DESIGN OF INTERGREEN INTERVALS IN SIGNAL-TIME SETTINGS : THE STATE OF THE ART

By

PROF. DR. V. THAMIZH ARASAN* & PROF. DR. ING. MANFRED BOLTZE**

CONTENTS

		Page
1.	Introduction	93
2.	Background	94
3.	Practice in the USA	99
4.	The German Practice	99
5.	Implementation	104
6.	Application for Mixed Traffic	106
7.	Concluding Remarks	107

1. INTRODUCTION

In a traffic signal setting, the time from the end of the green period for a traffic stream losing right-of-way to the start of the green period for a traffic stream gaining right-of-way is termed as the intergreen interval. The intergreen interval, provide a warning to approaching vehicles that the green light is about to change to red, and sufficient time for the vehicles in the intersection area to cross it. The intergreen interval, depending on the actual signal-time setting, may be indicated with an amber light or an amber light followed by an 'all red'. The all-red period is the duration of signal indication, with red light for all the streams of traffic at the intersection; and it is intended, on considerations of safety, to provide a clear time gap between passing of the tail end of the preceding traffic stream and the head of the succeeding traffic stream at the possible conflict area of the intersection.

Determination of intergreen interval is a crucial step in signal-timing design. Whereas other aspects of timing focus on the efficiency of traffic moving through a signalized intersection, the intergreen interval relates directly to safety, especially those

* Professor, Transportation Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai-600 036, India.

** Professor and Head, Section of Transport Planning and Traffic Engineering, Institute of Transportation Engineering, Technology University of Department, D-64287 Darmstadt, Germany.

elements associated with reassigning the right-of-way to conflicting traffic streams. When a driver is nearer to the intersection at the onset ofintergreen interval (Amber light signal), he/she is in a dilemma as to stop or not to stop. If he/she fails to respond safely, a major right-angle collision may occur. On the other hand, if the driver over reacts, and applies sudden brake, a rear-end collision is likely. Thus, safety becomes the major factor in determining the intergreen interval.

2. BACKGROUND

The background information provided in this section is general in nature and not specific to field procedures followed in different countries. A driver approaching a signalized intersection during the amber period will either have to stop at the stop line or cross the stop line (before the signal turns red) and proceed to clear the intersection. Fig. 1 shows the details of stopping and clearing distances for a vehicle approaching a signalized intersection at the start of the amber signal. The stopping distance is the distance required for the vehicles to stop before entering the intersection [Fig. l(a)]. The stopping distance can be calculated as :

$$X_s = tv + \frac{v^2}{2(a)} \quad \text{...} (1)$$

where,

X_s = stopping distance in m; t = reaction time of drivers in s; v = approach speed in m/s; a = deceleration rate in m/s^2.

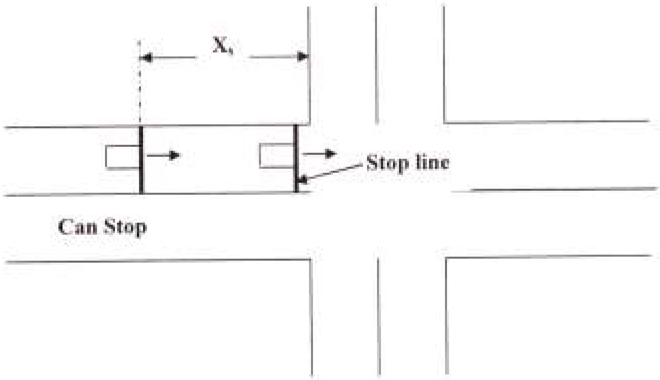
The crossing distance is the distance, on the approach, within which the vehicle can proceed to cross the intersection before the end of the intergreen interval [Fig. l(b)]. A vehicle intending to cross the intersection, therefore, has to travel a total distance equal to the sum of the crossing distance, the width of the intersection, and the length of the vehicle. Thus,

$$X_c = Iv - (W + L) \quad \text{...} (2)$$

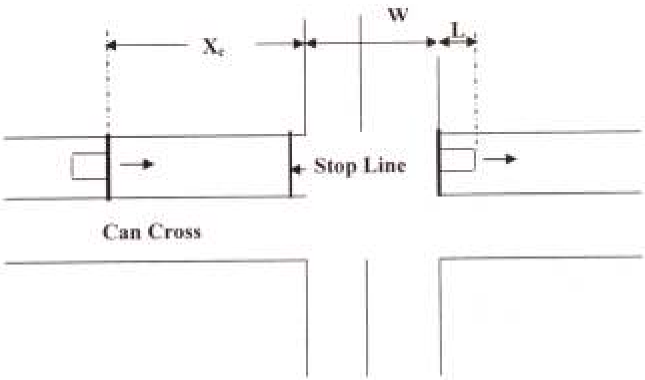
where,

X_c = crossing distance in m; I = intergreen interval in s; v = approach (and crossing) speed in m/s; W = intersection width in m; and L == length of the vehicle in m.

The intersection width should be measured along the actual path of the vehicle from the near-side stop-line to the far-side edge of the conflicting traffic lane, when there is no pedestrian traffic. It should be measured to the far-side of the farthest conflicting



(a) Stopping Distance



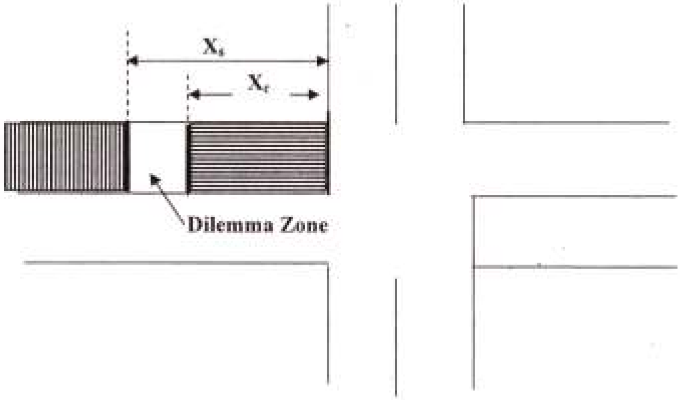
(b) Crossing Distance

Fig. 1. Geometry of Intersection for Designing Intergreen Interval

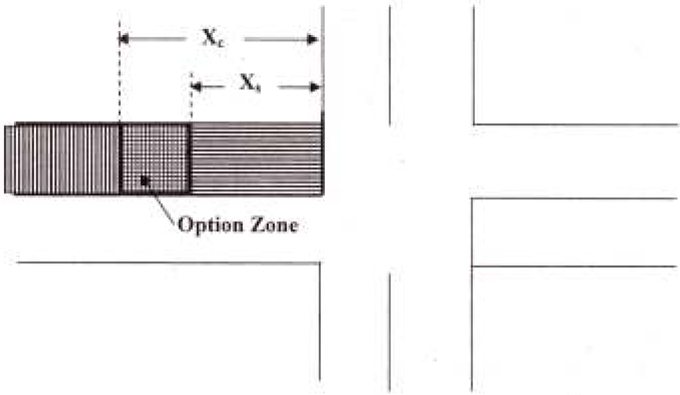
pedestrian cross walk when there is significant pedestrian traffic or when the cross-walk is protected by pedestrian signals. Equation (2) assumes that the driver, when faced with amber light, will proceed through the intersection with constant speed.

