The Development of the Displaced Right Turn Intersection

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Abstract. The concept of the Displaced Right Turn has been considered as an alternative intersection design to traditional at-grade and grade-separated intersections since the 1950s. It enables one or more conflicting movements to take place away from the main intersection at a new "crossover intersection", reducing the number of conflicts at the central node. Tests have shown intersection capacity can increase with a footprint similar to a large roundabout and only a small increase in costs. The Displaced Right Turn concept is an innovative traffic signal intersection being developed for the UK highway network by the Highways Agency. This paper summarises the research undertaken on behalf of the Highways Agency.

INTRODUCTION

In October 1998, Parsons Brinckerhoff Ltd and JCT Consultancy Ltd were commissioned by the Highways Agency (HA) to develop the Displaced Right Turn (DRT) concept for application on the UK highway network (*1*). This innovative design for a signalized intersection first appeared in the HA's Toolkit as an adaptation of the Continuous Flow Intersection design which is already established in Mexico and is being gradually introduced in some areas of the USA.

The idea of the DRT is to relocate one or more movements from the centre of the intersection. This reduces the number of conflicts at the central node, which can increase intersection capacity. The "displaced" conflicts occur upstream from the central node creating a new two-stage intersection. The right turning vehicles leave the main traffic stream some distance in advance of the main intersection making their right turn across the incoming traffic at the crossover node. These vehicles are then positioned to complete their manoeuvre parallel to their parent stream when that stream gains right of way at the central node (Figure 1). The concept reduces a conventional T-intersection from 3 UK stages (*2*) to 2 or a conventional crossroads from 3 or 4 stages to 2, improving capacity without necessarily expanding the footprint or making an appreciable increase in cost of the intersection.

The concepts behind the DRT are not new or the concept of having two or more intersections in close proximity, particularly if the intersections are co-ordinated; a signalized roundabout is a prime example of this. The founding principles of the DRT can be traced back through the literature to Lam in 1967/68 (*3, 4*) as the Storage Island Method and there are reports that the Road Research Laboratory developed similar schemes in the 1950s (*5*). Following the papers by Lam, the concept re-emerged in more detail in 1974 in a paper published by Al–Salman and Salter (*6*). Subsequently, the concept remained dormant until Goldblatt et al published a paper on the Continuous Flow Intersection in 1994 (*7*) applying the idea to the USA.

The relocation of the traffic movements and the resulting increase in potential stops for the turning movements leaves a key question concerning coordination. The separation of critical conflicts by geometric design will increase capacity, but lack of coordination could increase delay and stops. For a DRT to perform well, careful consideration must be given to the coordination of the nodes to ensure that traffic does not stop more than once. Generally, when looking at coordination in one direction, this is straightforward. However, because a DRT requires coordination in at least two directions, there will be a direct relationship between the allocation of green time at the central node, the cycle time and the cruise time between the two intersections. Therefore, in the design of a DRT, geometry and control are very closely related and need to be considered together as an integral part of the design. If movements are not fully coordinated, the length of the reservoir sections become a critical part of the design because they will need to be long enough to store all the traffic discharged during a single green period. Whether or not coordination has to be rigidly fixed or whether a certain amount of flexibility can be introduced is open for debate. However, if flexibility is introduced then it should not override safety implications. The geometric design of the central node and the crossover node are critical in ensuring that vehicles take the correct route through the intersection. At any crossover point, there will be a possibility that vehicles could turn onto the wrong carriageway. This needs to be carefully addressed in the geometric design with the use of appropriate signing and roadmarkings.

The A4311 Motorola intersection is a signalized 'T' intersection in the north-east corner of Swindon, UK. The intersection is the first of a series of traffic signal intersections on the new Northern Orbital Distributor Road constructed in preparation for major development proposals to the north of the town.

The intersection, designed by WSP Civils Ltd, JCT Consultancy Ltd and Swindon Borough Council, is the first operational DRT in the UK and was opened in August 2002 (Figure 2). Traffic volumes at the intersection are currently low, as it is designed to accommodate the planned development to the north and west of Swindon.

A simple 'T' intersection was originally considered but did not have the necessary capacity to cater for the design year traffic predictions. A signalized roundabout was also suggested but rejected on the grounds that it would not be 'consistent' with the neighbouring intersections on the Northern Orbital Distributor Road. Following a study into the different intersection types available and their suitability, the DRT became the favored option.

COMPARISON WITH OTHER INTERSECTION TYPES

A simple desktop study was undertaken comparing the DRT concept with a variety of intersection types, namely standard crossroads, a signalized roundabout (a variation on the traditional roundabout design where the movements at each entry/circulatory carriageway conflict point are signal controlled), a sig-nabout (a variation on the signalized crossroad that utilises approach flares, opposed right turning facilities and operates on a short cycle time to maximise flare usage) and a double through-about (an extension to the signalized roundabout design where straight through movements, e.g. N-S and E-W, are removed from the circulatory carriageway and catered for at-grade through the centre of a signalized roundabout. Further detailed descriptions of these junction concepts can be found in the Design Manual for Roads and Bridges (*8*). Generic layouts were developed for each intersection type and tested using a series of flow groups developed from three hourly flow bands. The flow bands ranged from 50 – 250 (low), 251 – 750 (medium) and 751 – 1000 (high). Each turn within a flow group was assigned a flow band and a flow was randomly generated for that turn from that band.

The assessment was undertaken using LINSIG for Windows™ (*9*) and the results were recorded in terms of Practical Reserve Capacity (%). LINSIG for Windows™ is the most widely used traffic signal design software in the UK and is of particular use in the detailed design and configuration of traffic signal intersections. The comparison summary (Figure 3) for each flow group shows the DRT to significantly outperform the many of the other intersection types considered. The signalled roundabout is shown to have similar performance although on average it is slightly below the DRT.

OPERATION OF THE DISPLACED RIGHT TURN INTERSECTION

Geometric Considerations

The concept can be applied to both crossroad and T-intersections. A crossroad requires two or four displacements (paired on the same road) to have any effect unless there are banned right turn movements. A T-intersection will have one of the right turn movement displaced either on the side road or the main road. From a geometric point of view there are a number of possible ways in which the 'displacement' can be designed and adopted to suit certain conditions.

Six generic examples have been shown in Figures 4 to 9 to demonstrate different ways in which the crossover can be geometrically configured. The first four examples all demonstrate different ways of configuring a crossover from the side road. The first two examples (Figures 4 & 5) demonstrate a two node option whereas the following two examples (Figures 6 & 7) demonstrate a three node option. The advantage of having three nodes is in the simplification of movements provided at node 1. However, this has to be weighed against the additional complexity required in coordinating all three nodes. Figures 4 and 5 are essentially the same but the later has a reduced footprint because the left turn manoeuvre (B) is incorporated within the control of node 1. In this case the design of node 1 would need to ensure that drivers do not turn left onto the wrong carriageway.

