Analysis of Unconventional Design for Signalized and Closely-Spaced T-Intersections

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Abstract

In order to increase the capacity and mitigate the traffic congestion at signalized and closely spaced T-intersections, an unconventional closely-spaced T-intersections design (UCTD) was proposed. Through setting back the main T-intersection's left-turn conflict point to the adjacent T-intersection, there is no need to change the road's land use or set additional pre-signals for the crossover segment. A two-phase scheme can be used in the main T-intersection for better performance of the heavy traffic flow. Micro simulation was developed to evaluate the UCTD's performance. In one scenario, the UCTD resulted in a reduction of average delays by 64%, stops by 46%, average stop time by 72%, average queue length by 50%, maximum queue length by 55%, and fuel consumption and related emissions by 14% compared to conventional T-intersections. Also, results found that the UCTD is suitable when the main T-intersection's traffic volume is much larger than that of the second one.

Keywords: Unconventional T-intersection design; Micro-simulation; Traffic organization; Traffic control.

INTRODUCTION

In recent decades, unconventional arterial intersection designs (UAIDs), which mitigate traffic congestion at at-grade signalized intersections, have become a hot research topic (El Esawey and Sayed 2013). Numerous studies have investigated the design of unconventional intersections and analyzed the operational and the safety performances of UAIDs. Several studies found that UAIDs had benefits of higher capacity, lower delays, and fewer crashes; meanwhile, some UAIDs with minor geometric modification requirements were also cost-effective. However, most UAIDs required a great deal of land to meet the right of way, which made them unfeasible in urban areas where land use was usually limited (El Esawey 2007). Furthermore, few studies considered impacts of pedestrian movement on the performance of traffic flow and environmental impacts of constructing unconventional intersections (El Esawey and Sayed 2013). If city planners and traffic engineers are considering deploying an unconventional intersection, constraints such as land use, budget, environmental impacts, and management difficulty can significantly affect the selection results of these designs.

In some UAIDs, such as USC and XDL (Tabernero and Sayed 2006; Abou-Senna and Radwan 2016), the configuration modifications create four secondary intersections (or crossovers). Previous studies suggested that the distance from the secondary intersection to the main intersection should represent a trade-off between potential spillback from the main intersection and longer delays of the re-routed movements (El Esawey and Sayed 2007; Reid and Hummer 2001; Zhao et al. 2015). The secondary intersections need to be signalized and coordinated with the primary intersection and the added pre-signal, which could also cause more stops (Ma et al. 2013). In addition, acceleration or deceleration as well as the idling process would cause more emissions (Pandian et al. 2009). Therefore, emission reductions caused by travel times and delay savings might be traded with higher emissions during acceleration or deceleration and the idling process (El Esawey and Sayed 2013). What's more, the performance analysis was usually limited to an isolate intersection, hence, the influence of the UAIDs on the closely-spaced intersections deserves further study. Furthermore, most of these UAIDs intersections were isolated four-leg intersections, and there have been limited studies on T-intersection designs.

Considering all these research deficiencies, this paper proposed a novel unconventional closely-spaced T-intersection design (UCTD) by using the crossover segment to set back the main intersection's left-turn conflict point into the closely-spaced second T-intersection (Li 2018). This UCTD is similar to the displaced left-turn (DLT), but different in that there is a secondary upstream intersection where the DLT occurs.. The remaining parts of this paper are organized as follows. Section 2 gives the detailed information of the UCTD. Section 3 introduces the case study, including simulation setting, field data collection, and the UCTD and corresponding signal schemes. Section 4 presents the results and discussion, and corresponding traffic performance analysis based on the micro-simulation method was processed. Concluding remarks are given in Section 5.

