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RESEARCH ARTICLE

Traffic Engineering

Increasing the effectiveness of T-junctions with an innovative geometrical and phasing arrangement

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Abstract: Improper usage of control mechanisms at intersections would lead to significant delays resulting in road user frustration. The traditional methods of traffic islands or traffic signals are no longer effective due to the high traffic movements at intersections, heterogeneity of such traffic, and uneven pedestrian movements. To minimize unnecessary delays and improve multi-user satisfaction, there is a need to use advanced traffic management systems which come at an increased cost. This research aims to develop an innovative yet cost-effective arrangement to use the existing traffic signals (modified) with a geometric alteration to reduce delays at T-junctions while catering to the high pedestrian demands effectively. The arrangement proposed in this study is twofold. First, the right turns from the minor road is forced to turn left and subsequently, a U-turn is arranged. Secondly, a signal phasing arrangement to manage the revised turning movements effectively and efficiently is introduced. The proposed arrangement was first designed using theoretical means identifying the proper scenarios, and later it was verified using an existing T-junction (case study) with real traffic and geometric data. For verification, VISSIM traffic simulation software was used after proper calibration to simulate local traffic conditions. Sensitivity analysis was also carried out to test for other possible scenarios. The results of the case study confirm that the proposed design for T-junction can reduce the delays at intersections by around 20 %, increasing the efficiency of the intersection.

Keywords: Delay reduction, junction capacity improvement, innovative signal phasing, traffic management, traffic signal design, VISSIM.

INTRODUCTION

Traffic congestion has been a widespread issue in a majority of urban centres at present. Lack of proper management and control of intersections have resulted in various problems creating unnecessary delays and wasting valuable time of road users (Liu & Chang, 2011). Among those, T-junctions of major-minor road intersections at town centres are prone to much delays due to improper usage of traffic control (Yu *et al*., 2012). The traditional geometric design, signal phasing, and green times given at some signalized intersections need revision to increase the efficiency of the intersection. At present most of the T-Junctions in Sri Lanka are uncontrolled or operated with traffic signals with three or more signal phases. Sometimes, manual control is imposed by the police for controlling the traffic signals during peak hours. One of the main reasons for such deficiencies is that the existing design and phasing arrangement does not possess the optimum condition (Liu & Chang, 2011). Not having regular updates for signal timing is another reason. Besides the optimization of signal design at such intersections, capacity increases at an intersection by means of adding extra lanes [(for the critical lane(s), mostly the right turns)] found to be a very common strategy in the urban environment (El Esawey & Sayed, 2013). However, the issue broadens due to the limited space availability when it comes to widening of

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intersections at town centres, where space is restricted for road widening.

One of the main challenges faced by traffic engineers when controlling the traffic at T-junctions is the right turns to and from the main road, which creates additional delays to other movements and pedestrian flows (Zhang & Zhang, 1988). To accommodate right turns to and from the major road, two separate signal phases (or time intervals in manual control) should be provided. This restricts the through movement on the main road in the opposing direction to the right turn. In addition, the through movement on the main road needs to be restricted to accommodate pedestrians to cross the main road. These effectively increase the cycle time and hence result in an increase in delays. Restricting right turns may not be a viable solution due to the fact that major disturbance to the public transport those who are making right turns, extra distance imposed on heavy vehicles (this create many other secondary problems) and of course affecting the user desire.

Therefore, this research aims to provide an innovative geometric design and supportive signal phasing arrangement to increase the efficiency of the T-junctions. In order to understand the existing knowledge on innovative intersection designs, especially with signals and phasing layouts, relevant past studies and various secondary data sources are referred to and briefly explained below.

Traffic congestion has been identified as a major issue in most countries (Li *et al*., 2011), which cannot be eliminated but can be managed through proper implementation of traffic control measures. As a result, various methodologies have been developed and implemented in the past, considering both geometric design (capacity increase) as well as signal design. One of the older methods developed was to use semi-graphical methods to optimize green splits in isolated intersections (Gazis, 1964; Muller, 1970). Increasing the throughput in every approach (Yu *et al*., 2012) has been the centre of attraction by introducing intersection treatments like lane additions, restrictions of turning movements and grade separations (Yu *et al*., 2012). These traditional treatments may increase the capacity of the intersection and relieve the traffic congestion but at a high cost. The traffic at downstream intersections may get deteriorated due to the increase of upstream arrivals (Yu *et al*., 2012). The situation can get worsened with the extended queues at downstream intersections, negatively affecting the upstream intersections also, despite the treatments at upstream intersections (Yu *et al*., 2012). The above phenomena are frequently observed in urban areas of almost all the countries, irrespective of whether they are developed or developing countries, and the situation can get worsened with high traffic volumes, longer cycle lengths and close proximity of intersections (Yu *et al*., 2012).

In order to solve the congestion issues at intersections, various techniques are proposed, including the conventional and unconventional arterial intersection designs (El Esawey & Sayed, 2013). The literature identifies basic conventional intersection designs and different types of unconventional intersection designs.

Conventional intersection designs can partially or fully prohibit the right turns, especially from minor roads. El Esawey and Sayed (2013) mentioned that the prohibited right could be replaced by a left turn followed by a median "U" Turn. However, the conventional designs alone would require sufficient space at the intersections. Most of the conventional designs have failed at high congestion levels when the geometric designs are not compatible with the traffic signal phasing and timings (Yang *et al*., 2012). Therefore, providing geometrical differences only can create additional conflicting scenarios at the junctions as well as at the median "U" Turn openings.