Figure 7 is a derivative of Figure 6, incorporating the left turn within node 1 without the safety implications in Figure 4. However, this solution may have capacity implications, particularly if movements B and C are relatively heavy because these movements conflict twice at node 1 and node 2 whereas on a conventional intersection this would not occur.

Figures 8 and 9 show the right turn displacement on the main road. Figure 9 has the disadvantage that movements D and E conflict twice.

CO-ORDINATION RELATIONSHIPS

A DRT developed for a 'T' intersection has certain special properties that may not be applicable at a crossroads. The DRT has two main stages that can be referred to as the ahead movements and the turning movements (right into and right out of) at the central node. Generally, the right turning movements are likely to require a smaller percentage of the green time than the ahead movements and as such this could lead to a more flexible approach with regard to the allocation of green time. The same is not necessarily true at a crossroads because the turning movements run in parallel with at least one of the ahead movements.

If the green times for conflicting stages at the central node are assumed to be equal, then for any given cycle time this will fix the cruise time required for coordination (and hence geometric displacement of the crossover node). If, however, the green times are varied to give proportionally more green to the ahead movements, then this will leave redundant time at the crossover node that can be utilised to either vary the cycle time or vary the displacement. If the green time allocated to the ahead movements is reduced below 50%, then perfect coordination is not possible.

A relationship between geometric displacement (cruise time), cycle time and green time has been developed for a generic layout (Figure 4). In order to obtain this simple relationship it has been assumed that the intergreen values between conflicting movements are the same (the intergreen being the minimum periods of separation between the end of the green on one phase and the start of green on any other conflicting phases). In practice, these intergreens will vary slightly and can be taken into account in the detailed design. The variables are defined as follows:

C Intersection Cycle Time (seconds)
I An average intergreen value (seconds)
w Proportion of available green time (C-2I) given to the MAIN road
T Cruise time between the cross over node and the main intersection (seconds)
G_m Green time for MAIN road (Movement A) = w (C-2I) .... (1)
G_s Green time for SIDE road (Movements B, C, D and E) = (1-w) (C-2I) .... (2)

Note: T is used as a proxy for the distance between the adjacent nodes. There is a direct relationship between cruise time and the geometric separation for a given speed. The speed between intersections will depend on the distance and it is likely that higher speeds could be expected with greater separation.

Assuming the MAIN road traffic (Movement A) starts at time 0 (beginning of the cycle), it will terminate at time G_m. Then calculating the offsets on the SIDE road movements relative to A:

Start of B / C: $G_m + I$
End of B / C: $C – I$

To coordinate the movement from B to D the timings at D will be movement B plus the Cruise time T. Hence

Start of D = $G_m + I + T$ .... (3)
End of D = $C – I + T$ or $T – I$ .... (4)

The offsets of Movement E can be calculated relative to either conflicting Movement D or to maintain coordination, Movement C. Hence:

Start of E: $T – I + I = T$ (relative to D) .... (5)
or Start of E: $G_m + I – T$ (relative to C) .... (6)

End of E: $G_m + T$ (relative to D) .... (7)
Or End of E: $C – I – T$ (relative to C) .... (8)

Evaluating the start and end time for the cruise time, T, provides a range of values for T within which perfect coordination between the central node and the crossover can be achieved.

For the Start of E:

T (equ. 5) $= G_m + I – T$ (equ. 6)
Hence $T = (G_m + I) / 2$
$= (w (C-2I) + I) / 2$ .... (9)

For the End of E
$G_m + T$ (equ. 7) $= C – I – T$ (equ. 8)
Hence $T = (C – G_m - I) / 2$
$= (G_s + I) / 2$
$= ((1-w) (C-2I) + I) / 2$ .... (10)

Equations 9 and 10 give the upper and lower range of cruise time for coordination for a given cycle time and green time. Rearranging equations 7 and 8 in terms of cycle time give the following:

$$C = (2T + I\,(2w - 1)) / w \qquad (11)$$
$$C = (2T + I\,(1-2w)) / (1-w) \qquad (12)$$

Equations 9 to 12 are intended to show the flexibility in cycle time and displacement of the crossover node if the green allocation is biased towards the MAIN road. These equations have been plotted in Figures 10 and 11 to show the added flexibility that is introduced as the proportion of green time given to the main road increases. In the case of Figure 10, the results have been plotted for a 60 second cycle time, showing that the window for the cruise time opens out as the proportion of main road green becomes larger. In Figure 11, for a fixed 15 second cruise time, the opportunity for variation in cycle time is also apparent.

APPLICATION TO A4311 MOTOROLA DISPLACED RIGHT TURN INTERSECTION, SWINDON

The geometric design of the A4311 Motorola intersection was based upon the concept shown in Figure 4, with a single displacement on the side road (Cricklade Road). There was also a requirement to provide pedestrian facilities across the south-west side of the intersection. These facilities have been designed to operate in parallel with non-conflicting traffic movements. Essentially, there are two primary stages but a third stage is required to enable southbound traffic on Cricklade Road to clear the intersection. This stage from a capacity point of view has the same effect as Stage 1. To accommodate this design on a UK traffic signal controller, the intersection had to be configured with 13 phases (4 pedestrians) and 3 stages (Figure 12).

A constraint in the design was the spacing of the two intersections. Due to land restrictions, the crossover node could only be positioned approximately 75m (246.1ft) away giving a cruise time between the two nodes of about 8 seconds. In order to achieve coordination for both right turn manoeuvres and run the pedestrian movements including clearance periods, the minimum cycle time is in the region of 40 seconds giving only 13 seconds to each right turn manoeuvre. This may seem short but on a relative short cycle time, the right turn capacity is more than adequate. Hence, if the cycle time is varied, it is only to vary the green time on the main road (Stage 1). In practice, Stage 1 is curtailed because either there are no more demands or a queue has built up on the right turn (Phase K) which will utilise all of the next green period to discharge. This situation may be considered unique in comparison to most other sites because of the geometric restrictions. In this particular case, the only way to vary green splits and ultimately capacity is to adjust the length of Stage 1. The Phase / Stage arrangement is shown in Figure 13 for a 60 second cycle; Stages 2 and 3 are of fixed duration.