If the stopping distance, X_s is greater than the clearing distance, X_c, a dilemma zone will exist within which, a driver faced with amber, could neither stop nor clear the intersection [Fig. 2(a)]. If $X_s < X_c$, an option zone will exist within which the driver can choose between stopping and crossing the intersection [Fig. 2(b)]. For $X_s = X_c$, the failure and option zones are eliminated.

The basic principle in determining the intergreen interval and the included amber period, is to eliminate the dilemma zone. This is possible only when the stopping and



(a) Dilemma Zone $X_s > X_c$



(b) Option Zone $X_s < X_c$

Fig. 2. Definition of Dilemma and Option Zones

clearing distances are equal. Accordingly, equating the stopping and crossing distances of equations (1) and (2), respectively, the required intergreen interval can be obtained as :

$$I = t + \frac{v}{2(a)} + \frac{(W + L)}{v} \qquad \text{.. (3)}$$

The variation of stopping distance with respect to the approach speed of the vehicle is curvilinear in nature as shown in Fig. 3(a). Whereas, the variation of crossing distance over the approach speed of vehicles, is found to be linear in nature as shown in Fig. 3(b). The zones of safe stopping and crossing distances are also indicated in Fig. 3(a) and 3(b), respectively. The superposition of the two plots [Fig. 3(a) and 3(b)] enables identification of the distance (distance, on the approach, behind the stop-line) at which the dilemma zone is eliminated by making the stopping and crossing distances to be equal [Fig. 3(c)].

The formula for arriving at a value for intergreen interval, given in equation (3), was developed by Gazis et al. (1960). The equation of Gazis et al. has been modified by several researchers including Williams (1971); Parsonson and Santiago (1980); and Bissel and Warren (1981). A number of researchers have attempted to reassess the applicability of the equation developed by Gazis et al. (e.g., May 1968; Wortman and Fox 1986; Lin 1986; and Lin, Corke and Vijaya Kumar 1987) and found that the equation in general is valid for estimating intergreen intervals under most situations. Other researchers have examined the reaction time and deceleration rate for use in the equation (e.g. Chang et al. 1985; Olson and Rothery 1972). Several studies have been conducted to determine the intergreen interval on empirical basis (e.g. Lin and Vijaya Kumar 1988; and Horst 1986). Sheffi and Mahmasani (1981), and Wortman and Mathias (1983) have studied the driver behaviour on the onset of amber signal. Easa (1993) has proposed a reliability based design procedure for intergreen interval. In his study, he has considered the factors

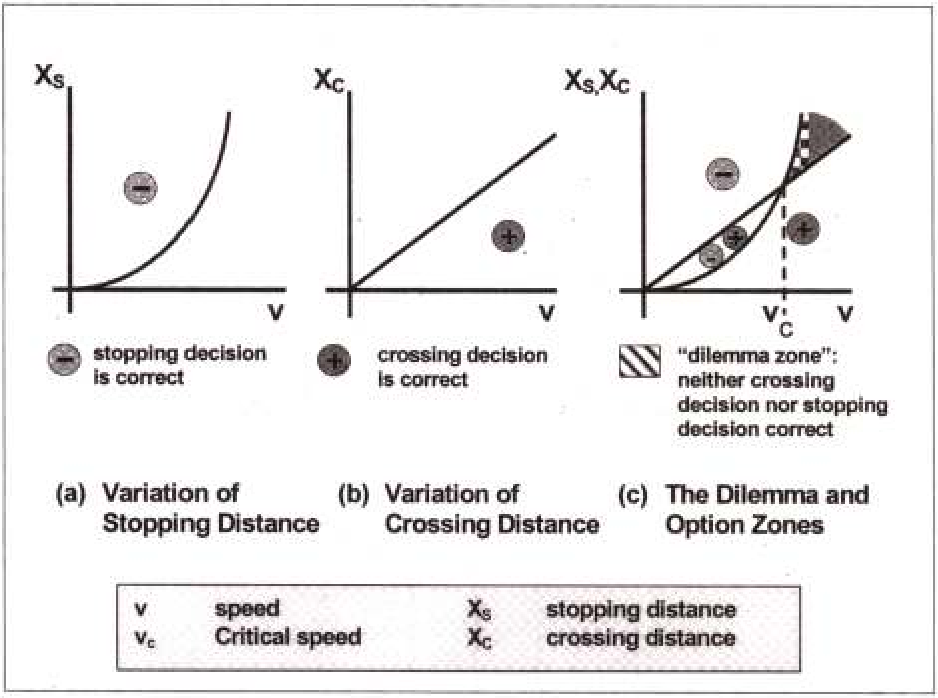


Fig. 3. Variation of Stopping and Crossing Distances with Respect to Approach Speed

influencing intergreen interval as Interco-related random variables, and has arrived at a solution through probabilistic approach. Satish Chandra (1999) applied the equations of Gazis to determine intergreen intervals at a few selected signalized intersections in Delhi urban area, India, under heterogeneous traffic conditions; with the main objective of studying driver behaviour.

