum queues of four critical movements for each direction and each interval were collected. The four critical movements were eastbound left turn movement (EBL), westbound left turn movement (WBL), southbound right turn movement (SBR), and northbound left turn movement (NBL). The following Figure 2 indicates the calibration results for four movements accordingly.

From the chart, it can be seen that there is still some differences between the field data and the simulation results. However, the difference between the field data and the simulation data was less than three vehicles. The results should be quite similar and consistent with the field observation. For EBL, it could be seen that the difference of the simulation data and the field data are within acceptable range. Since WBL is adjacent to the airport, the volumes by interval may have a sharp increase or decrease because of the departure or arrival times of flights. Thus, the interval 5 has the supreme volume of all the intervals. From the figure it could be seen that the field data and the simulation results mapped very well. As for the SBR, the difference between the simulation data and the field data is even less than the EBL, which means the simulation data can well depict the movement volume and its changes. For NBL, it could be seen that the simulation results and field results spiral coherently. That indicates the calibration is successfully.

The calibration process provided the firm relationship between the real world and the VISSIM model. The model can therefore produce reliable results as depicted in the field. There are still other problems like the lane change behavior being inconsistent with the real world. Also, the calibration just exhibited four critical movements from each direction, however, the other factors did not significantly influence the average delay and other MOEs.