METHODOLOGY

As shown in Figures 1 and 2, the moving back of the conflict point in the main intersection can eliminate the arterial left-turn conflicts with the sub-arterial left-turn traffic; by this way, we can release the left-turn traffic of the arterial road and sub-arterial road in the main T-intersection simultaneously. This paper used VISSIM, which was widely used in UAIDs studies (El Esawey and Sayed 2013), to evaluate the intersection's traffic performance considering pedestrians' movement signals and two intersections' signal coordination. The UCTD possesses the following merits:

1) This design sets back the conflict point in the main T-intersection, which improved the security of the main T-intersection. Meanwhile, the crossover segment was set in the closely-spaced second intersection and controlled by the second intersection's signal. Therefore, there is no need to set an additional pre-signal for the crossing segment, and the number of stops and emissions can be reduced.

2) By utilizing a two-phase signal timing scheme in the main T-intersection and coordinating two T-intersection's signal schemes, the UCTD can significantly reduce delays and increase the intersection's capacity.

3) This design had minor geometric modification and little change in footprint, which made it cost effective. This design also maintained the number of the lanes and the area of land use. Furthermore, we used field traffic data for simulation. All these indisputably increase the credibility of the comparative performance simulation analysis.

4) This paper considers the impact of setting the pedestrian phase on the traffic flow, and the design's influence on the closely-spaced second T- intersection.

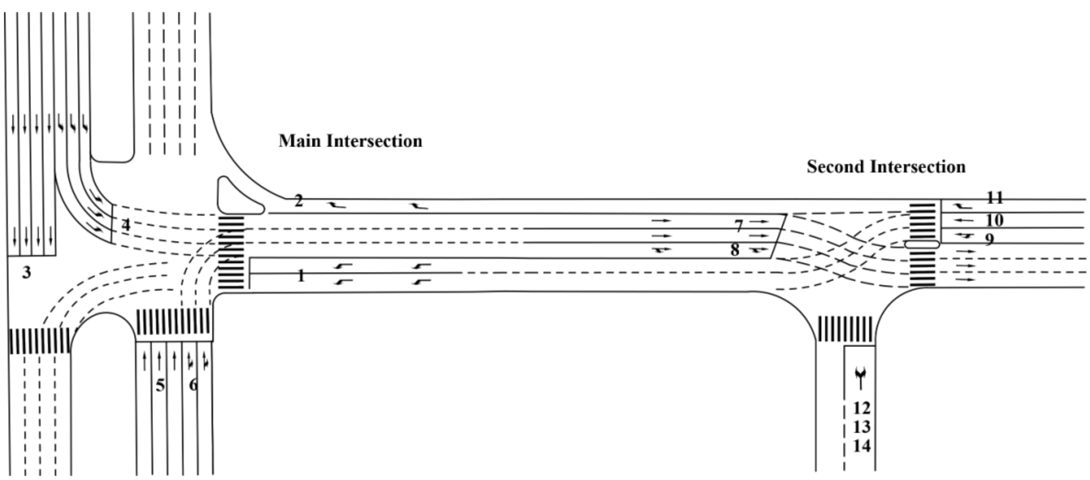
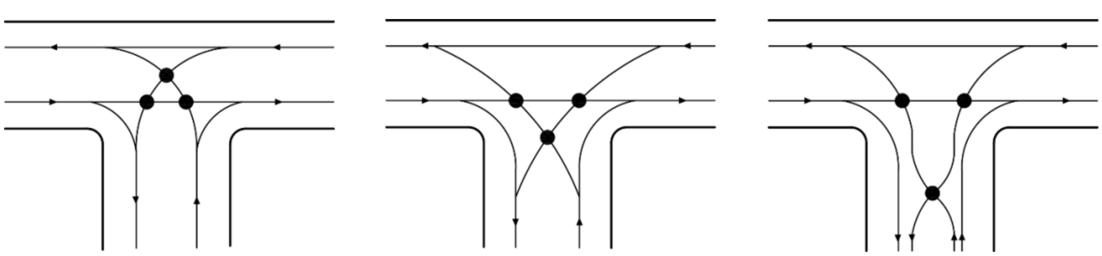


Figure 1. Illustration of the UCTD



(a) (b) (c)