Figure 13 shows the durations and relative offsets of each phase within the intersection. One interesting thing to note is the time given to the right turn movements into and out of Cricklade Road. Turning out of Cricklade Road, the controlling Phase (K) runs for 13 seconds but only receives 11 seconds on exiting Phase (E). Similarly, turning into Cricklade Road, the controlling Phase (C) runs for 13 seconds but only receives 11 seconds on exiting Phase (J). Coordination of the signals in this way does not generally trap vehicles at the second stop line due to a phenomenon known as platoon compression. The explanation of this stems from the fact that the first vehicle at the stop line is starting from rest and takes longer to traverse the distance between the two stop lines than the last vehicle which is travelling at cruise speed. This effect is only observed over relatively short distances (*10*).

As a result of the fixed stages, it is possible to use either vehicle actuation or MOVA (*11*) control to vary the length of Stage 1 according to main road traffic demand. However, because the right turn manoeuvres can only receive a fixed green, Stage 1 needs to be curtailed if the right turn demand reaches the capacity dictated by the available green time.

MONITORING STUDY

The final constructed intersection is shown in Figure 2. A 3 month monitoring study included a review of speeds through the DRT and a conflict study. The conflict study (*12,13*) was undertaken as an alternative to the traditional accident investigation study that would have required a minimum of three years of accident data to enable an assessment to take place. A brief investigation showed that since the introduction of the DRT in August 2002 there have been no reported personal injury accidents.

Speed surveys were conducted in September and November 2002 to investigate whether there would be any change in speed through the DRT, as drivers grew more familiar with the layout. The review showed that vehicle speed did not change over the three months and speeds for the crossover sections remained lower (approximately 32 km/h (20 mph)) than vehicle speeds for more traditional movements, such as the straight ahead and left turns (up to 60 km/h (37.3 mph)).

Conflict studies were undertaken at the DRT and a new convention 3-arm signalized intersection on the same corridor. The control intersection was used for comparison purposes as it was similar geometrically and in terms of turning volumes. The conflict study observed 4 conflicts at the control intersection and 14 conflicts at the DRT over the 12-hour survey period. Upon further inspection it was found that over 65% of the conflicts at the DRT were caused by lane discipline issues at the upstream intersection and minor design issues that could easily be mitigated through a review of the signing and roadmarkings at and on the approaches to the DRT.

Once these conflicts are mitigated the number of incidents at the DRT may be equivalent to a traditional highly trafficked traffic signal intersection.

CONCLUSIONS

The lineage of the DRT concept can be traced to the late 1960s when Lam discussed the Storage Island method of traffic signal control. The early designs failed to consider the complete signalisation of the intersection and caused concern over large volumes of traffic needing to give way at the initial crossover. This raised issues over the safety and footprint of the intersection especially when traffic flows are high. The more recent studies incorporated a fully signalized layout and illustrated that the DRT could be expected to have a footprint similar to that of a conventional roundabout.

There are several forms of the DRT concept depending on the number of arms at the intersection and the number and location of crossovers incorporated into the design. There is little difference in the performance of the possible layouts and the optimum layout will depend on the physical surroundings at each location. The fundamental principle of the DRT design is the coordination between the signal nodes. Good coordination is essential to control the geometric layout of the intersection given that the footprint will be a major design factor.

Furthermore, the desktop analysis showed that provision for pedestrians and cyclists could easily be provided at a DRT without compromising the capacity using "Walk with Traffic" facilities. The pedestrian and cyclists provision also have the advantage over a traditional signal intersection because the short cycle times necessary ensure pedestrian/cyclist delays are kept to a minimum.

The construction of the A4311 Motorola DRT has shown that the concept can be successfully incorporated onto the UK highway network. The subsequent assessment of vehicle conflicts at the DRT showed there to be more conflicts at the intersection. However, these could be removed with further modifications to the geometric layout and a review of the signing strategy at the upstream intersection. With these conflicts mitigated, the number of conflicts at the DRT may be of the same magnitude as a traditional traffic signal intersection.

The conclusions of this work would suggest that the DRT concept is an appropriate intersection type for use on the UK highway network. The DRT can provide:

- Operational benefits, in terms of capacity, where there are heavy right turns;
- Full non-motorised users provision throughout the intersection;
- An accident record that is unlikely to differ from any other large signalized intersection.