From equation (3) it is clear that the important factors that influence intergreen intervals are: (i) the reaction time of the driver; (ii) the approach speed of the vehicle; (iii) the deceleration rate of the vehicle; (iv) the length of the vehicle; and (v) the geometry of the intersection. Under fairly homogeneous traffic conditions, for a given intersection, it is possible to arrive at a value of time that is required for a vehicle to reach the stop line from the option zone [Fig. 3(b)]. Let this time be represented as t_a. Also, the signal-time settings must address the two conflicting objectives of maximizing capacity and safety simultaneously. This can be done by determining the intergreen interval by taking the possible conflict point in the intersection area as the reference point for calculating the components of the intergreen interval (Fig. 4). Let the time taken by a vehicle of a preceding stream to traverse the distance from the stop line to the possible conflict point (the rear of the vehicle reaching the conflict point) in the intersection area, be t_c. Also, let the time taken by a vehicle of the succeeding stream to reach the conflict point (the front

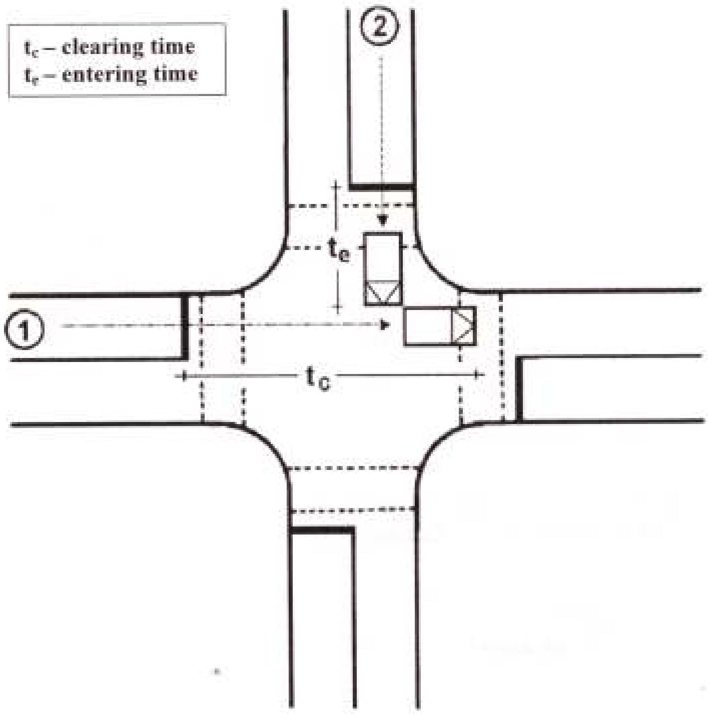


Fig. 4. Clearing and Entering Times with Respect to the Point of Conflict

of the vehicle reaching the conflict point), from the corresponding stop line, be t_e. Then, the required intergreen interval (I), for the given traffic and intersection conditions, can be written as, $I = t_a + t_c - t_e$ (Retzko and Boltze, 1987). With this background information, it will be worthwhile to see how the design of inter green interval is attempted in practice.

3. PRACTICE IN THE USA

The Institute of Transportation Engineers (ITE), USA, an advisory body dealing with guidelines and standards on traffic and transport related aspects, has been modifying its guidelines for determining intergreen interval, over the past, based on the outcomes of several investigations carried out by a number of researchers on the topic. The Table in Appendix I shows how the procedure of determining intergreen interval has undergone change over the past.

It can be seen from the Table that the latest formula for calculation of intergreen interval, as recommended by ITE, is as follows :

$$y = t + \frac{V}{2a + 64.4g} + \frac{W + L}{V} \quad \text{.......................................} (4)$$

where,

y = the intergreen interval in s; t = reaction time of driver in s; a = deceleration rate in ft/s^2; g = grade of approach expressed as a decimal; W = width of the intersection in ft.; L = length of the vehicle in ft.; and V = approach speed of vehicle in ft/s.

From equation (4), it is clear that the green signal for an entering stream of traffic will be provided only after the tail of the leaving stream crossed the intersection area. This, obviously, is a conservative approach leading to greater values of intergreen intervals which may be resented by the road users. In fact, it is enough if the intergreen interval enabled the tail end of the leaving stream of traffic just to cross the conflict area in the intersection before the head of the entering stream of traffic reached the conflict area (Retzko and Boltze 1987). This is the basic principle behind the German method of design of intergreen interval. Thus, the principles and the procedure of determination of intergreen interval, illustrated using equations (1) through (3), discussed under the section, Background, are general in nature and not compatible with the German practice, discussed in the following section.

4. THE GERMAN PRACTICE

As per the German practice (Richtlinien fur Lichtsignalanlagen, Ausgabe 1992-Draft English Version: Guidelines for Traffic Signals, 2003, edited by the German Road

Traffic and Transport Research Association), the intergreen time is given as :

$$T = t_a + t_c - t_e \qquad (5)$$

where,

T = the intergreen interval in s; t_a = the approach time - the time taken by the last vehicle in the approaching stream that crosses the intersection, to reach the stop line of the approach, after the onset of the amber signal, in s; t_c = clearing time - the time taken by a crossing vehicle to reach a point in the intersection, from the stop line, such that the rear of the vehicle is just clear of the possible conflict point with the succeeding stream of traffic, in s; and t_e = entering time - the time taken by the first vehicle of the succeeding stream of traffic, to reach the point of possible conflict in the intersection area, from the stop line of the approach, in s.

The concept can be better understood by considering specific cases as illustrated in the Guidelines for Traffic Signals.

Case 1: Straight-Ahead Traffic

This case is depicted in Fig. 5. hi this case, the approach time (t_a) for straight-ahead vehicles, based on theoretical considerations and a number of field studies under varying roadway and traffic conditions in Germany, has been taken as 3 s. for a maximum allowable speed of 10 m/s. The clearing distance (d_c), as shown in the Fig., consists of two parts: (i) the basic clearing distance (d_b) which is the distance between the stop-line and the point of possible conflict in the intersection area, measured along the centerline of the traffic lane, and (ii) the length of the vehicle. The length of vehicle, as an average, is taken as 6m. Then, the sum of the approach time and clearing time for this case will be,

$$t_a + t_c = 3 + \frac{d_b + 6}{10} \qquad (6)$$

Case 2: Turning Traffic

This case is depicted in Fig. 6. The approach time for turning vehicles, has been fixed as 2 s (a lesser value when compared to straight-ahead traffic because of the unavoidable reduction in approach speed due to curvature). The clearing speed, on empirical basis, has been taken as 7 m/s (relatively, a lesser value based on the same reason cited earlier). The clearing speed will be reduced to a value of 5 m/s when the