Figure 2. Moving rearward conflict point in T-intersection

This paper determined the cycle length based on the Webster method and trial-and-error method based on the field data (Araghi et al. 2015). After the cycle length based on the Equation 1 was determined, we calculated the signal splits based on the ratio of critical lane volumes and the requirement of minimum green time according to Equation 2.

$$C = \frac{L}{1-Y} = \frac{\sum_k (L_s + AR)_k}{1 - \sum_k \max(\frac{q_{ki}}{Q_i})} \tag{1}$$

Where C is the cycle length, s. L is the total lost time, s. Y is the sum of the max flow ratio. L_s is start loss time, s. AR is all-red intervals' time, s. q_{ki} is the traffic volume of in let$i$ in the phase k, pcu/h. Q_i is the design saturated flow of the inlet i, pcu/h.

$$g_k = \begin{cases} \frac{q_k}{\sum_k q_k}(C-L) & if\, q_k (C-L)/\sum_k q_k > g_{mk} \\ g_{mk} & if\ q_k (C-L)/\sum_k q_k < g_{mk} \end{cases} \tag{2}$$

Where g_k is the effective green time in the phase k, s. g_{mk} is the minimum green time for phase k, s, when considering the pedestrian phase, the minimum green time is the pedestrian passing time; otherwise, it would be the minimum passing time for vehicles.

CASE STUDY

Simulation Framework

This paper used VISSIM to conduct the micro-simulation of the UCTD during the morning peak and evening peak. The results also evaluated the intersection's traffic performance considering pedestrians' movement signal and two intersections' signal coordination. The principles of the simulation are as follows:

1) Factors such as number of lanes per approach, lane width, number and length of storage bays, etc., are kept unchanged. Meanwhile, right of way availability is regarded as one constraint that controls potential construction (El Esawey and Sayed 2007).

2) The simulation time is 1 hour for both the morning and evening peak.

3) The traffic origin and destination, as well as traffic volume and composition, were collected from the field measurements and remained unchanged during the stimulation.

As the traffic volume in the main intersection was large, this paper introduced two signal schemes for the main intersection: one set the pedestrian phase, and the other was without pedestrian phase but added footbridges instead. In order to investigate the influence of the pedestrian phase on the traffic performance on two intersections, we considered three scenarios in this study:

Scenario 1: original traffic control scheme.

Scenario 2: UCTD traffic control scheme considering the pedestrian phase.

Scenario 3: UCTD traffic control scheme without the main intersection's pedestrian phase (setting overpass in the main intersection).

Field Data Description

The T-intersections introduced in this study are located in the urban area of Shenzheng, China, with a speed limit of 80 km/h. The main T-intersection is composed of the arterial Shennan Avenue and sub-arterial Xiangmei road. The second T-intersection is composed of the Xiangmei Road and Xinwen Road. The details of the road alignment layout are shown in Figure 3. We took videos to collect the field traffic data during the morning peak (8:00 – 9:00) and evening peak (17:00 – 18:00) at two T-intersections from Tuesday (Apr 5, 2018) to Thursday (Apr 7, 2018). The vehicles were divided into three categories (small, medium-sized and large) and then summarized into passenger car units. The traffic flow at each entrance of the T-intersection was counted individually. The peak hour traffic volume of the T-intersection is shown in Table 1.