ACKNOWLEDGEMENTS

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LIST OF FIGURES

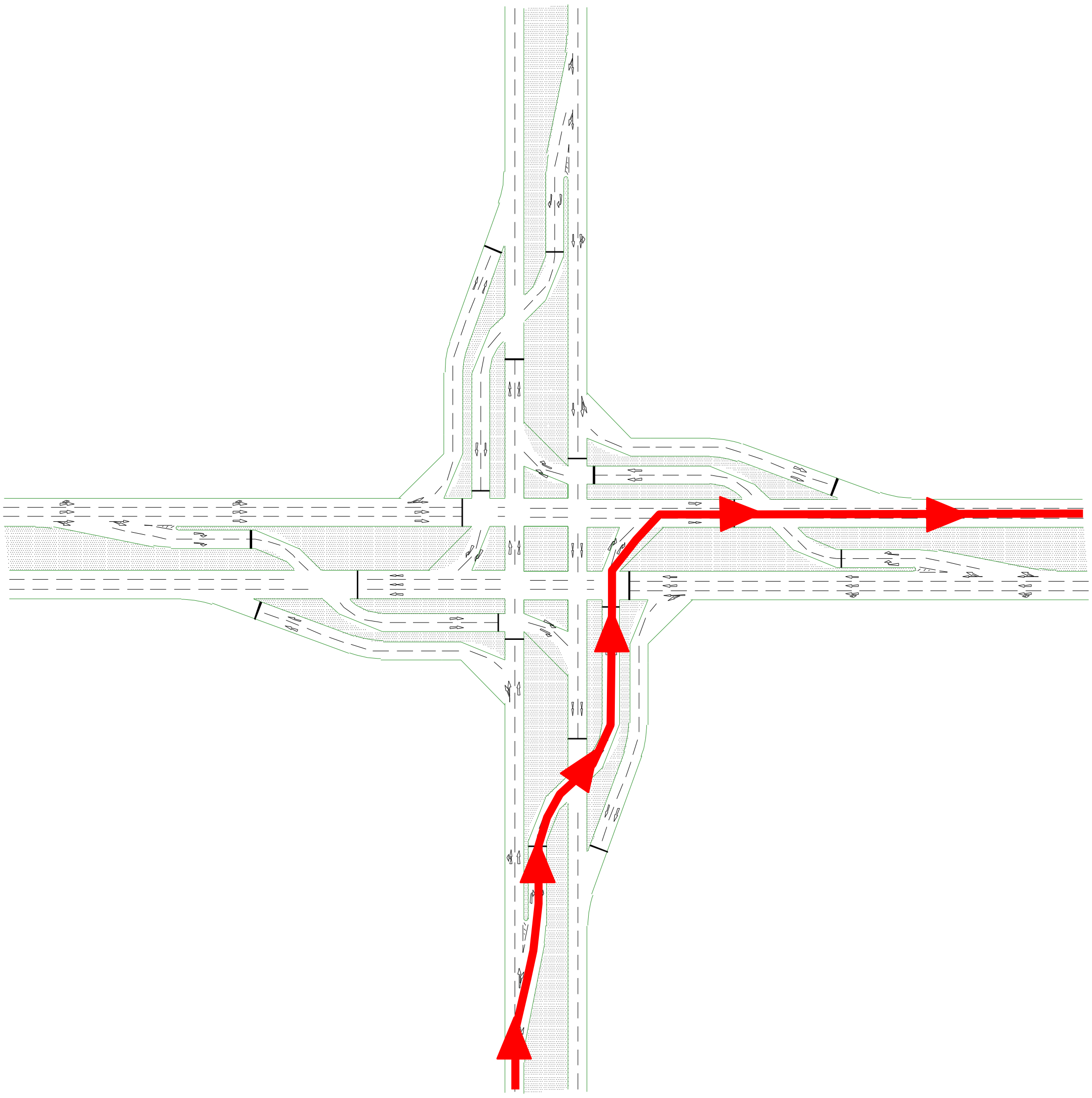

FIGURE 1 4-arm Displaced Right Turn intersection

FIGURE 2 A4311 Motorola intersection at Swindon

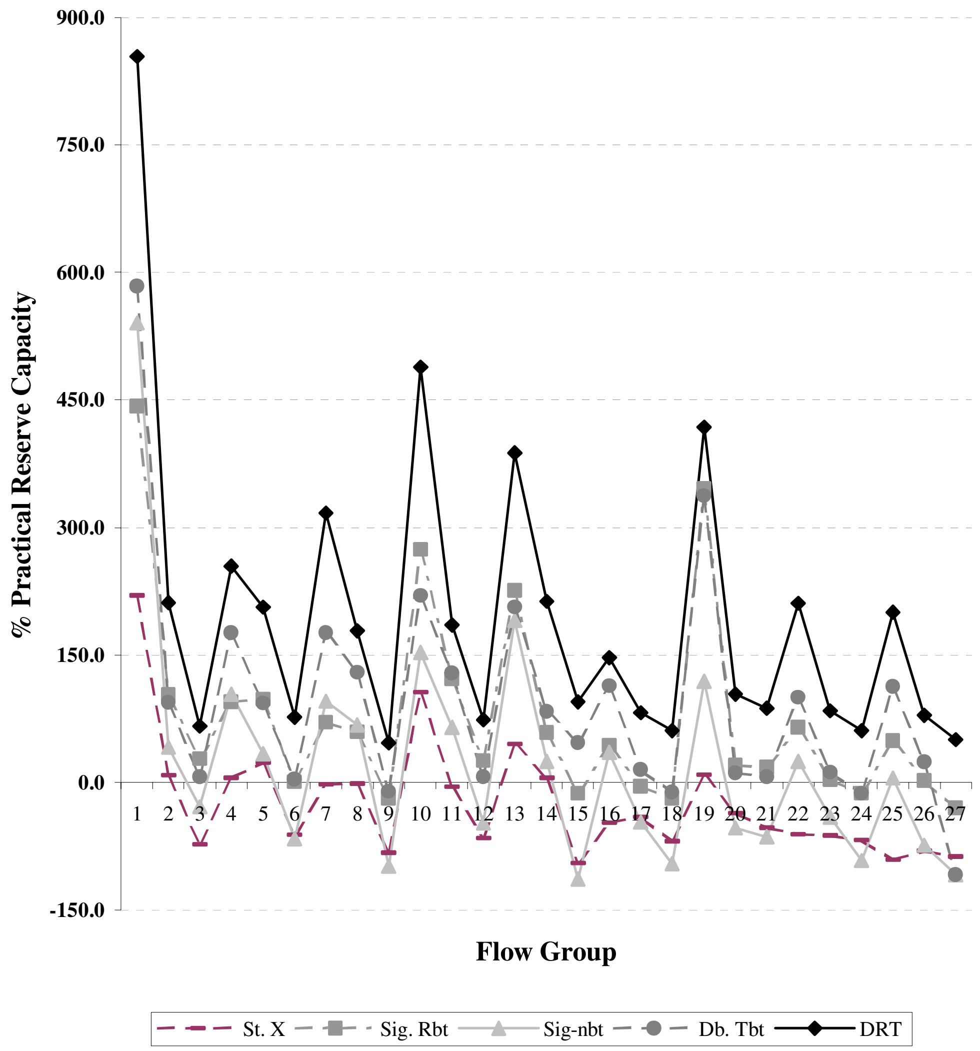

FIGURE 3 Capacity test for each flow group and junction type

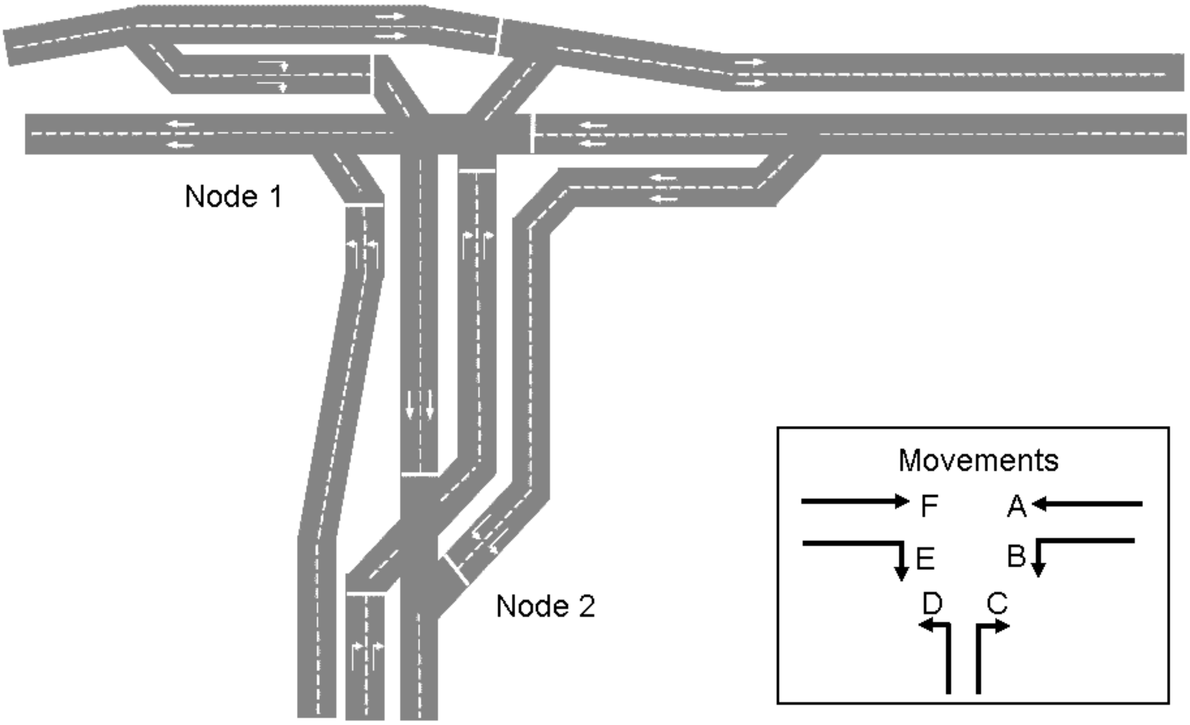

FIGURE 4 Generic 3 Arm Displaced Right Turn Intersection with displacement on side road