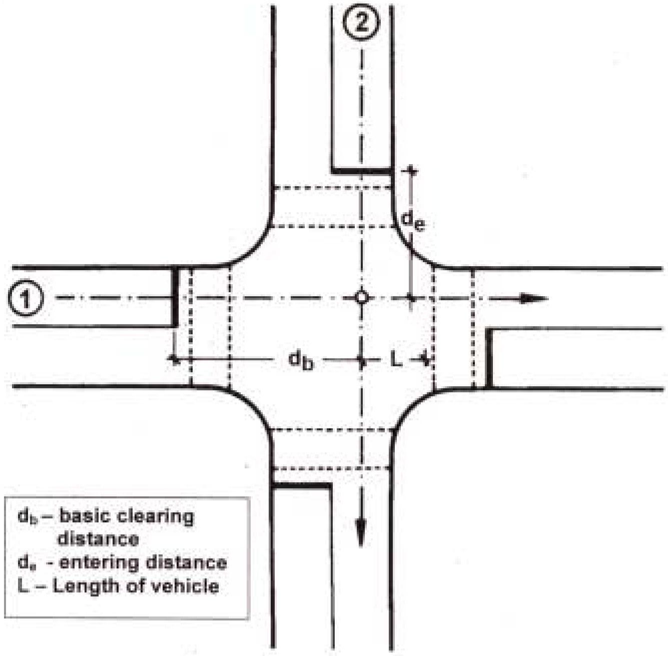


Fig. 5. Clearing and Entering Distances for Straight-Ahead Motorized Vehicles

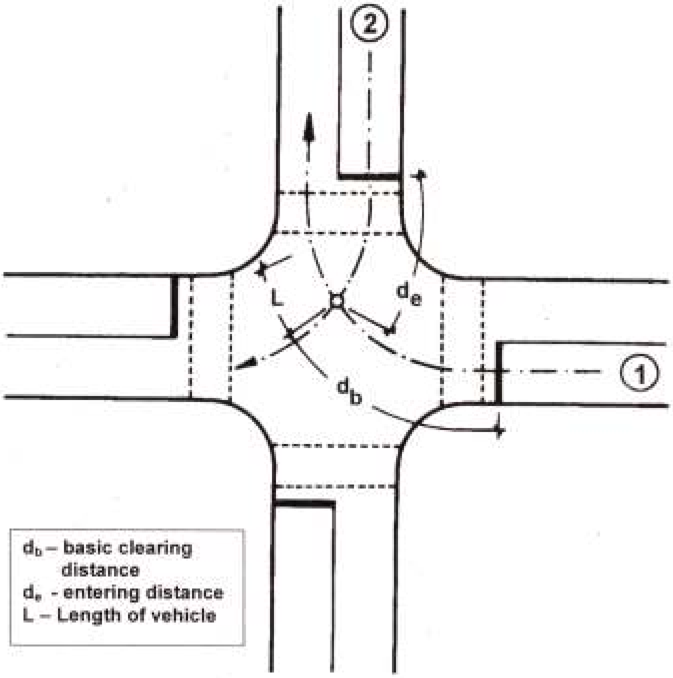


Fig. 6. Clearing and Entering Distances for Turning Motorized Vehicles

radius of the curve (R) along the inner edge of the turning lane is less than 10 m. Thus, the sum of the approach time and clearing time, in this case, will be :

$$t_a + t_c = 2 + \frac{d_b + 6}{7} \text{ when } R \geq 10 \text{ m} \quad \text{........ (7)}$$

$$t_a + t_c = 2 + \frac{d_b + 6}{5} \text{ when } R < 10 \text{ m} \quad \text{........ (8)}$$

Case 3: Bicycle Traffic

This case has been depicted in Fig. 7. The approach time for bicycles, considering the lesser speed of the vehicle, is taken as 1 s. The clearing speed, based on German conditions, has been taken as 4 m/s. It may be noted, by referring to the Fig. that the length of the vehicle has been neglected in calculating the clearing distance (It has been found that the length of bicycles, being less than 2m, may not affect the clearing distance

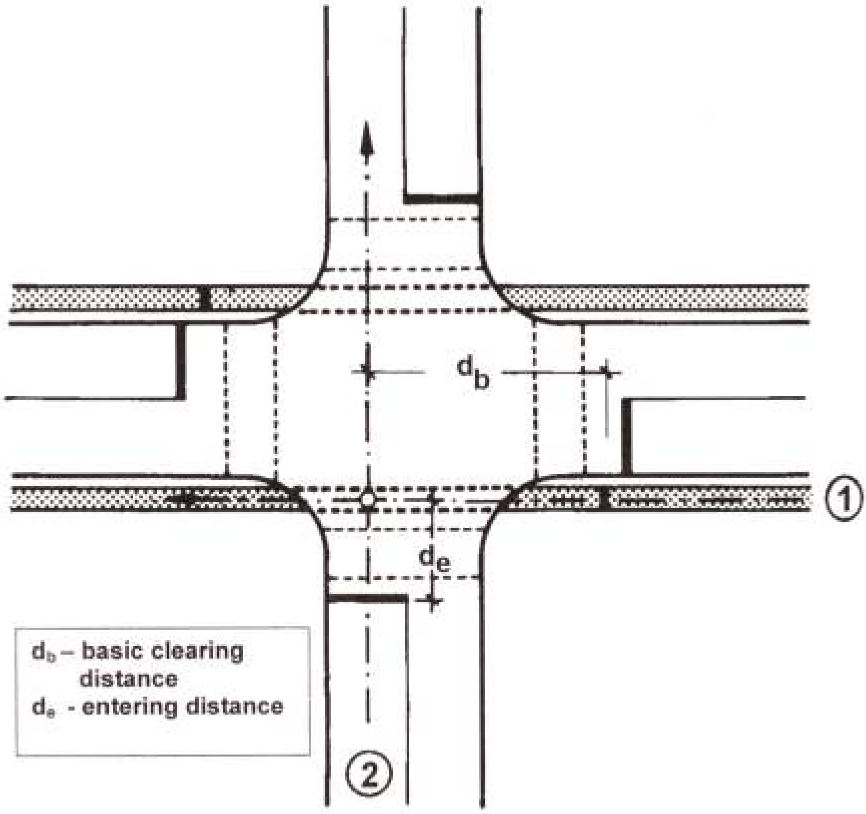


Fig. 7. Clearing and Entering Distances for a Crossing of Bicycles and Motorized Vehicles

in the overall context. Thus, the sum of the approach and clearing times, in this case, will thus be :

$$t_a + t_c = 1 + \frac{d_b}{4} \qquad (9)$$

Case 4: Pedestrian Traffic

This case is depicted in Fig. 8. With reference to this case, it may be noted that, in Germany, the signaling system for pedestrian movements does not have amber light indication. The approach time for pedestrians, considering the very small value of pedestrian speed (assuming that pedestrian will not step on to the road after the onset of red for pedestrian movement), is taken as zero. The clearing speed of pedestrians, under normal circumstances, is taken as 1.2 m/s. When the pedestrian signal has to cater to handicapped or elderly people, a lower value may be taken. However, the value should not fall below 1 m/s, as a very low clearing speed assumed for pedestrian traffic, will