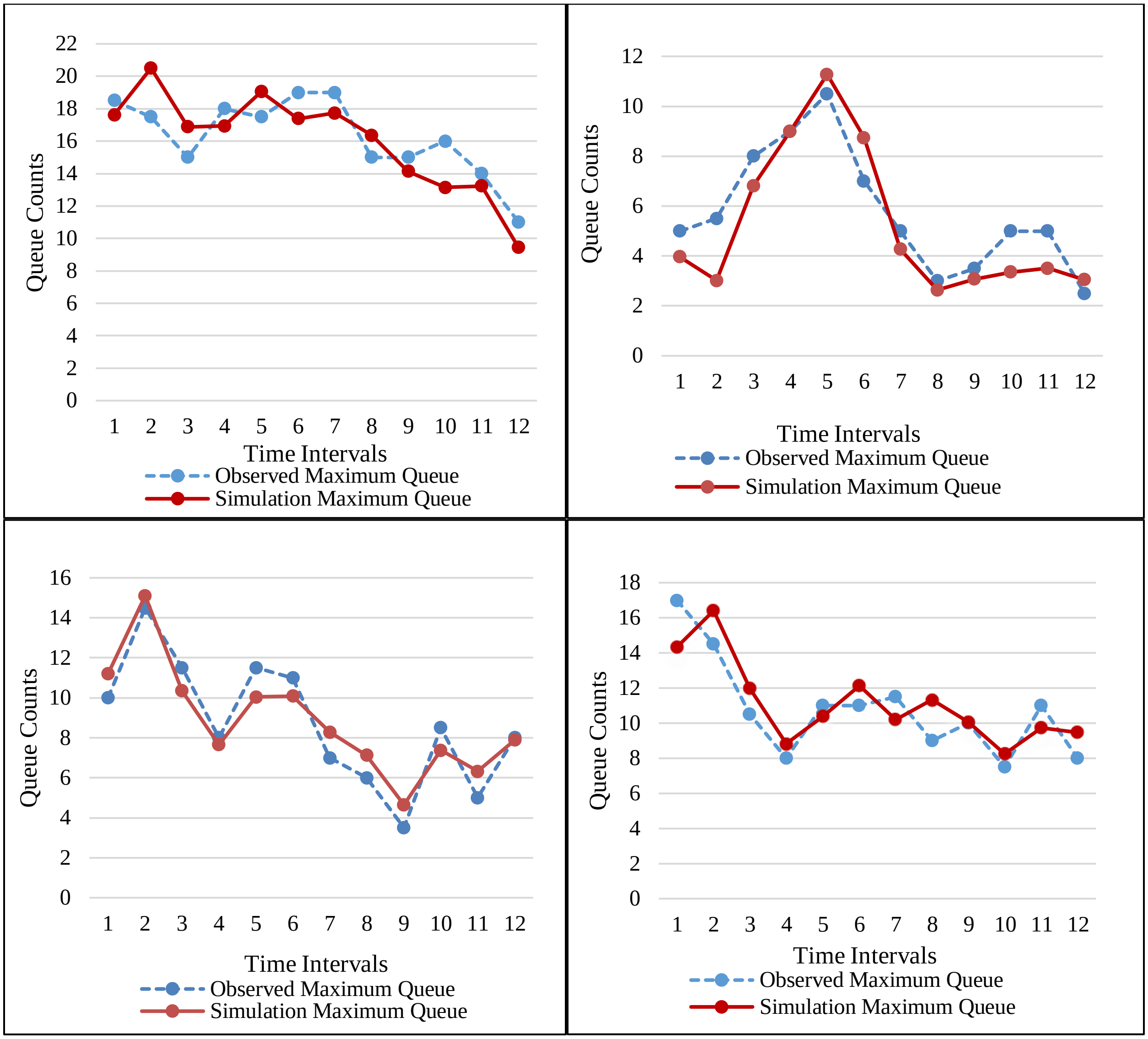

FIGURE 3 Calibration of VISSIM model (EBL, WBL, SBL and NBL accordingly)

EVALUATION RESULTS AND ANALYSIS

The evaluation results for the 35 cases for each interchange will be collected and performed in the following figures. Ten simulation runs were conducted by VISSIM with different random seeds for each case. Three MOEs were selected to perform the operational efficiency of both interchanges, they are average delay, average speed and average queue length. The results for the MOEs were performed accordingly.

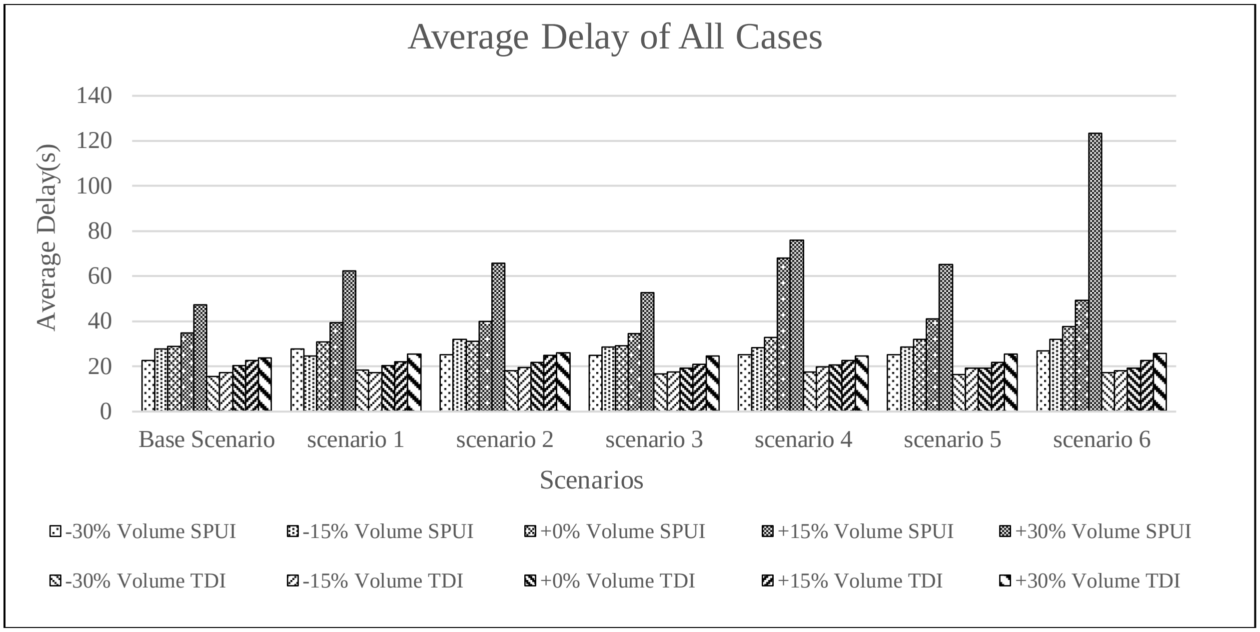

FIGURE 4 Comparison of Average Delay under various volume scenarios.