In order to reduce the conflicting movements at the intersections, unconventional intersection designs are proposed (Olarte & Kaisar, 2011). Unconventional intersection designs can also be of various types, but the most common ones would be right turn displaced or bypassed lanes and diverging lanes (Olarte & Kaisar, 2011). The main highlight of the unconventional intersection designs is that the minor road traffic volumes are not allowed to cross the intersections (through movements and right turns) (El Esawey & Sayed, 2013). Only the major road through movements are allowed (but right turns for major roads are also prohibited) (El Esawey & Sayed, 2013).

Most unconventional geometrical arrangements would be beneficial when a majority of the light vehicles are present (Hanowski *et al*., 2007). However, when heavy vehicles, buses and commercial vehicles are a considerable component in the traffic mix, the unconventional intersection designs require additional space at the intersection to cater for the higher turning radius of these types of vehicles (Hanowski *et al*., 2007). As per Hanowski *et al*. (2007), unconventional arrangements can generally fail when land acquisition at the intersection is not possible. This would further increase the congestion levels away from the Junction at median U-turn openings due to the slow turning manoeuvring speeds of the heavy vehicles, including buses (Hanowski *et al*., 2007).

In addition to this, continuous flow intersections (Intersection clusters where both major directions are coordinated) are also introduced and has become quite popular in the early years of 2000, and could only be used for newly planned cities (Park & Rakha, 2010; Sun *et al*., 2015). The main reason behind that was the requirement of sufficient lands at and near intersections, which is highly impossible in established cities where the acquisition of the land at the intersection is fairly difficult. Most of the time, the congestion would take place due to the non-availability of sufficient space at the intersections. Therefore, techniques like continuous flow intersections are highly discouraged for already congested intersections.

solutions that are not only geometric based but also tied up with an appropriate traffic signal phasing arrangement.

Xuan *et al*. (2011) suggested providing mid-block openings with pre-right turns bays, which is controlled by a pre-signal as a mechanism of elimination right turns just at the intersection. Similarly, the authors also carried out a study looking at how effectively an advanced centre median opening can accommodate U-turns, eliminating U-turns at the intersection. The delay reduction due to this arrangement was found to be around 10 % (Jayasooriya *et al*., 2016).

Making use of unutilized right turn areas have also been researched to make them utilized in allowing vehicles to wait at the spaces provided (Yang *et al*., 2012). Xi *et al*. (2013) has also analyzed the concepts of right turn waiting areas to be utilized for the improvement of the efficiency of the intersections.

However, all these geometric solutions will require sufficient space just at the intersection in order to obtain the maximum benefit. However, most of the intersections which are over-saturated currently do not have the possibility to acquire more space just at the intersection. Wu and Yang (2013) has developed a model to solve the above issues using RFID detector data for the estimation of the real-time queue. This model addresses the issues with the traditional input-output based method, and the model has been validated using real-time practical scenarios (Wu & Yang, 2013). Further to these, several important models such as 'RHODES real-time traffic-adaptive signal control system' (Mirchandani & Head, 2001), RT-TRACS Real-time adaptive Control System (Gartner *et al.*, 2001) are also developed which use real-time traffic flow data as input data to solve a particular traffic problem. Another modern way of controlling the real-time signals is to use multi-modal high-resolution data (Muralidharan *et al.*, 2016) in the management of intersections.

However, these advanced methods also require plenty of additional space and significant technological advancements, which are not possible or affordable for most congested intersections, especially in developing countries.

MATERIALS AND METHODS

In most congested intersections, it is not possible to provide any of the solutions discussed above due to the limited space available. Therefore, it is required to come up with innovative mechanisms such as a limited number of signal phases to increase the efficiency of the intersection management.

However, prohibiting the right turns, which cause the major issues at an intersection, will not be a wise decision from the perspective of road users when considering the convenience. The new system should be able to cater to all the demands at the intersection and should be able to reduce the overall delays. The research methodology focuses on developing different scenarios to capture the effects due to different arrangements. Therefore, the following methodology is proposed.

Step 1: convert right turns from minor roads at an intersection to left turns, followed by a U-turn at a given specific location

Step 2: re-design the signal phasing with two phases accommodating additional left and U-turns with pedestrians allowed to cross the main road only from the right-hand side of the minor road

Converting all right turns to left turns would certainly reduce the delay at an intersection, but the additional U-turns may add delay to users. However, there will be a delay reduction due to the reduced number of phases, but again additional green times given to make left and U-turns may increase the delay. Therefore, this proposed solution need a thorough investigation before application. Thus, we propose the following mechanism to test the viability of this proposed solution.