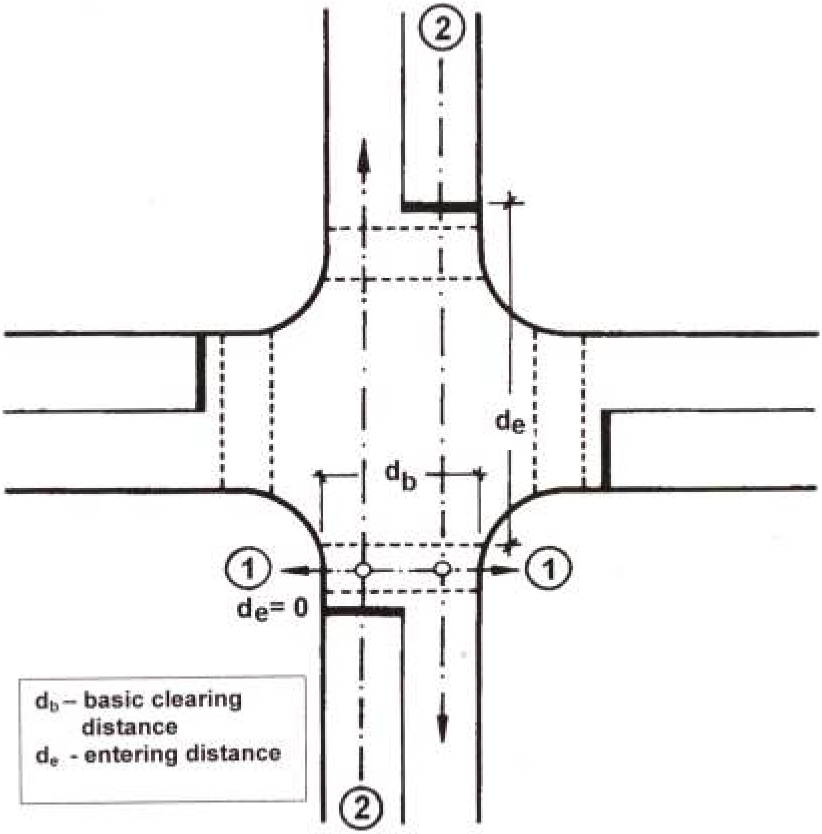


Fig. 8. Clearing and Entering Distances for a Crossing of Pedestrians and Motorized Vehicles

lead to additional delay for other road users. Thus, for a normal case, the sum of the approach and clearing times, here, will be :

$$t_a + t_c = \frac{d_b}{1.2} \qquad \text{.. (10)}$$

Entering Time

In the four cases considered, the method of arriving at the sum of the approach and clearing distances was discussed. The entering time which is a component in the calculation of intergreen interval [equation (5)], is determined by the following procedure. Any motorized vehicle (other than public transport vehicles), on the onset of green signal, is assumed to cross the stop-line at a maximum speed of 40 km/h (based on prevailing speed limits in Germany). The entering time, then, is calculated as :

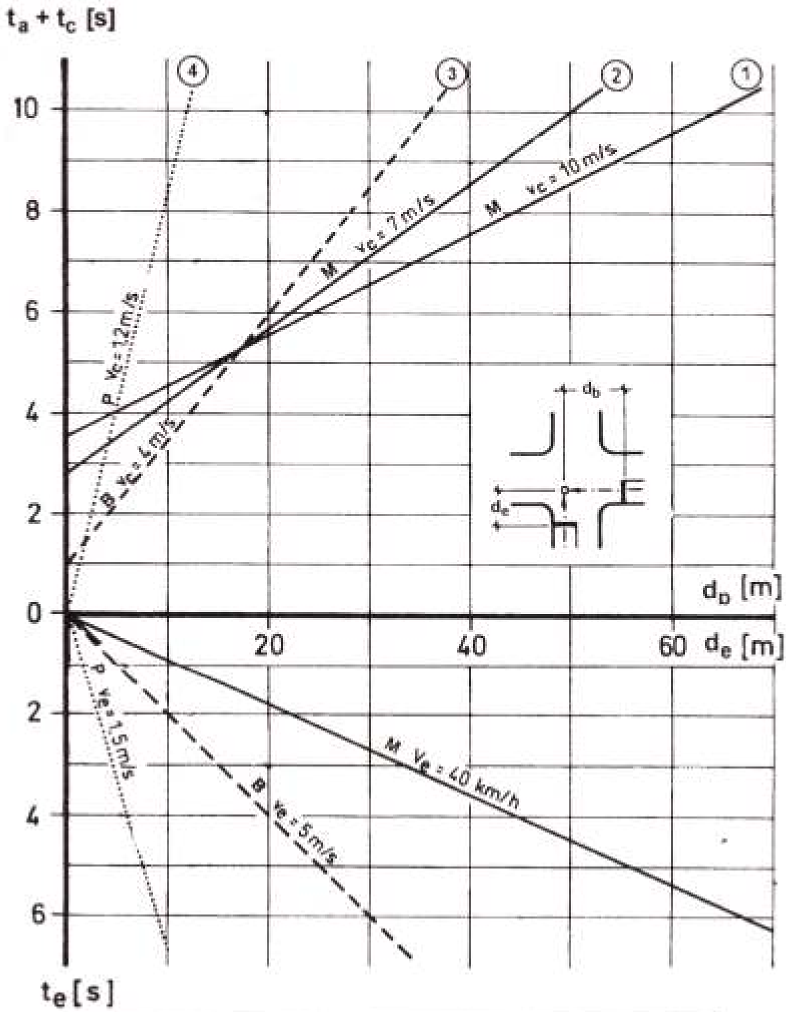
$$t_e = \frac{(3.6)d_e}{40} \qquad \text{.. (11)}$$

Public transport vehicles, considering their low maneuvering capability, are assumed to enter the intersection (cross the stop-line) at a speed of only 20 km/h. Bicycles, if jointly signalized with motorized vehicles, are not relevant in the calculation of entering time. However, if bicycles, on separate lanes, are provided with exclusive signals, then, the bicycles will be assumed to cross the stop-line, at the start of the green signal, at a speed of 5 m/s. If the conflict area between pedestrians and vehicles begin directly at the traffic lane edge, the "entering process" is not taken into account. Otherwise, the entering speed of pedestrians is taken as 1.5 m/s.