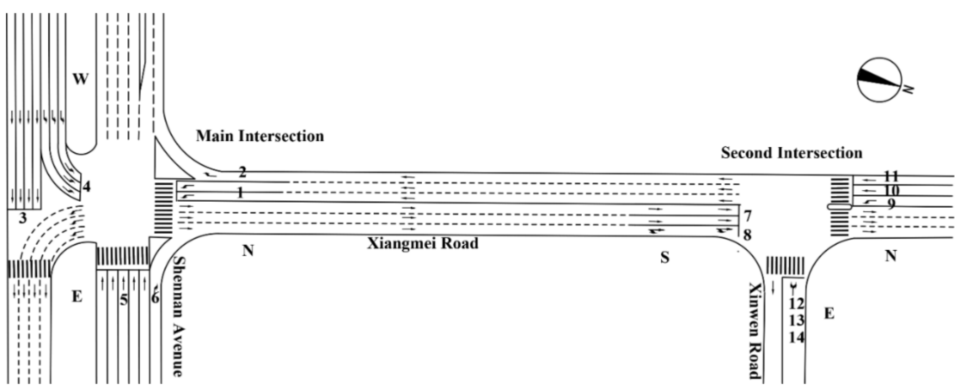


Figure 3. Road alignment layout of the original intersections

Table 1. The Peak Hour Traffic Volume of T-Intersections

	Main	North inlet		West inlet			East inlet		
	Intersection	L-1	R-2	S-3	L-4		S-5	R-6	
Morning peak	Traffic (pcu/h)	741	526	4121	1454		2637	513	
	Second	South inlet		North inlet			East inlet		
	Intersection	S-7	R-8	L-9	S-10	R-11	L-12	L-13	R-14
	Traffic (pcu/h)	1774	193	61	631	431	95	110	54

	Main	North inlet		West inlet			East inlet		
	Intersection	L-1	R-2	S-3	L-4		S-5	R-6	
Evening peak	Traffic (pcu/h)	493	710	2304	1009		4069	703	
	Second	South inlet		North inlet			East inlet		
	Intersection	S-7	R-8	L-9	S-10	R-11	L-12	L-13	R-14
	Traffic (pcu/h)	1540	172	54	352	598	112	87	60

* L: Left; R: Right; S: Straight.

There are two current signal time schemes for the morning peak and evening peak. As shown in the Figure 4, the signal cycle is 200 s and the yellow time is always 3 s. For the main intersection, there are three main signal phases: 1, 3, and 4. As there is no conflict traffic with the main T-intersection's W-E traffic flow, the length of signal group 2 was decided by the cycle length and the pedestrian signal. For the second intersection's signal phase, the cycle length is 74 s and there are three main signal phases: 1, 2, and 3.

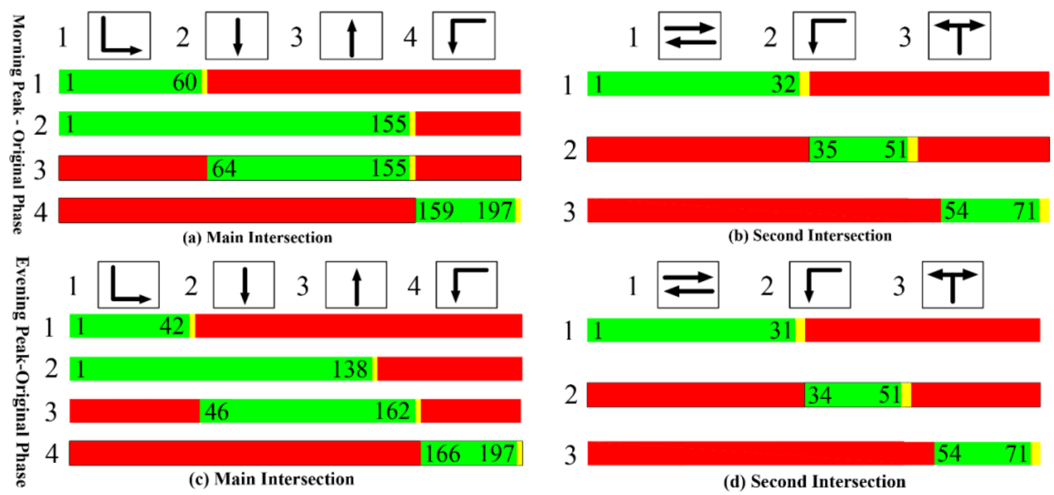


Figure 4. Intersection's original signal phase during morning and evening peak

Shennan Avenue is a 25.6 km arterial road. The main intersection suffered extra-large unbalanced commuting traffic flow during the morning and evening peak. After a long period of traffic investigation, it was found that there were serious traffic congestions in the main intersection during the peak hour. During the morning peak, the traffic volumes from East to West and East to North were too high to be accommodated by the East inlet of the Shennan Avenue. During the evening peak, the traffic volumes from West to East were too high to be accommodated by the West inlet of Shennan Avenue. The left turn vehicles of the Shennan Avenue sometimes need to wait two signal cycles to pass through the intersection. Meanwhile, for the second T-intersection, the traffic volume in the South inlet of the Xiangmei Road was relatively high and caused a long queue in the approach. There are three main reasons for these problems:

1) For the main T-intersection, the traffic in the Shennan Avenue was unbalanced and too high during different peak hour. The left-turn vehicles in approach 4 of Shennan venue and left-turn vehicles in approach 1 of the Xiangmei Road cannot be released at the same time. This increased the signal phase and cycle length, and thus increased queue length and delays.

2) The signal timing schemes cannot well accommodate the traffic volume, and the conflict points in the main T-intersection are relatively close. All of these would cause a serious reduction in the speed, the continuity of the vehicles, and the capacity of the intersection.

3) The main intersection's cycle length is 200 s, which is too long for drivers and pedestrians to wait. As the long queueing time in the intersection, some drivers would try to cross the intersection when the light was yellow, and this might result in more collision.

Illustration of UCTD and Signal Timing Scheme

The characteristic of this UCTD was to set back one conflict point, which is caused by the conflict of the left-turn traffic from the West inlet and North inlet of the main T-intersection, to the closely-spaced T-intersection. This way, there was no need to set pre-signals for the crossover segment as the conflict of the crossover segment could be controlled by the signals in the adjacent T-intersection. Meanwhile, the main intersection could adopt the two-phase scheme as the left-turn traffic from the West inlet and North inlet can be released at the same time. What's more, with the approach of coordinated control (Diakaki et al. 2003), the traffic flow could move continuously and smoothly though the adjacent T-intersections.

In this part, we set a two-phase signal timing scheme for the main intersection and kept the three-phase signal scheme for the second T-intersection. Considering the requirement of setting the pedestrian phase, coordinating two intersections signal phase, and making the contrast results more reliable, we set the same cycle length 74 s for two intersections. In this case, we could have better knowledge of the impact of the main intersection on the second intersection as the second intersection's cycle remained unchanged. Figure 5 shows the intersections' signal schemes during different peak hours for Scenario 2 and 3. The main difference of the two scenarios' signal schemes is whether the main intersection considers the pedestrian phase (denoted as P). For coordinated control of two intersections, we set a phase difference to make the signal group 4 in the second intersection to turn green when the left-turn flow in the main intersection reached the second intersection.