Development of the scenarios

In order to establish the theoretical background, the existing situation is compared with the following three main scenarios (Figures 1-3)

Scenario 1: Signalized intersection with no separate right-turn lanes (one lane for each leg)

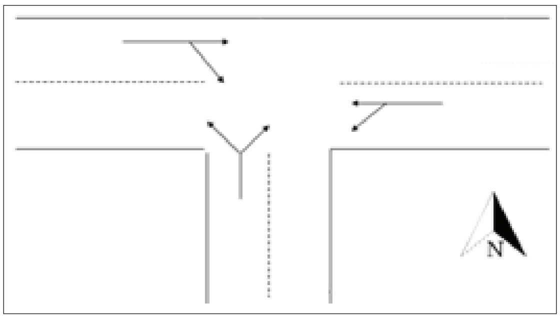

Figure 1: Lane arrangement for Scenario 1

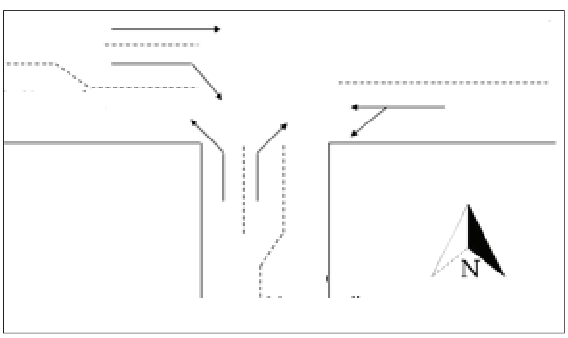

Figure 2: Lane arrangement for Scenario 2

Scenario 1 focuses on a situation where the traffic signals are introduced to an intersection, with a single lane is used in all directions, without any separate turning lanes.

Scenario 2: Signalized intersection with separate right-turn lanes

Scenario 2 focuses on providing separate turning lanes for major road right turns and minor road right turns.

Scenario 3: New Phasing arrangement for the proposed development

Scenario 3 focuses on eliminating the right turns from a minor road and replacing them with a left turn followed up by a U-turn at the centre median. A separate loon is to be provided when the space available for 'U'turn manoeuvring is not sufficient, especially when large vehicles are present.

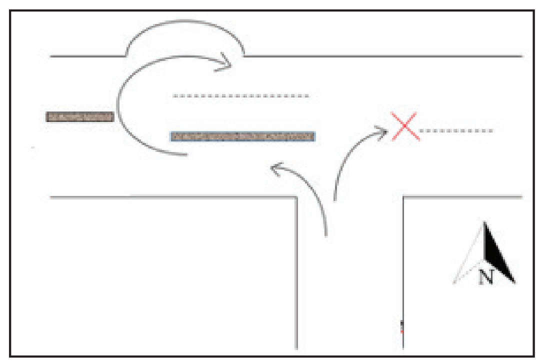

Figure 3: Lane arrangement for Scenario 3

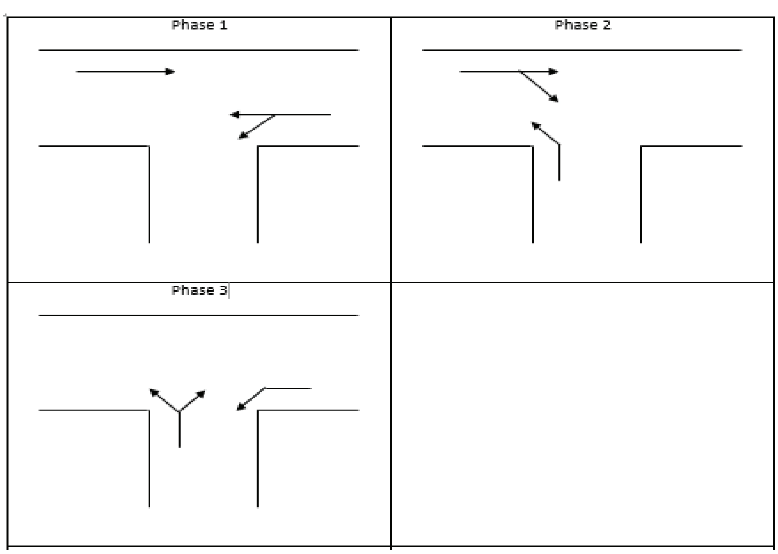

Figure 4: Basic three-phase arrangement at a signalized "T" Junction

Phasing arrangement for the scenarios

The basic arrangement of the three-phase systems at a signalized intersection is shown in Figure 4. This phasing arrangement is used in Scenario 1 and Scenario 2, where the difference is the availability of separate right turns lanes.

The arrangement of the new phasing system is proposed to be used in Scenario 3. The main intention is to eliminate the impact created by right turns from a minor road at an intersection. However, as discussed previously, complete prohibition of right turns will not solve the problems, and thus it is required to provide an alternative for the restricted right turns while reducing the impact.

For this purpose, a left turn followed up by a 'U' turn at a separate opening of the centre median is proposed (Figure 3).

The main highlight of this arrangement is the elimination of the right turns from minor roads, and the provision of a left turn followed up by a 'U' turn at the centre median of the main road.

The respective phasing arrangement for the new system is shown in Figure 5.