The German guidelines include a plot for each of the four different cases relating the basic clearing distance (d_b), the entering distance (d_e) and the thee components of intergreen interval namely, t_a, t_c, and t_e. The plots for the four cases, made on the same set of axes, are shown in Fig. 9. It can be seen that the minimum intergreen interval for any given case can be determined as the difference between the values of (t_a + t_c) and t_e. For example, the intergreen interval for a case involving straight-on motorized vehicles (Case: 1), with a basic clearing distance of 20 m and entering distance of 15 m, the value of (t_a + t_c) is equal to 5.5 (corresponding to 20m), and the value of t_e is equal to 1.3 (corresponding to 15 m). Therefore the intergreen interval required for this case is 5.5-1.3 = 4.2 say 5 s (after rounding to a higher whole number for safety reasons).

5. IMPLEMENTATION

Field implementation of the calculated intergreen interval implies the incorporation of the calculated values in the signal cycle-time setting in such a way that the time allotted to the different streams of traffic to safely cross the intersection, is optimal. For



t_a – approach time ; tc – clearing time; te – entering time
v_c – clearing speed; v_e – entering speed
d_b – basic clearing distance; d_e – entering distance
M – Motorized Vehicles; B – Bicycles; P – Pedestrians

Fig. 9. Plot Showing the Variation of Approach, Clearing, and Entering Times for Various Types of Traffic

this purpose, for a given stream of traffic, the intergreen times have to be calculated for all possible combinations of conflicting traffic flows, and the time intervals that are appropriate have to be chosen for the signal phase involving the subject stream of traffic. The implementation will be easier if pedestrians, bicycles, motor vehicles, and public transport vehicles were considered as four separate groups for the purpose of signaling, though two or more of them may be combined in certain cases. It is usual to compile the calculated intergreen intervals in the form of a matrix for better understanding of the inter-correlation in the timings, between the different traffic streams involved at an intersection. As an illustration of this process, the layout of a typical signalized intersection (under German conditions) with the signals for the different streams of traffic indicated therein, and the corresponding matrix of intergreen intervals for the different streams of traffic, along with the signal timing diagram, is given in Appendix II.

6. APPLICATION FOR MIXED TRAFFIC

The design of intergreen interval in signal-time settings, as indicated earlier, is directly related to the level of traffic safety at signalized intersections. Hence, the design needs special attention, with due consideration to the extent of mix of different types of vehicles in the traffic streams. Traffic in developing countries, such as, India, is highly heterogeneous comprising vehicles of wide ranging static and dynamic characteristics. As could be understood by the foregoing discussions, the most important factors that influence the value of intergreen interval at signalized intersections are: (i) the approach speed of vehicles, (ii) the deceleration rate of vehicles, (iii) the vehicle length, (iv) the reaction time of drivers (v) the width of the intersection, and (vi) the gradient of the approach to the intersection, if any. It can be seen that, of all these factors, the ones that are related to vehicles, are only the first three, namely, approach speed, deceleration rate, and vehicle length. These are the three factors which needs special attention in the case of mixed traffic when compared to homogeneous traffic conditions.

As is evident from the earlier discussions, the intergreen interval needs to be designed exclusively for each of the different types of vehicles passing through an intersection, taking their respective approach speed and deceleration rate into account. The intergreen interval between any two signal phases will then be decided by taking into account the different types of vehicles involved in the phases and their approach, clearing, and entering times. Accordingly, under mixed traffic conditions, as the first step in the design of intergreen interval, the different types of vehicles involved in the traffic are to be grouped based on their approach speeds, deceleration rate, and overall length. Based on the three factors (all considered simultaneously), the vehicles, under Indian conditions, can be grouped as follows.

(i) Bicycles and Tricycles, (ii) Motorised Two-Wheelers, (iii) Mororised Three-Wheelers, (iv) Cars and Light Commercial Vehicles, and (v) Buses and Trucks. Then, for the given intersection, considering its relevant geometric features, the approach, clearing and entering times for the six categories of vehicles are to be calculated separately. The intergreen interval is to be arrived at by considering the vehicle groups that will pass through the intersection in the concerned pair of signal phases.

Out of the two methodologies, for determination of intergreen intervals, discussed earlier (the ITE, USA method and the German method), for a given intersection, the ITE method, if adopted, will give a higher value of intergreen interval (as the method assumes that the succeeding stream can cross the stop-line only after the preceding stream has completely cleared the intersection area), when compared to the German method. Considering the heavy traffic demand at signalized intersections in India, and the consequent need for facilitating the vehicles to clear off the intersection in the shortest possible time, it seems better to adopt the German guidelines for design of intergreen interval.

7. CONCLUDING REMARKS

Though traffic signal cycle-time design, in general, should aim at minimizing overall average delay to vehicles and pedestrians, it should also ensure the required level of safety while the conflicting streams of traffic pass through the intersections. This can be ensured by proper design of intergreen intervals in the signal-time settings. To enhance the level of safety at traffic signals, under heterogeneous traffic conditions, such as, in India, there is a need to develop an appropriate methodology for determination of intergreen intervals in signal time settings, in the light of the practices adopted in other countries.

ACKNOWLEDGEMENTS

This technical Paper is an outcome of the Indo-German collaborative research project work on, "Development of a Methodology for Enhancing Level of Safety at Traffic Signals" being carried out jointly by the authors. The project is funded by the German Federal Ministry of Education and Research (bmb+f). The authors acknowledge the funding provided, which has enabled closer interaction between the authors resulting in the writing of this Paper.

The authors also wish to place on record the assistance rendered by Mr. Achim Reusswig, Research Scholar, Section of Transport Planning and Traffic Engineering, Darmstadt University of Technology, D-64287 Darmstadt, Germany, in preparing this Paper.

REFERENCES

1. Bissel, H. H., and Warren, D. L. (1981). "The Yellow Signal is not a Clearance Interval". ITE Journal, 51(2), 14 - 17.
2. Chang, M.S., Messer, C.J., and Santiago, A.J. (1985). "Timing Signal Change Intervals Based on Driver Behavior." Transportation Research Record 1027, Transportation Research Board, Washington, D.C., 20-30.
3. Easa, S.M. (1993). "Reliability-Based Design of Intergreen Interval at Traffic Signals." Journal of Transportation Engineering, ASCE, 119(2), 255-271.