Figure 4 summarizes the average delays for all cases. Average delay kept significantly increasing as the volume level increased for both interchanges. Nevertheless, delay of SPUI-F seemed to have a dramatic growth trend, especially in the cases of +15 and +30 scenarios. In contrast, a stable increase trend was found regarding the delay of TDI. Moreover, the delay of SPUI-F at -30% volume level was even larger than TDI delay at +30% volume level, which implies that TDI is superior to SPUI-F. Therefore, TDI outperformed SPUI-F in view of average delay, which also supported the previous studies concerning the operational difference between SPUI-F and TDI.

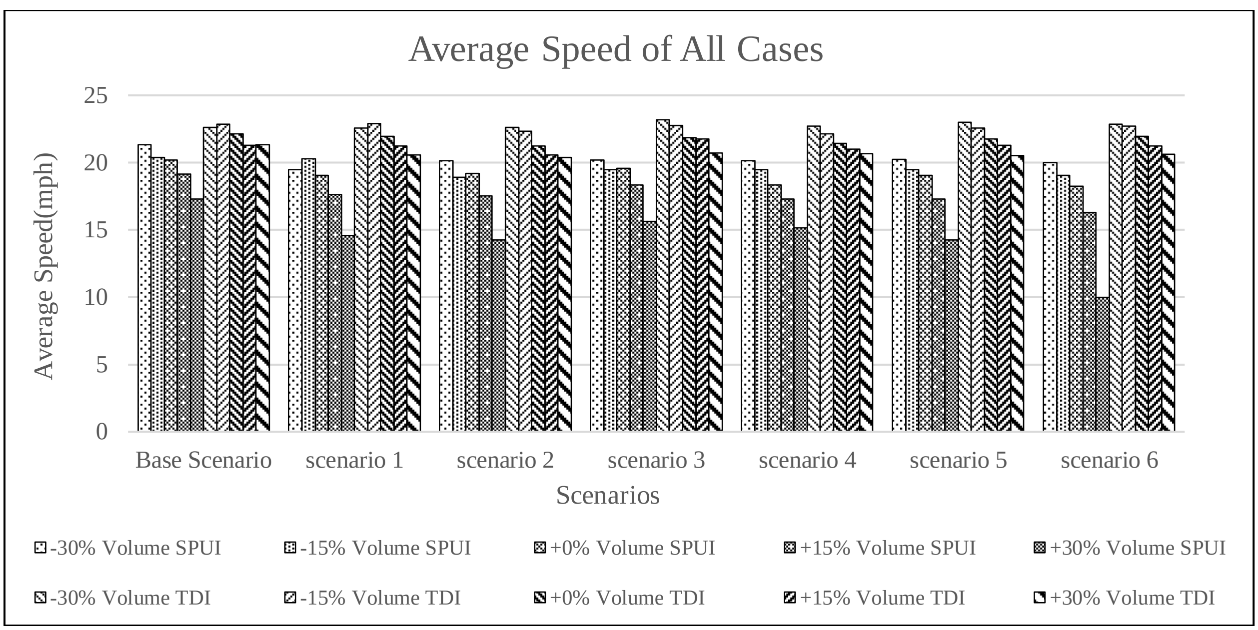

FIGURE 5 Comparison of Average Speed under various volume scenarios.

Figure 5 illustrates the average speed performance for all cases. With the previous results from average delay, it was not surprised that the average speed of TDI generally performed better than SPUI-F. For reliability, the range of SPUI-F was almost twice larger than TDI in any scenario, which proved that TDI was more reliable. Therefore, the results from average speed reinforced the results from average delay and consistently demonstrated the performance of TDI was obviously better than SPUI-F.