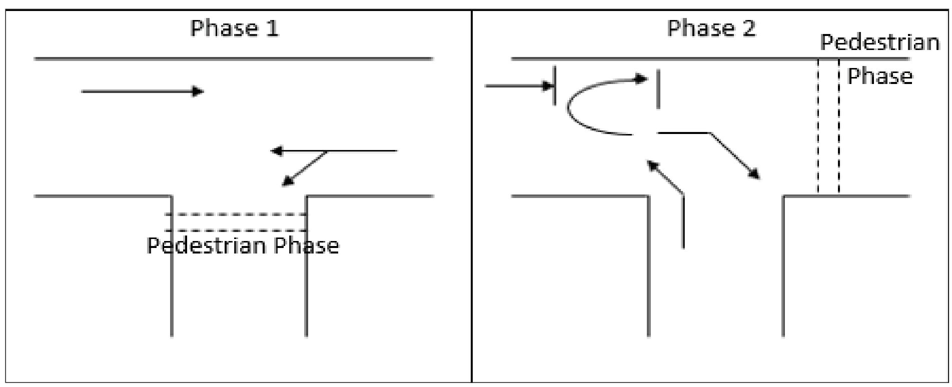

Figure 5: New phasing arrangement

The phasing for right turns from the minor road is prohibited at junctions, which is the main consideration of this phasing arrangement when compared to the base scenario. The traffic would be handled by a basic two-phase arrangement. Pedestrians would be facilitated along a minor road in phase 1 and the main road in phase 2 (Figure 5). However, depending on the volume of pedestrians, the timing for the pedestrians can be adjusted, and the lead/lag green phase for pedestrians can also be provided within the given phase timings. Since phase 1 caters for the major road with high vehicular volumes, the timings provided for phase 1 would generally be high when compared to phase 2. Therefore, pedestrians would have sufficient time for identification of the gaps with respect to the left-turning vehicles. On the other hand, there will not be an issue for the pedestrians in phase 2 since there is no conflicting vehicle traffic.

Phase 1 of the new phasing system would be similar to phase 1 of the traditional base scenario, which would allow only the through and left turns on the main road for both directions. The right turns from the west direction will get themselves stored on the right turning lane.

Phase 2 would facilitate the main road right turns to the minor road along with the left turns from the minor road. The through movement from the main road would be stopped upstream of the U-turn opening, allowing the vehicles wanting to turn right from a minor road, to get themselves stored at the space, created due to advance stopping of through traffic after taking the U-turns at the centre median in the same phase. After a certain time, phase 1 would re-start as usual, and the new system would continue throughout.

Since there can be situations when the roads are narrow, and the proper turning radius is not available. In such situations, when the turning radius at the centre median opening is not sufficient, a loon should be provided along with the U-turn opening (Figure 6) so that

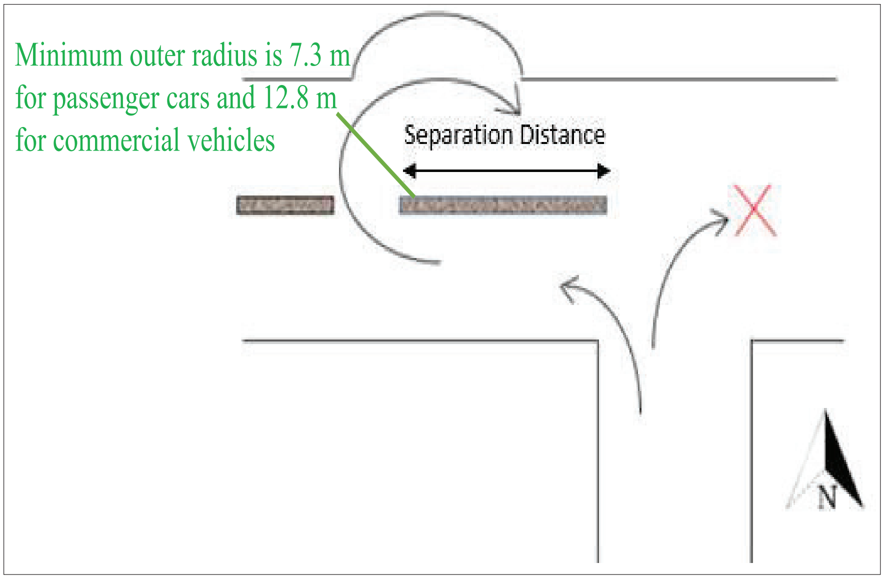

Figure 6: Separate opening with the loons provided

the minimum outer turning radius of 7.3 m for passenger cars and 12.8 m for commercial vehicles are satisfied (CCDP, 2018), so that turning vehicles can make their turns smoothly.

This new phasing and geometrical arrangement would reduce the three-phase signal arrangement to synchronized two phases and would thus reduce the delays at the intersection.

Simulation-based analysis

For verification purposes, VISSIM traffic microsimulation software was used. Since the simulation software has to be calibrated for the local condition, which experiences heterogeneous traffic, non-lane behaviour, different vehicle mix, the calibration parameters provided by the authors' previous work (Jayasooriya *et al*., 2018) were used. The calibration has been done considering the queue length and travel time as calibration parameters.

For analysis purposes, a case study was conducted. The calibrated software was first utilized to model the existing situation and then to model the three scenarios developed in Section 3A. The micro traffic simulations using VISSIM software was performed for a total time period of one and half hours. The first half an hour has been utilized as the warm-up period, and the following one hour was used for obtaining indicators for evaluation. Since the objective is to increase the efficiency of the intersection by minimizing the delays, the mean delay per vehicle was considered as the key performance indicator of the Junction.

Case study

Kochchikade-Madampalle Junction was selected as a case study. This intersection has three approaches, as shown in Figure 7 and Figure 8.