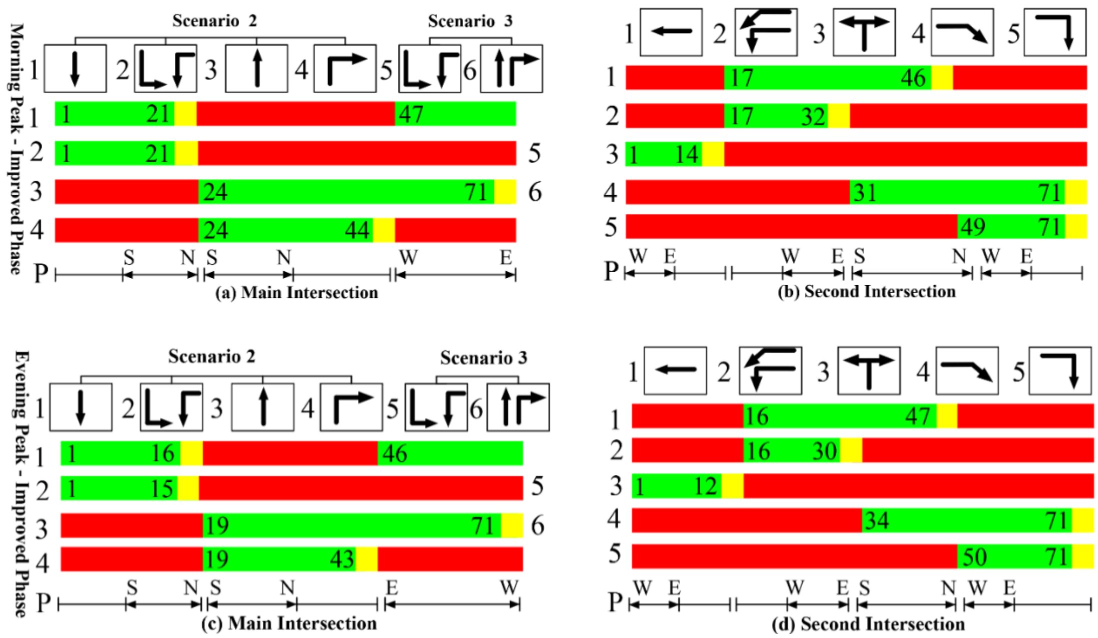


Figure 5. Intersection's improved signal phase during morning and evening peak

RESULTS AND DISCUSSION

Average delays, number of the stops, average length of the queue, maximum length of queue, fuel consumption, CO and NOx emissions were used as the indicators to evaluate the UCTD's performance. The simulation results are shown in Table 2 (at end of paper). All performance measures declined in Scenario 2 and 3, and the overall performance of the UCTD was approximately the same during the morning peak and evening peak. Therefore, these indicated that the UCTD had a better performance than the conventional T-intersections when facing the grossly unbalanced traffic flow during AM and PM peak hours. According to Scenario 3, the UCTD can reduce 64% of the average delays, 46% of the stops, 72% of the average stop time, 50% of the average queue length, 55% of the maximum queue length, and 14% of the fuel consumption. As emissions were calculated by the fuel consumption, the CO and NOx would show a decline in results proportional to those of fuel consumption.

When neglecting the requirement of pedestrian phases in the main intersection (i.e. Scenario 3), the main intersection had a better performance than it did in Scenario 2. It was showed that the main T-intersection can reduce delays by 35%, stop time by 31% and queue length by 33% than the results in the Scenario 2. However, the second T-intersection worked worse than the results in Scenario 2. The results showed that it increased delays by 6% in the morning peak and by 27% in the evening peak, stop time by 2% in the morning peak and 19% in the evening peak, and queue length by 23% in the morning peak and by 13% in the evening peak than the results in Scenario 2. According to the detailed simulation reports, the results were mainly caused by the huge traffic flow in the South inlet of the second T-intersection, which exceeded the capacity of the South inlet. This phenomenon showed that the main intersection would have a bad influence on the traffic performance of the second T-intersection even though the performance of the main T-intersection was still improved. This indicated that there might be an optimal phase scheme when the total performance of the two T-intersections reach the maximum value. At that point, the increasing rate of the main intersection's performance might equal the decreasing rate of second intersection. What's more, the conflict points in the second T-intersection were increased though the traffic volume in the sub-arterial of the second intersection only to a small degree. Raised medians and other appropriate traffic control devices are needed for guiding the traffic direction in the second intersection.

The results also indicated that the UCTD shows considerable potential for situations where the following conditions exists:

1) The UCTD is suited for a main T-intersection with a closely-spaced secondary T-intersection.

2) The traffic volume in the main intersection is too high to be accommodated by a conventional T-intersection, especially for the T-intersection with unbalance arterial traffic volume. Meanwhile, the traffic volume is relatively small in the second T-intersection.

3) The left-turn volume in the main intersection is large, and the conflict points in the main T-intersection are relatively close.