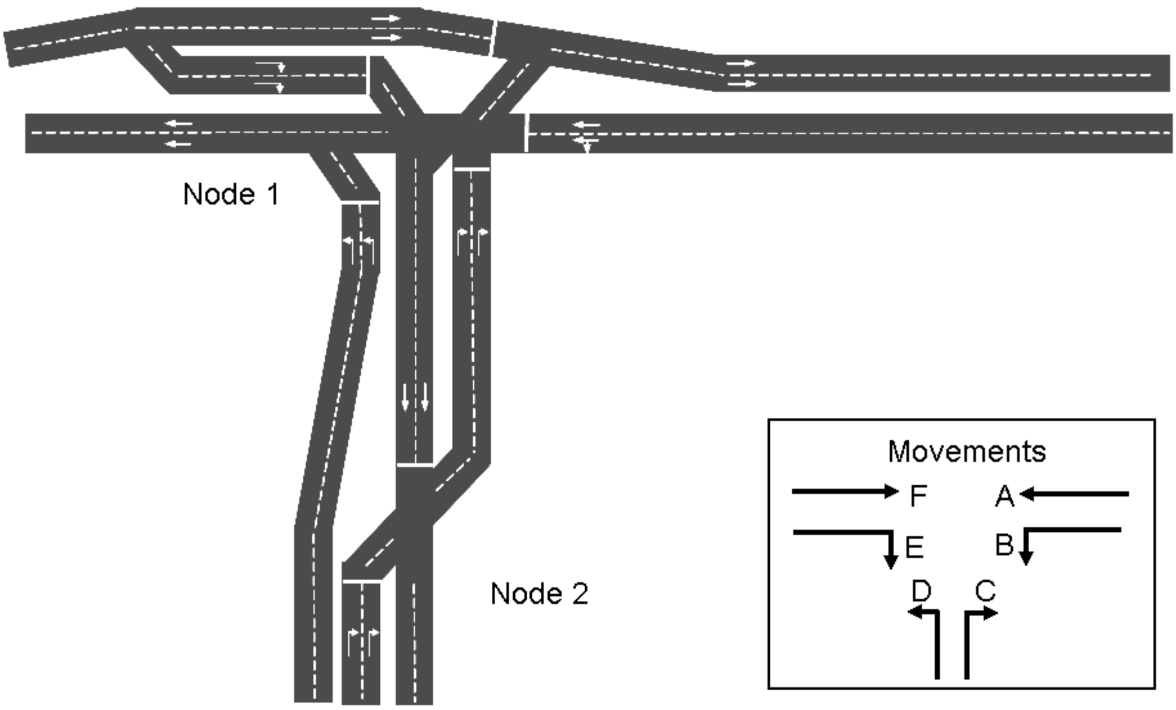

FIGURE 5 Generic 3 Arm Displaced Right Turn Intersection with left turn within intersection

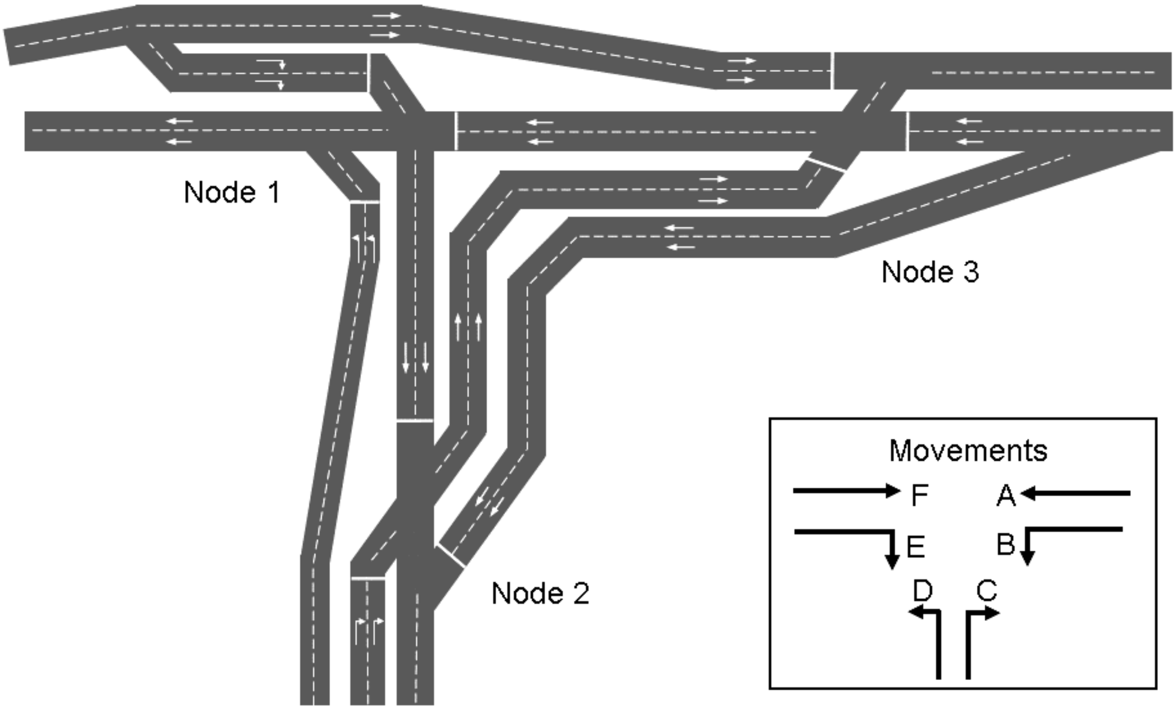

FIGURE 6 Generic 3 Arm Displaced Right Turn Intersection with displacement on main road (with node 2 left turn) and side road arms