Currently, the intersection is uncontrolled, and it is proposed to introduce traffic signals to control the intersection. The current existing pedestrian crossing can be moved to the east side of the Junction across the main road when modelling the other scenarios. The existing pedestrian crossing is expected to be moved further east after the Junction, as per the bus stop locations proposed. Moving the pedestrian crossing to the east side of the Junction would also facilitate the smooth functioning of the traffic signal system and the proposed schemes.

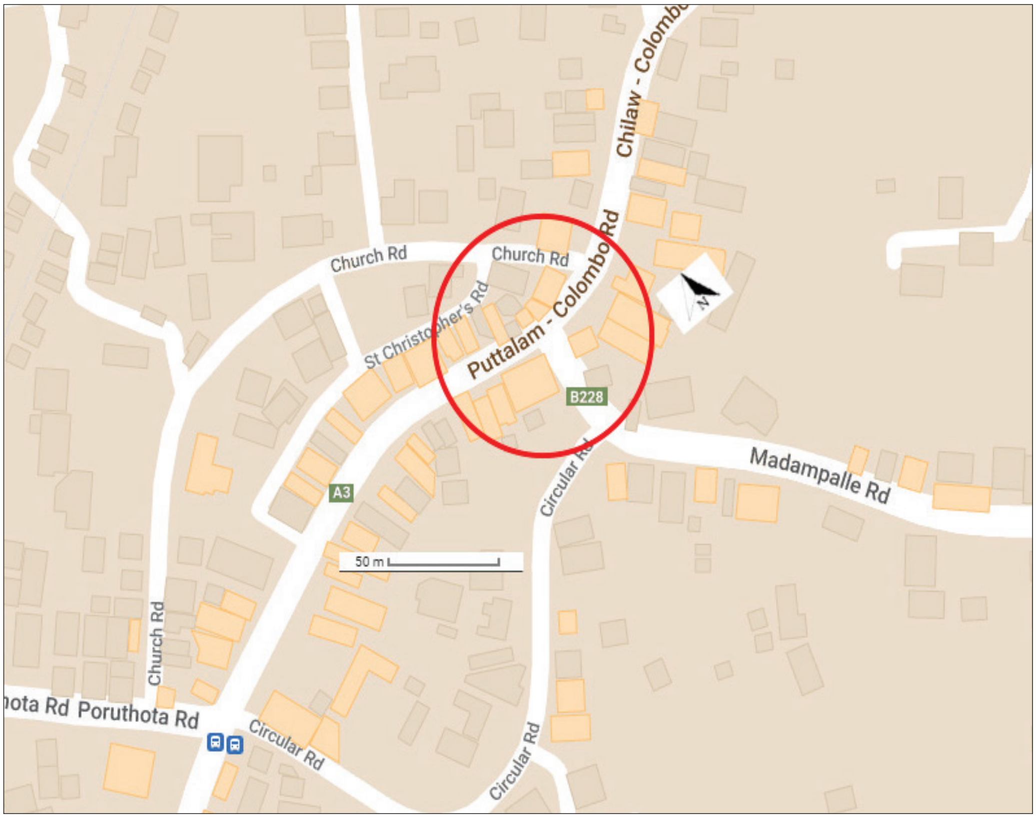

Figure 7: Kochchikade-Madampalle Junction

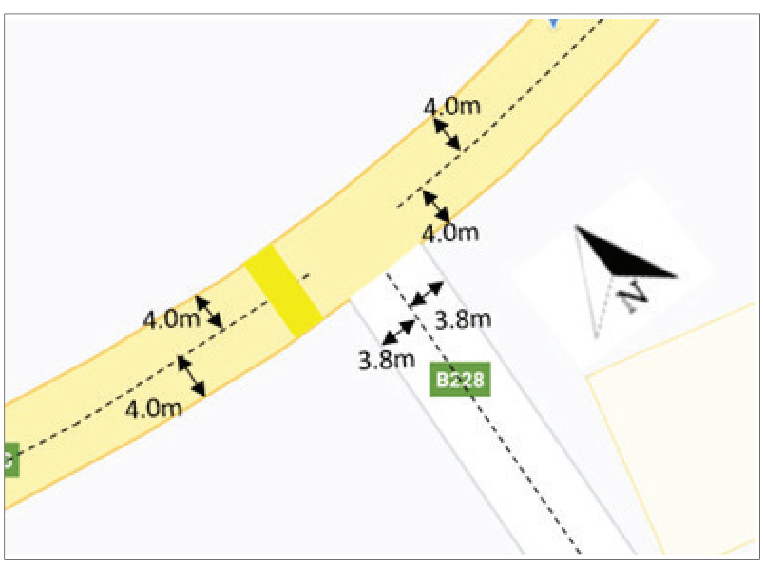

Figure 8: Kochchikade-Madampalle Junction Geometry

A traffic survey was carried out to obtain the existing traffic condition at the intersection on a usual day. Traffic flow volumes observed in the morning peak hour from 7 am to 8 am are depicted in Figure 9.