4. Gazis, D., Herman, R., and Marududin, A. (1960). "The Problem of Amber Signal Light in Traffic Flow." Operations Research, 8(1), 112-132.
5. German Road Traffic and Transport Research Association FGSV (Editor) (1992/2003). "Signal Program Design." Guidelines for Traffic Signals (Draft English Version), 16-29.
6. Horst, R. V. (1986). "Drivers' Decision-Making at Signalized Intersections: An Optimization of the Yellow Timing." Traffic Engineering and Control, 27(12), 615-622.
7. Lin, F.B. (1986) "Timing Design of Signal Change Intervals" Transportation Research Record 1069, Transportation Research Board, Washington D. C., 46-54.
8. Lin, F.B., Cooke, B.D. and Vijayakumar, S.(1987). "Utilization and Timing of Signal Change Interval" Transportation Research Record 1114, Transportation Research Board, Washington D. C., 86-95.
9. Lin, F., and Vijakumar, S., (1988). "Timing Design of Signal Change Interval." Traffic Engineering and Control, 29(10), 531-536.
10. May, A.D. (1968). "Clearance Interval at Traffic Signals". Highway Research Record 221, Transportation Research Board, Washington D.C. 41-71.
11. Oslon, P. L., and Rothery, R. W. (1972). "Deceleration Levels and Clearance Times Associated with the Amber Phase of Traffic Signals." Traffic Engineering and Control, 42(4), 16-19.
12. Parsonson, P. S., and Santiago, A. J. (1980). "Design Standards for Timing the Traffic Signal Clearance Period Must be Improved to Avoid Liability." Compendium of Technical Papers, Institute of Transportation Engineers, Washington, D.C., 67-71.
13. Retzko, H. G., and Boltze, M. (1987). "Timing of Intergreen Periods at Signalized Intersections: The German Method." ITE Journal, 57(9), 23-27.
14. Satish Chandra (1999). "Driver Behaviour at Signalised Intersection at On-Set of Amber Time" Highway Research Bulletin 61, Indian Roads Congress, New Delhi, 161-177.
15. Sheffi, Y., and Mahmasani, H. (1981). "A Model of Driver Behavior at High-Speed Signalized Intersections." Transportation Science, 15(1), 50-61.
16. Williams, W. L. (1977). "Driver Behavior During the Yellow Interval." Transportation Research Record 644, Transportation Research Board, Washington, D.C., 75-78.
17. Wortman, R. H. and Fox, T.C. (1986). "A Reassessment of the Traffic Signal Change Interval". Transportation Research Record 1069, Transportation Research Board, Washington D. C., 62-68.
18. Wortman, R. H. and Mathias, J. S. (1983). "Evaluation of Driver Behaviour at Signalized Intersections" Transportation Research Record 904, Transportation Research Board, Washington D. C.

Appendix I

History of Practices Adopted for Signal Change Interval based on the Recommendations of ITE, USA

Year	Source	Equations(s)	Discussion	All-Red Interval
1941	ITE Traffic Engineering Handbook, 1st edition	$y = 0.8 + 0.04V(0.682) + \frac{0.7W}{V(0.682)}$ $y = \frac{(W+S)}{V} - \frac{D}{V_c}$	Two methods proposed. Either equation is suggested. In the second eqn. S is drawn from a Table of observed values	Not Used.
1950	ITE Traffic Engineering Handbook, 2nd edition	$y = 0.8 + 0.04V(0.682) + \frac{0.7W}{V(0.682)}$ $y = \frac{(W+S)}{V} - \frac{D}{V_c}$	Same as 1941 Case	Some use all-red for intervals above 5 sec. Some use 1-2 sec. of all-red at all intersections
1965	ITE Traffic Engineering Handbook, 3rd edition	$y = t + \frac{V}{2a}$ $y = t + \frac{V}{2a} + \frac{W+L}{V}$	Based on the 1960 work of Gazis et al. 1st eqn. represents the minimum duration of yellow. 2nd eqn. gives the minimum value plus time for vehicles to clear intersection.	If hazardous conflict is likely, and the calculated value exceeds five seconds, all-red is used.
1976	ITE Transportation and Traffic Engineering Handbook, 1st edition	Some equations as in 1965	Same eqns. and purpose as in 1965. First eqn. is for minimum duration of yellow. However, the second equation is now called the non-dilemma yellow.	If a hazardous conflict is likely, and the calculated value exceeds five seconds, all-red of 2 to 3 seconds is provided.
1982	ITE Transportation and Traffic Engineering Handbook, 1st edition	Same equations as in 1965 and 1976	Same eqns. As in 1965 and 1976. First used in areas with permissive yellow rules, minimum value of 3 sec. Second used in areas with restrictive yellow rules.	If a yellow indication of greater than 5 sec. is required, an all-red can be used.

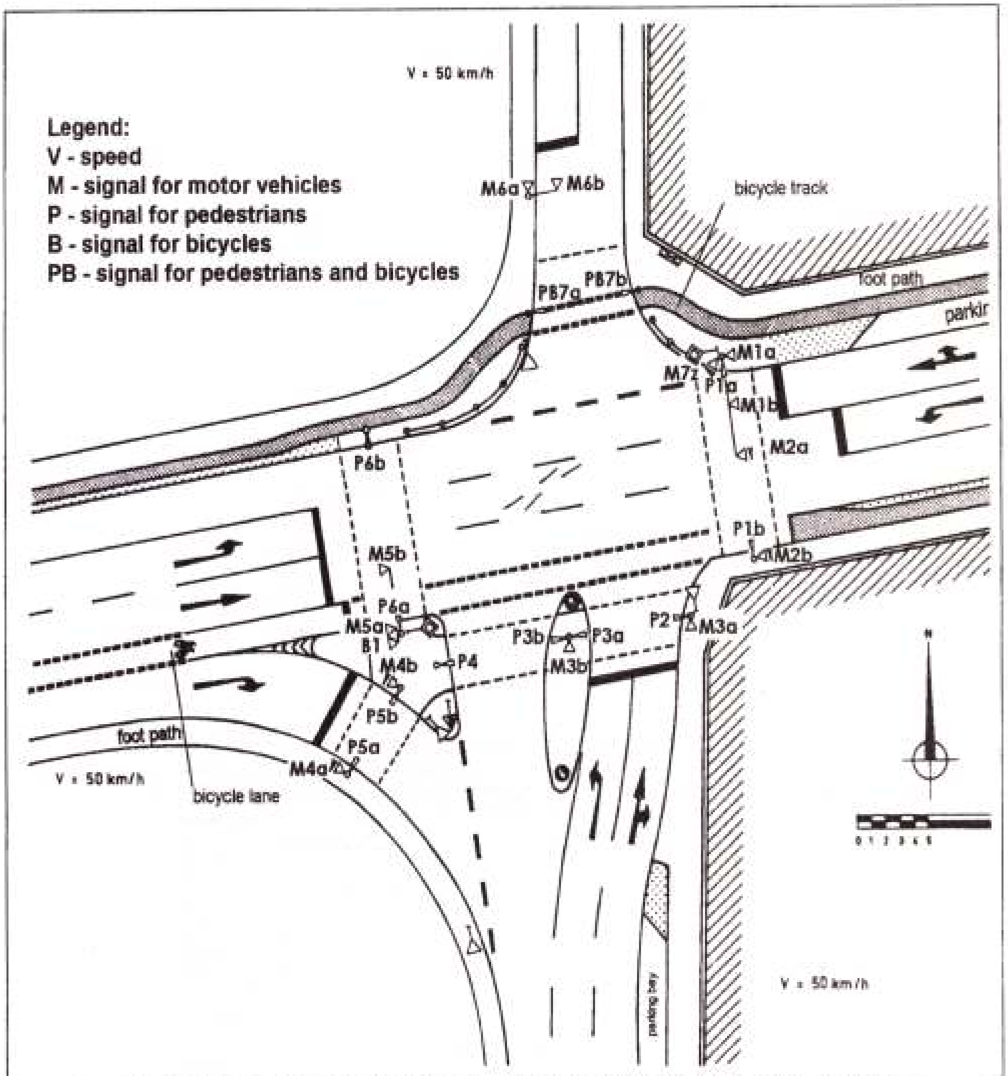
Appendix I (Contd.)