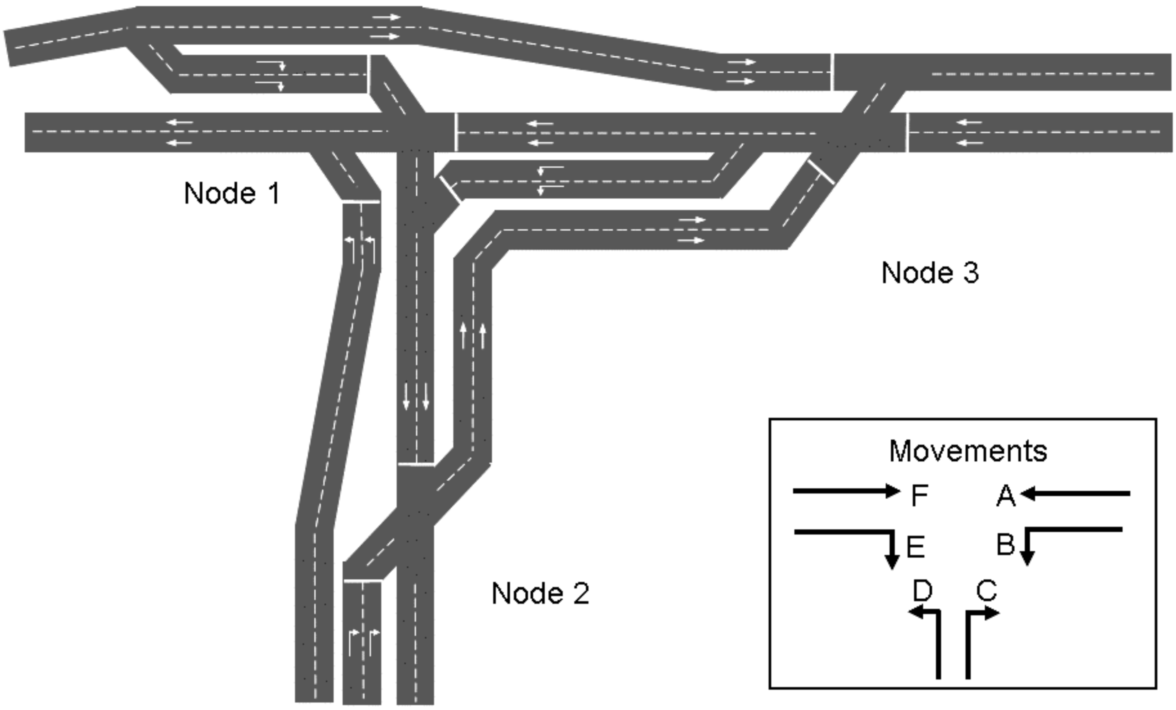

FIGURE 7 Generic 3 Arm Displaced Right Turn Intersection with displacement on main road (with nod 1 left turn) and side road arms

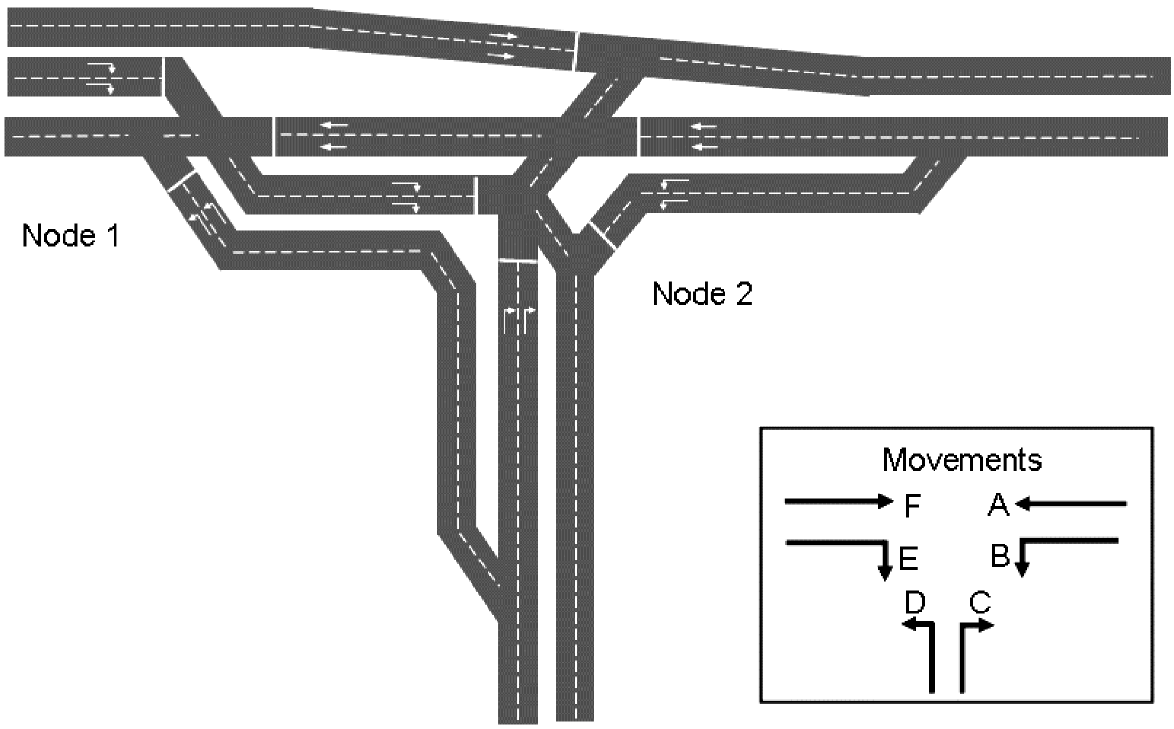

FIGURE 8 Generic 3 Arm Displaced Right Turn Intersection with displacement on main road and upstream left turn on side road