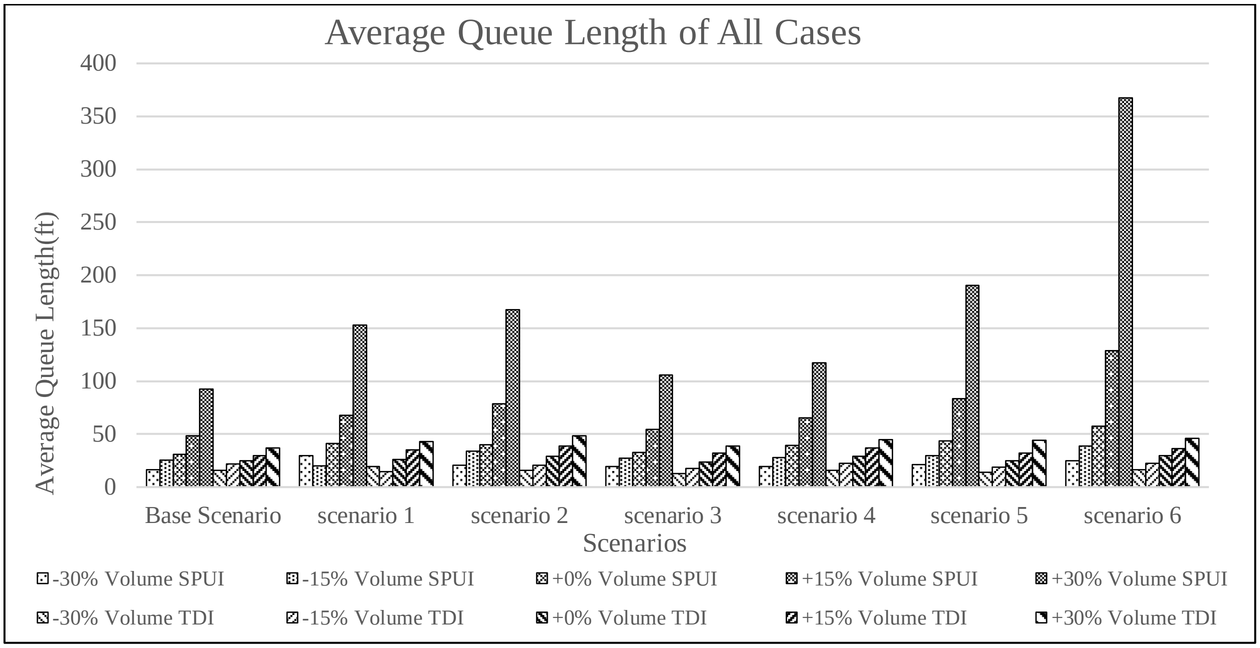

FIGURE 6 Comparison of Average Queue Length under various volume scenarios

Figure 6 demonstrates the average queue lengths for all cases. A consistent trend was found for the average delay and speed results. The general trend indicated that SPUI-F was eager to block more vehicles once the volume increased. For low traffic volume conditions, the difference in average queue length for SPUI-F and TDI was not obvious. However, the situation started to turn down at moderate volume levels and heavy volume levels. Hence, TDI still performed better than SPUI-F in term of average queue length.

SUMMARY

Previous research mainly focused on the evaluation of the operational efficiency between the SPUI and TDI, while there lacks a study for the SPUI-F. In this research, the operational efficiency of SPUI-F was evaluated and filled this gap. Also with the motivation offered by the NDOT project, a specific case was employed by this research and the results could provide guidelines for the general selection of interchange configurations.

For guaranteeing the reasonable results, the calibration process was conducted and the outcomes indicated the strong relationship with the field data. The methodology aims to present multiple scenarios and sensitivity analysis by volume, in total 35 cases were tested. In simulation, different combinations of signal timing parameters were tested to find the one with the most efficient MOEs. The results and analysis discussed the outcomes from the evaluation simulation. Average delay, average speed and average queue length were selected to present the operational efficiency. Their outcomes and preference work are in concert with each other and further enhanced the convincible of results, that is, the TDI outperformed the SPUI-F in both the operational efficiency and in reliability.

Future works can be focused on the trip generation from a specific site influence towards the SPUI-F and TDI. Hardware in the loop simulation may participate in the research to make the research more realistic. On the other hand, the signal coordination of the Plumb Lane could be enhanced after this research; new signal coordination plans could be developed and implemented.

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