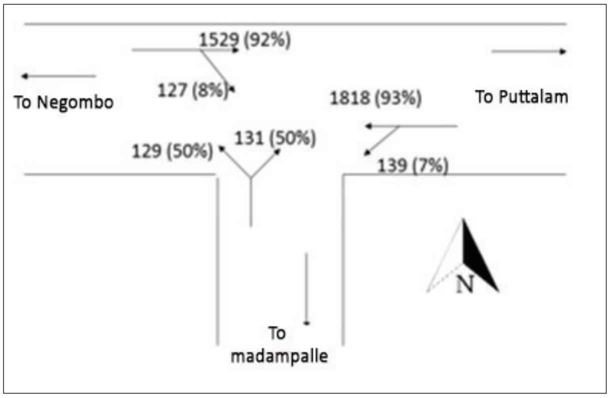

Figure 9: Existing traffic volumes observed at the morning peak hour (in PCU)

In order to have a good understanding of the present condition, the calibrated VISSIM microsimulation software was used to model the existing condition of the Junction. The existing scenario, based on the traffic flows mentioned in Figure 10, generates a mean vehicle delay of 78 s/veh.

Scenario 1: Signalized intersection with no separate right-turn lanes

As for Scenario 1, a basic three-phase arrangement is proposed using Webster's Method (1958) with the following phasing and timings (Table 1), as per the guidelines developed by authors' previous work carried out on limiting the cycle time to a maximum of 90 to 120 seconds (Jayasooriya & Bandara, 2019).

The phasing arrangement of Figure 4 is used for Scenario 1 with the following timings (Table 1). The calculated timings of phase 3 have to be increased to facilitate pedestrian movements.

Table 1: Timings used for Scenario 1

Phase	Timing
Phase 1	32 s
Phase 2	42 s
Phase 3	16 s
Total cycle time	90 s

The simulation using VISSIM traffic microsimulation software for a period of one hour has generated the mean vehicle delay of 72 s/veh for Scenario 1.

Scenario 2: Signalized intersection with separate right-turn lanes

With the introduction of right-turn lanes for the main road and the by road, the following phasing arrangement and timings were observed.

The phasing arrangement of Figure 4 is used for Scenario 2 also with the following timings (Table 2)

Table 2: Timings used for Scenario 2

Phase	Timing
Phase 1	58 s
Phase 2	16 s
Phase 3	16 s
Total cycle time	90 s

In both situations, the cycle times calculated were very high due to the heavy flows encountered at the intersection. As per the location-specific details and traffic level and also for proper comparison purposes, cycle time is kept as the 90 s as per the guidelines proposed in the previous work of the authors (Jayasooriya & Bandara, 2019).

VISSIM traffic microsimulation of Scenario 2 has estimated the mean vehicle delay as 42 s/veh. Compared to Scenario 1, the mean vehicle delay estimated in Scenario 2 was found to be significantly reduced, which was simply due to the provision of separate right turning lanes.

Scenario 3: New Phasing System with the modified geometrical arrangement

As for the new phasing arrangement, the simulation was conducted keeping the same base case scenario but with a modified phasing arrangement and geometrical modification depicted in Figure 10. The number of phases is reduced to two phases, and subsequently, the total cycle time was reduced to the 70 s.

For easy understanding, phase 1 is structured into two sub-phases, as shown in Figure 11.

The signal timings obtained for Scenario 3 are as follows (Table 3)

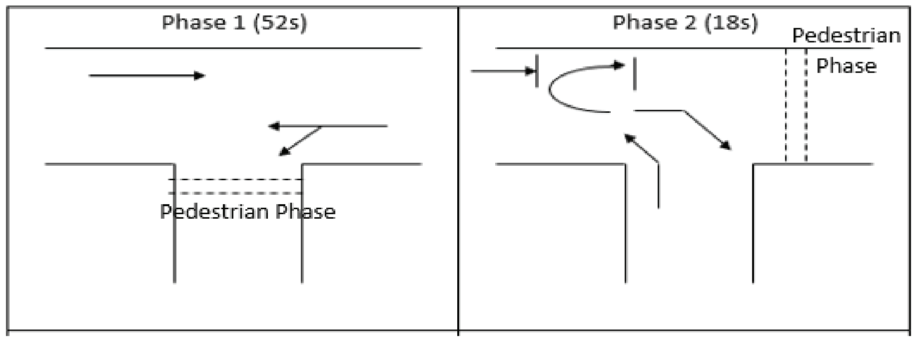

Figure 10: Phasing and timing for Scenario 3

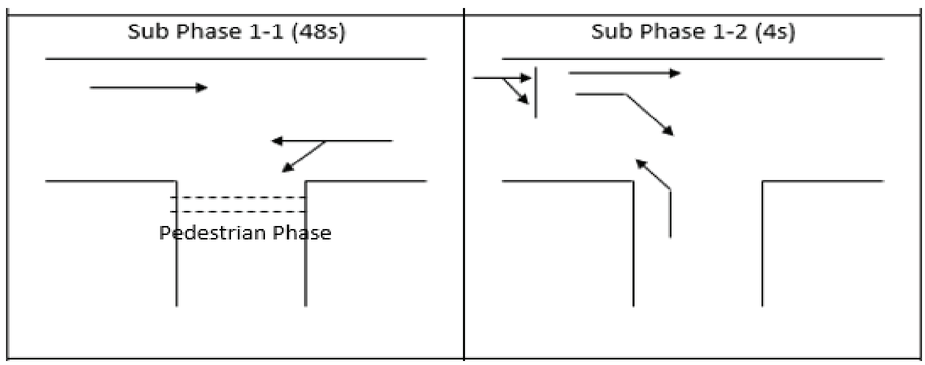

Figure 11: Sub phases of phase 1

Table 3: Signal timings for Scenario 3

Phase	Timing
Phase 1	52 s
Phase 2	18 s
Total cycle time	70 s

In this arrangement, the pedestrian phases are also provided across Madampalle Road in phase 1 and also across Main Road towards Puttalam side in phase 2 (Figure 5 and Figure 10).