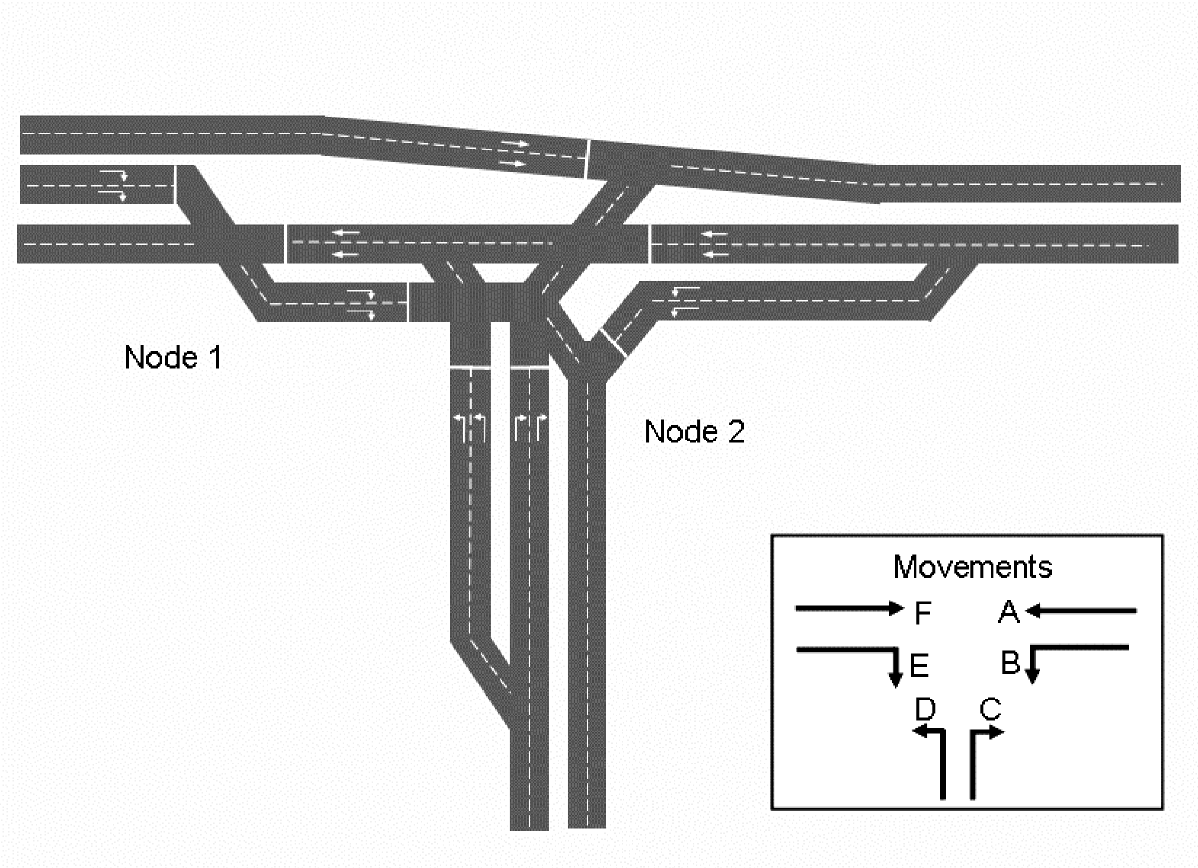

FIGURE 9 Generic 3 Arm Displaced Right Turn Intersection with displacement on main road

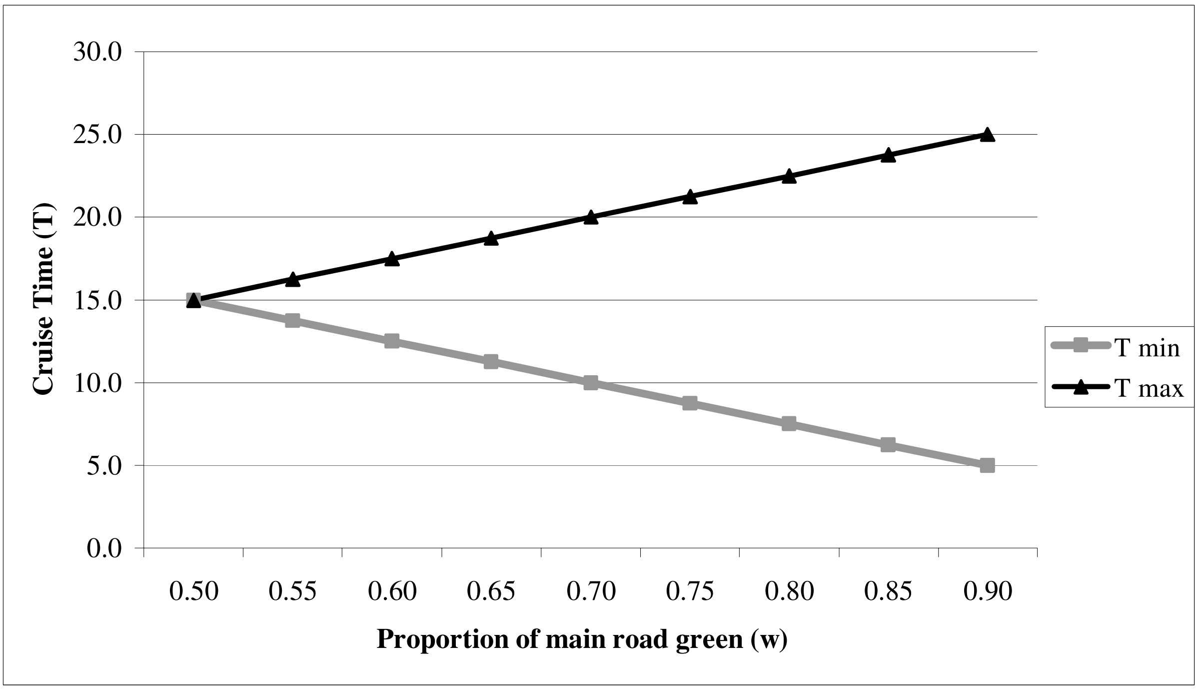

FIGURE 10 Cruise time/main road green split relationship with respect to coordination