History of Practices Adopted for Signal Change Interval based on the Recommendations of ITE, USA

Year	Source	Equations(s)	Discussion	All-Red Interval
1982	ITE Manual of Traffic Signal Design	$y = t + \frac{V}{2a} + \frac{W+L}{V}$ $y = t + \frac{V}{2a + 64.4g} + \frac{W+L}{V}$	Equation calculates non-dilemma change period, notes as yellow plus all-red. 1st eqn. is same as 1965 and 1976. The 2nd eqn. includes effect of grade on stopping ability. Some use first two terms rounded up to the nearest 0.5 sec. as yellow interval.	Depends on agency, balance of time is all-red if required to clear intersection or for safety at wider intersections.
1985	ITE "Determining Vehicle Change Intervals: A proposed Recommended Practice."	$y = t + \frac{V}{2a + 64.4g}$ $r = \frac{W+L}{V}; r = \frac{P}{V}; r = \frac{P+L}{V}$	1982 eqn. divided into 2 equations. First is for yellow interval. If used, second is all-red clearance.	If clearance interval is used, it should be all-red. One of the three depending on area of conflict and policy of agency.
1992	ITE Traffic Engineering Hnadbook, 4th edition	Same equations as in 1985	Same equations and procedures as in 1985.	Same as in 1985.
1999	ITE Traffic Engineering Handbook, 5th edition	$y = t + \frac{V}{2a + 64.4g} + \frac{W+L}{V}$	The third term of the kinematic equation is added back to the eqn. as it was in 1982. Application requires exercise of engineering judgement.	For intervals longer than 5 sec. an all red is typically used. Some use value of third term as all-red.

Note : The equations are represented in U.S. Standard Units. For ease of presentation, they have all been expressed with a uniform set of variables. The variables in the equations represent the following parameters: a=deceleration rate, in ft./s^2 ; D = distance from potential conflict point and position of conflicting movement, in ft. ; g = grade of approach, expressed as a decimal; L = length of the vehicle, in ft.; P = width of intersection, in ft. measured from the rear side stop line to the far side of the farthest conflicting pedestrian crosswalk along the actual vehicle path; r = length of all-red in sec.; S = stopping distance, in ft.; t = perception-reaction time, in sec.; V = approach velocity in ft/sec.; V_c = Approach velocity of conflicting vehicle; in ft/sec.; and W = width of intersection in ft.

Appendix II



Source: Guidelines for Traffic signals, German Road Traffic and Transport Research Association.

Fig. A(1) Layout of Intersection

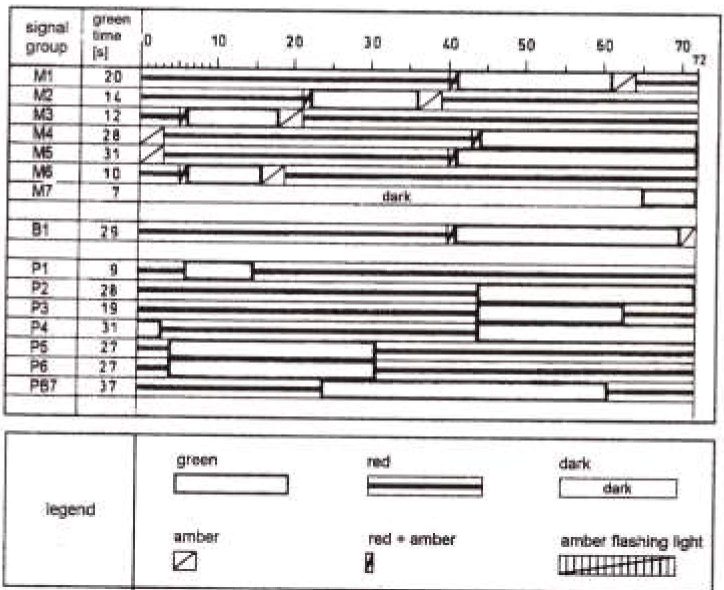
Fig. A (1) shows the layout of a typical signalized intersection under German Conditions (keep-Right Traffic). It can be seen that the geometry of the intesection has been governed by the traffic volume on the legs of the intersection and the available land space at the location. It may also be noted that the intersection design has taken into account the permitted on-street parking in the vicinity of the intersection. There are basically three sets of signals, one each for motor vehicles, bicycles, and pedestrians provided on each leg of the intersection. The intergreen interval calculated for the signal setting of this intersection is shown in the form of a matrix, in Fig. A (2). The timing diagram for the signal cycle is shown in Fig. A (3).

Appendix II (Contd.)

	starting signal groups														
ending signal groups	M1	M2	M3	M4	M5	M6	M7	B1	P1	P2	P3	P4	P5	P6	PB7
M1			4			4	4		4					7	
M2			5	8	5	4		5	2		8	8			
M3	6	4			4			1		4	4				6
M4		2				2							4		
M5		3	6			5			6					3	
M6	6	6		12	7			4			7	7			6
M7															
B1		2	6			2			8					2	
P1	10	7			6			5							
P2			6												
P3		4	6			3									
P4		4				3									
P5				5											
P6	8				8			10							
PB7			3			6	4								

Source: Guidelines for Traffic signals, German Road Traffic and Transport Research Association.

Fig. A(2) Matrix of Intergreen Interval



Source: Guidelines for Traffic signals, German Road Traffic and Transport Research Association.

Note: Signal group M1 includes the signals M1a and M1b; the same applies to the other signal groups.

Fig. A(3) Signal-Timing Diagram