Out of the two pedestrian phases provided, the critical phase for pedestrians' movement would be phase 2 (Figure 5 and Figure 10) due to two reasons. One is that the pedestrian demand will usually be high across the main road, and the second reason is that the provided timing to cater for main road pedestrians will be comparatively low, which is only 18 s, opposed to 52 s across the minor road. However, since there is no conflicting movement from vehicles for pedestrians, the delays for vehicles due to pedestrians will not occur. Therefore, only the adequacy of timing for pedestrians to safely cross the road is checked as indicated in Table 4, subject to the following assumptions.

- The average walking speed of a pedestrian is 1.2 m/s
- The total width of the road for crossing is 11 m
- Cycle time is the 70 s (Table 3)
- Start-up delay (ε) for pedestrians to enter the crossing is taken as 7 seconds for critical situations.

As per the analysis using the pedestrian data for the considered time period, the provided timing of 18 seconds is found to be satisfactory (required timing is only 16 seconds).

Table 4: Pedestrian flow and analysis

Time	Pedestrian demand (per hour)			Total ped. per hour	No. of cycles per hour	Ped. per cycle	Required time to cross (s)	Total time required	Total time provided
	North to South	South to North	Total						
7.00 – 7.15	32	8	40	174	51	3.38	9.2	16.2	18.0
7.15 – 7.30	32	10	42						
7.30 – 7.45	34	11	45						
7.45 – 8.00	20	18	38						

However, when it comes to phase 1, the situation would be different, where the pedestrians will have to cross in between the vehicles. Therefore, as per the data collected for the pedestrians, the disturbances that could occur for vehicles due to the provided pedestrian crossing has to be incorporated in the analysis in the considered simulation for phase 1 (It is not required to consider the adequacy of timing for pedestrians for this phase, since the timing provided for phase 1 would be 52 seconds, which is more than adequate for pedestrians to cross).

Satisfying the requirements, the simulations were performed for the new phasing system, and the estimated mean vehicle delay was found as 34. When compared with the two previous scenarios, through the introduction of the new phasing arrangement, the delay per vehicle has been reduced from 42 s/veh to 34 s/veh, which is a 19 % reduction of delay times.

To make sure that the analysis is applicable for all the scenarios with respect to pedestrian changes, the number of pedestrians catering in phase 1 was doubled, and the simulation was performed again. As per the analysis, the total vehicle delay was increased by only 1 s/veh, where the total delay was observed as 35 s/veh, which is still a 17 % reduction when compared with the previous scenarios.

Sensitivity analysis: changing minor road turning movements

In the case study considered, the right turn and left turn percentage from the minor road is observed as 50 % each. However, this may not be the case when various other T junctions are considered, and therefore, a few more highly likely situations (scenarios) were created (as described below) so that the concept is applicable elsewhere also. The scenarios are analyzed using the VISSIM microsimulation model, and results from the VISSIM model is presented in Table 5.

Scenario 3.1. Right turns from minor road 70 % and left turns from minor road 30 %
Scenario 3.2. Right turns from minor road 60 % and left turns from minor road 40 %
Scenario 3.3. Right turns from minor road 40 % and left turns from minor road 60 %
Scenario 3.4. Right turns from minor road 30 % and left turns from minor road 70 %

Table 5: Results of Scenario 3.1 & Scenario 3.2

Consideredscenario	Mean vehicle delay (seconds/vehicle)
Scenario 3.1 (70 % right and 30 % left)	41 s
Scenario 3.2 (60 % right and 40 % left)	37 s
Scenario 3.3 (40 % right and 60 % left)	31 s
Scenario 3.4 (30 % right and 70 % left)	30 s

The values obtained through the sensitivity analysis in all the scenarios are lower than the values obtained through Scenario 1 (72 s/veh) and Scenario 2 (42 s/veh). However, as expected, the mean vehicle delays increase with the increase of right turns from the minor road is increasing.

Sensitivity analysis: changing major road right turning movements

Another sensitivity analysis is conducted, changing the major road right turning movements to capture the possible variations of the off-peak peak scenarios and also to check the validity of the proposed method in varying traffic demands.

Taking the current scenario as the base scenario (8% right-turning vehicles), four more additional scenarios were considered, changing the main road right-turning percentages to 5 %, 10 %, 15 % and 20 %. The same simulation analysis is conducted (keeping other parameters the same), and the mean vehicle delays

Table 6: Results for Scenarios - changing major road right turning movements

Scenario	Main raoad right turning percentage	Delay (seconds/veh)	Maximum queue length (m)	Proposed maximum separation distance to U-turn opening (m)
Scenario 4 (Current)	8 %	34 s	12.35	13 m
4.1	5 %	32 s	7.43	8 m
4.2	10 %	36 s	14.87	15 m
4.3	15 %	39 s	22.30	23 m
4.4	20 %	41 s	29.73	30 m

per vehicle is obtained. Further to this, the maximum queue length that is generated due to the right turning movements of the main road is obtained from the simulations. The results are indicated in Table 6.