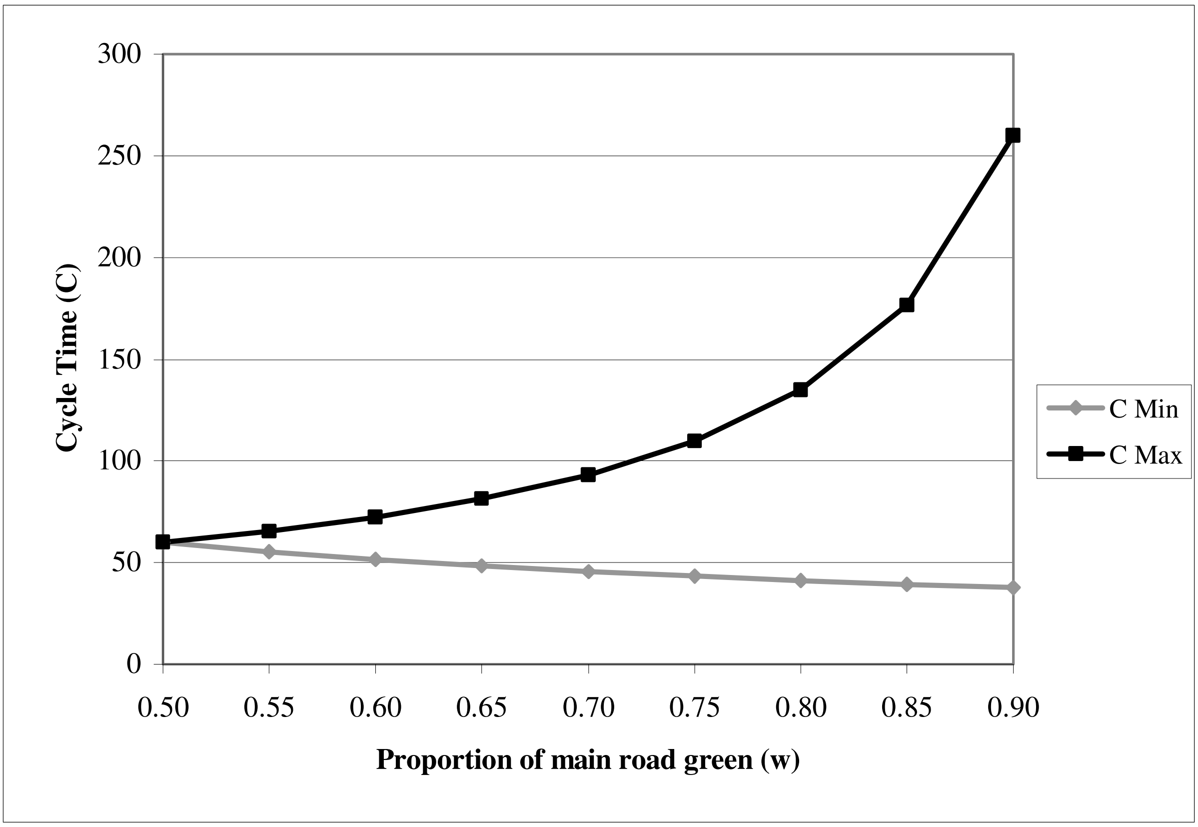

FIGURE 11 Cycle time/main road green split relationship with respect to coordination

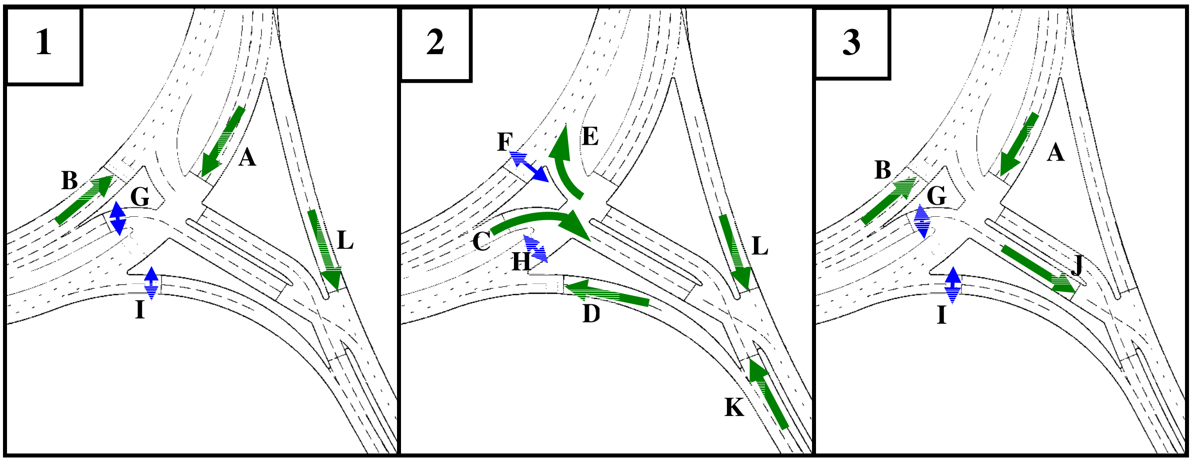

FIGURE 12 3-stage, single stage stream

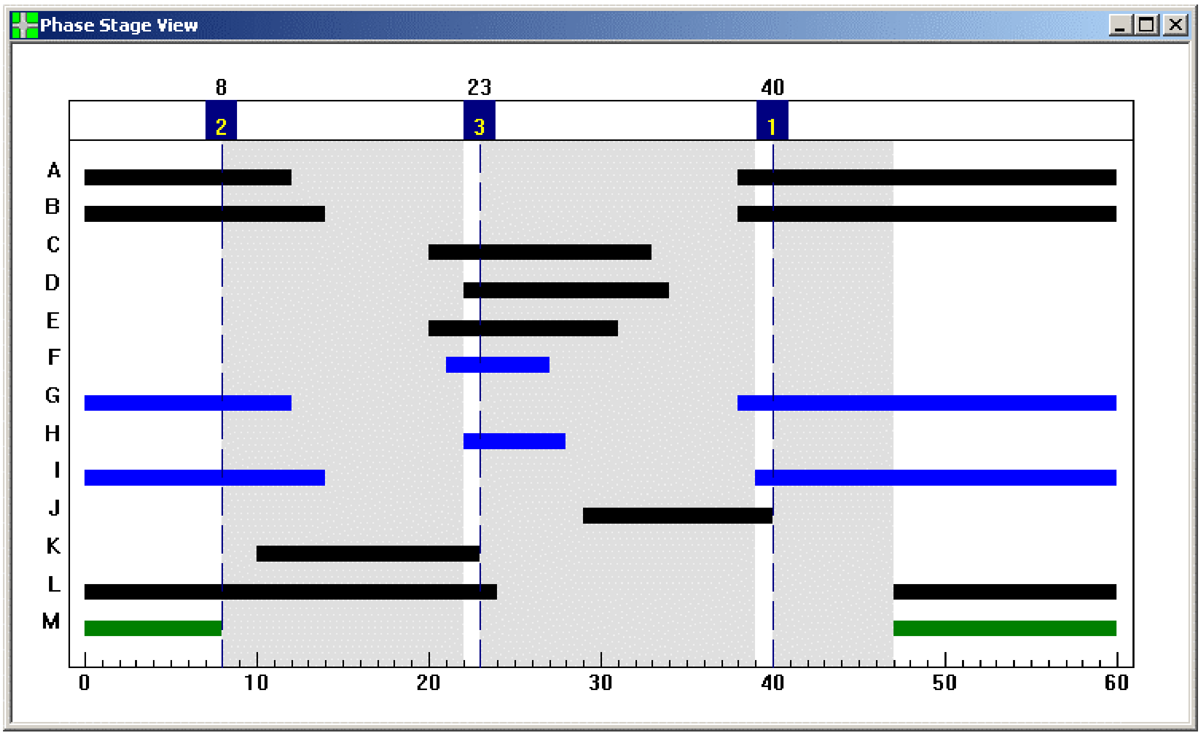

FIGURE 13 Phase/Stage View taken from LINSIG for Windows™