CONCLUSION

This paper proposed an unconventional design to improve the traffic performance at closely-spaced T-intersections. In order to set back the left-turn traffic's conflict point in the main T-intersection, which could make the traffic movements smoother and safer, the crossover segment was set in the second T-intersection and controlled by the second intersection signal. By this way, we could set two-phase scheme in the main T-intersection and there is no need to set additional pre-signals which usually result in more stops and delays. What's more, we coordinated two closely-spaced T-intersections' signal schemes for better performance of traffic movement. The case study was conducted using a micro-simulation with three scenarios: original condition, UCTD considering the pedestrian phase and without the pedestrian phase. Simulation results showed that the UCTD had a better traffic performance than the conventional T-intersections. We also found that removing the main T-intersection's pedestrian phase, which could highly promote the main T-intersection's traffic performance, would have a negative impact on the traffic performance of the second intersection. This indicated that there might be an optimal phase scheme for the optimal total performance of the two T-intersections, and it is highly likely that this would occur when the increasing rate of the main intersection's performance equals the decreasing rate of the second intersection.

It can be concluded that the UCTD provided a novel traffic organization design for the closely-spaced T-intersections with relatively close left-turn conflict points and huge traffic volume. It is especially suitable for the T-intersection reconstruction in urban areas as the UCTD maintains the number of the lanes and the area of land use. Future study could focus on the safety analysis based on human behavior studies as the field implementations of UCTDs took place, and the methodology to obtain the optimal phase scheme for the optimal total performance of the two T-intersections.

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TABLE 2. The Simulation Results of Three Scenarios

	Scenario		Delays (s)		Stop number		Stop time (s)		queue (m)		Max queue (m)		Fuel (gal)		CO (g)	NOx (g)
Morning peak	1	Main	29.5		0.47		22.7		27.3		185.5		264.74		18505.9	3600.6
	1	Second	29.1		0.83		14.8		17.1		274.1		86.48		6044.9	1176.1
	1	Total	29.4		0.56		20.7		22.2		274.1		351.22		24550.8	4776.7
	2	Main	13.0	56	0.42	11	6.4	72	11.7	57	89.9	52	231.82	12	16203.7	3152.6
	2	Second	15.6	46	0.42	49	9.8	34	12.8	25	99.4	64	78.42	9	5482.0	1066.6
	2	Total	13.6	54	0.42	25	7.3	65	12.3	45	99.4	64	310.24	12	21685.6	4219.2
	3	Main	8.4	72(35)	0.27	43(36)	4.6	80(28)	8.1	70(31)	79.9	57(11)	223.88	15(3)	15649.5	3044.8
	3	Second	16.6	43(-6)	0.44	47(-5)	10.0	32(-2)	13.2	23(-3)	99.4	64(0)	79.12	9(-1)	5530.2	1076.0
	3	Total	10.5	64(23)	0.32	43(24)	6.0	71(18)	11.2	50(9)	99.4	64(0)	303.00	14(2)	21179.7	4120.8
	Scenario			%		%		%		%		%		%		
Evening peak	1	Main	27.9		0.48		21.1		23.3		226.1		245.16		17137.1	3334.3
	1	Second	29.9		0.83		17.6		21.2		183.7		77.62		5425.9	1055.7
	1	Total	28.4		0.56		20.3		22.3		226.1		322.78		22563.0	4389.9
	2	Main	11.1	60	0.37	23	6.0	72	9.6	59	73.3	68	214.16	13	14970.1	2912.6
	2	Second	14.0	53	0.38	54	9.0	49	12.7	40	121.0	34	68.30	12	4773.8	928.8
	2	Total	11.8	58	0.37	34	6.7	67	11.5	48	121.0	46	282.46	12	19744.0	3841.5
	3	Main	7.6	73(32)	0.25	48(32)	3.9	82(35)	6.2	73(35)	66.0	71(10)	207.84	15(3)	14527.6	2826.5
	3	Second	17.8	40(-27)	0.49	41(-29)	10.7	39(-19)	14.3	33(-13)	121.0	34(0)	70.70	9(-4)	4941.6	961.5
	3	Total	10.1	64(14)	0.30	46(19)	5.6	72(16)	11.1	50(3)	121.0	46(0)	278.52	14(1)	19469.2	3788.0

*The second column number is the decline percentage compared to the results in Scenario 1, the number in the bracket is the decline percentage compared to the Scenario 2