It is proposed to provide the storage space equivalent to the expected maximum queue length for more efficient management of the entire system. This is considered as the maximum separation distance. Increasing the separation distance more than the required amounts can create unnecessary delays due to the proposed arrangements due to high all-red times and additional time required to cross the intersection.

RESULTS AND DISCUSSION

The summary of the results obtained through the scenarios conducted above is mentioned in Table 6.

Table 6: Summary of the results for scenarios

Scenario	Mean vehicle delay (seconds/vehicle)	Storage space required (separation distance to the centre median opening)
Existing Situation	78 s/veh	Not Applicable
Scenario 1	72 s/veh	
Scenario 2	42 s/veh	
Scenario 3	34 s/veh	
Scenario 3.1	41 s/veh	
Scenario 3.2	37 s/veh	
Scenario 3.3	31 s/veh	
Scenario 3.4	30 s/veh	
Scenario 4	34 s/veh	13 m
Scenario 4.1	32 s/veh	8 m
Scenario 4.2	36 s/veh	15 m
Scenario 4.3	39 s/veh	23 m
Scenario 4.4	41 s/veh	30 m

As per the results obtained for the existing situation, delays at the intersection is very high, which is around 78 s/veh, whereas the accepted delay per vehicle at an intersection according to Highway Capacity Manal is 35 s/veh. However, when compared with the existing situation, Scenario 1 reduces delay by only 6 seconds/vehicle. The main reason is that even in the existing situation and Scenario 1, no proper geometrical improvement has been introduced to the intersection. This clearly indicates that the said benefits of traffic signals cannot be harnessed if no proper geometrical improvements can be carried out.

This is further verified when considering Scenario 2, where the delays are considerably reduced to 42 s/veh with the introduction of right turn bays for the intersection. However, the introduction of right turn bays comes at a cost. If the land use surrounding the intersection does not permit such an improvement, the option is not viable. Therefore, the decision should consider the existing land uses, such as buildings adjacent to the major and minor roads.

In Scenario 3, the mean vehicle delay is further reduced to 34 s/veh due to the proposed innovative phasing arrangement as well as the geometric changes introduced. The additional savings obtained through the proposed phasing arrangement, when compared with the existing situation, is considerable. When analyzing the above results, the delay saving applicable per vehicle is around 44 s/veh (The difference between the existing scenario (78 s/veh) and the proposed scenario (34 s/veh). The daily traffic at this intersection is estimated to be 53,000 vehicles based on the traffic flow counts available. When considering average occupancy of around 2.5 persons/vehicle, the expected savings can be around Rs.130 million over a year (USD 0.65 million) if the value of travel time is considered as Rs. 220 /hour/person (Jayasooriya *et al*., 2019). This is a considerable amount of saving. However, this improvement also needs some land to be acquired (to provide a loon), not at the Junction, but a little away from it (as per the guidelines provided). Therefore, one-time expenditure needs to be set off against the opportunity cost savings.

In addition to this, the sensitivity analysis conducted by varying the main road right-turning percentage also provides a good indication of the success and applicability of the proposed method. It also provides a clear indication of the separation distance that should be provided for the centre median opening for the "U", which can be considered as the storage space.

The overall results clearly indicate that the new phasing arrangement would reduce the delays at intersections even when the turning movements are varied. When the minor road right-turning percentage is higher than left turns, the situation becomes more critical than when left turns are higher, justifying that right turns from the minor road is the critical movement

However, in order to have a successful operation of the proposed phasing arrangement, it is important to have a sufficient turning radius for the vehicles making U-turns at the centre medians. Especially when buses and heavy vehicles are turning right at the intersection and replacing that movement with a left turn and U-turn at the centre median has to be carefully looked into. This can create additional issues when the required turning radius is not available.

When the turning radius is not available for the U-turns, it is required to provide loons to facilitate the vehicle manoeuvring. However, the additional land required to provide a loon will be very minimal compared to land required for a lane addition at the intersection, and also, the land for a loon is taken away from the intersection, which further reduces the negative impact.

CONCLUSION

In order to manage the increasing traffic congestion and delays at intersections, given the limitations of space available as well as land acquisition, it is required to introduce a novel solution when the situation cannot be easily controlled by conventional phasing arrangements or simply applying many other traffic management options.

As a result, this research was focused on replacing the minor road right turns at three-leg signalized junctions, with a left turn followed up by "U" turn at the centre median opening. When the required turning radius is not available, a loon area is provided to facilitate smooth manoeuvring.

First, the research approach focussed on the development of theoretical background and new phasing arrangement. Secondly, it was verified using a traffic simulation conducted at a 3-leg junction at Kochchikade using calibrated VISSIM simulation software.

The results show a comparison among the existing situation and a conventional three-phase signalized system with the new phasing arrangement proposed, which reduces the three phases to two phases. The proposed system has reduced the delays at an intersection by 44 s/veh, which is a delay reduction of around 56 % when compared with the existing non signalized situation.

The sensitivity analysis conducted at the intersection varying the turning movements from the by road and also from the main road also showed that the new phasing arrangement would be desirable for most of the traffic flow conditions, but high benefits can be obtained when the right turning percentages are less.

Further research can focus on other types of arrangements using the same concept, such as replacing the major road right turns with a through turn followed up by a U-turn downstream. Further, the same concept can also be applied at the four-leg junctions to reduce the conventional four-phase system to either a three-phase or two-phase system, which will, in return, reduce the vehicle delays.

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