Proposed methodology for designing the signal change interval.

Mohammed Mujeebullah. Khan

Civil Engineering

Decembeer 1996

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Existing yellow interval timing were evaluated in relation to violations and rear-end conflicts. The existing timing was found to be significantly less than the 85th percentile yellow interval demand and the yellow obtained by the ITE method. A 10 to 30% increase in the existing yellow interval timing will significantly decrease the run-red violations and thereby reduce the risk of right-angled accidents.

The developed 85th percentile yellow demand model was compared with the ITE developed yellow interval timing. The ITE method gives little conservative estimate of yellow timing compared to the developed model, but it was found to give incorrect yellow interval timings for approaches with low approach speeds.

Proposed Methodology for Designing the Signal Change Interval

by

Mohammed Mujeebullah Khan

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
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UMI Number: 1385820

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COLLEGE OF GRADUATE STUDIES

This thesis, written by

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under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements for the degree of

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11/6/97
Date

كلية الدراسات العليا
COLLEGE OF GRADUATE STUDIES

for

my beloved parents

and

brothers

Acknowledgments

All praise is due to Allah *Subhanahu wa ta'ala* for giving me the courage and patience to complete this work. Acknowledgement is due to K.F.U.P.M for providing me financial support during my stay here.

I wish to express my sincere gratitude and appreciation to my thesis advisor Dr.Shukri Al Senan for his continued support, advice and encouragement throughout the period of my thesis. I like to thank Dr.Gökmen Ergün who served as the co-chairman of my thesis committee for giving me the necessary help and guidance during critical junctures of this study. Appreciation is due to Dr.N.T.Ratrout and Dr.H.M.Al Ahmadi for their helpful comments.

Last but not the least I would like to thank my friends in North Compound and the K.F.U.P.M community in general for making my stay here a pleasant one.

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List of Abbreviations

ITE : Institute of Transportation Engineers

Y_d : Yellow interval demand, sec.

Y_{ITE} : Yellow interval obtained by ITE method, sec.

Y_a : Actual or existing yellow interval, sec.

Y_m : Mean yellow interval demand, sec.

C : Correction factor, sec.

X : Vehicle supply, veh/cycle.

AR : All-red interval, sec.

VEY/Cycle : Vehicles entering during yellow per cycle

VER/Cycle : Vehicles entering during all-red per cycle

TOTVEYR/Cycle : Total vehicles entering during yellow and all-red per cycle

SVREC/Cycle : Slow vehicle rear-end conflict per cycle.

TOTREC/Cycle : Total rear-end conflict per cycle

TOTCI : Total change interval.

NCL : Number of clusters.

CCC : Cubic clustering criterion

PSF : Pseudo F statistic

PST2 : Pseudo T-square statistic.

Abstract

Name: MOHAMMED MUJEEBULLAH KHAN

Title: PROPOSED METHODOLOGY FOR DESIGNING THE SIGNAL CHANGE INTERVAL

Major Field: CIVIL ENGINEERING

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Master of Science Degree

King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

December 1996

ملخص الرسالة

الاســــــــــم : محمد مجيب الله
العنـــــــــوان : مقترح لتصميم فترة الاشاره الضوئيه الصفراء
المجال الرئيسي : هندسه مروريه – الهندسة المدنية
تاريـخ الدرجة : ديسمبر ١٩٩٦ م

ان تعيين فترة الاشاره الضوئيه مهم جداً في عملية تصميم توقيت الاشاره الضوئيه . أن الهدف الرئيسي لهذه الدراسه هو تصميم الفتره الضوئيه الصفراء بحيث تتناسب وسلوكيات السائقين .ان الوقت الذي تحتاجه أخر سياره واقفه عند الاحمر تعبر خط التوقف (يسمى مقدار الطلب للاصفر) قد وجد ان له علاقه ذات دلاله مع وفرة السيارات (ويعرف هذا بعدد السيارات الواقفه عند خط التوقف لمدة الخمس الثواني الاولى . ولقد كان بالامكان الربط بين المئوي الـ ٨٥ لمقدار الطلب للاصفر (85th Percentile) ووفرة السيارات ، حيث كان بالامكان ربطهما في إنموذج . وبالامكان استخدام هذا الانموذج لعملية توقيت فترة الاشاره الضوئيه الصفراء ليعطي توقيتاً سليماً وصحيحاً .

ولقد تم في هذه الدراسه ايضاً الربط بين المخالفات للضوء الاصفر والتضاربات الحركيه من الخلف بين التوقيت المعمول به لنجد ان التوقيت المعمول به هو أقل مما يعطيه الانموذج بل وأقل ايضاً مما تعطيه طريقة الـ ITE .

لذا فإن زيادة قدرها من ١٠ الى ٣٠ بالمائه للتوقيت المعمول به كفيل بتخفيض مستوى المخالفات للضوء الاصفر وبالتالي تخفيض حوادث التصادم الزاوي القائم .

ولقد وُجد ايضاً ان طريقة الـ ITE تعطي تصميم للاصفر اكثر من الحاجه ومما يعطيه الانموذج المطور ولكن الـ ITE تُعطي نتائج غير صحيحه عند مداخل التقاطعات والتي تتصف بسرعات منخفضه .

درجة ماجستير العلوم
جامعة الملك فهد للبترول والمعادن
الظهران ، المملكة العربية السعودية
ديسمبر ١٩٩٦

Chapter 1

INTRODUCTION

1.1 General

Signal change interval (yellow phase) is an indispensable element of a signal operation. It is used in a signal cycle to allow safe transfer of the right-of-way. The purpose of the yellow indication is to alert approaching drivers that a red light will be displayed shortly [1]. During the change interval the vehicle can legally enter the intersection. The all-red period which is followed by the yellow interval is called the clearance interval which is the means by which the intersection is cleared [2].

If the change interval is not properly timed, operation at the intersection becomes dangerous, due to the fact that some drivers may be forced to choose between abruptly stopping or proceeding into the intersection on red. Abrupt stopping may cause rear-end crashes, while crossing on red may cause right-angle crashes [3].

1.2 Problem Statement

In Saudi Arabia, the current practice in designing the change interval (CI) is to use a yellow interval in the range of 2.9 - 3.10 sec . This timing is of concern because of the following:

1. It is based on a rule of thumb, rather than on any standard method. Moreover there is no clear criteria or guidelines to set the yellow interval timing at signalized intersections.

2. In a study done in Riyadh [4], run-red violations and rear-end conflicts occurred at a higher rate at signalized intersections indicating the inappropriateness of the yellow interval timing.

An appropriate design of the change interval is normally achieved through accommodation of the geometrical and traffic characteristics as reflected by recommended practice [2]. There is however, an indication in literature that the driver behavior is as important a factor as the geometric and traffic characteristics [5, 6, 7].

1.3 Goals and Objectives

The main goal of the study is to evaluate the existing yellow timing procedures and to design the yellow interval that would accommodate driver behavior at signalized intersections in the Eastern Province of Saudi Arabia. This goal will be achieved by the following specific objectives:

1. Evaluating existing yellow interval timing in relation to violations and rear-end conflicts.

2. Developing a methodology for designing the yellow interval timing which is based

on driver behavior at signalized intersections.

3. Validating the developed methodology.

4. Comparing the developed method for timing the yellow interval with the method used by the Institute of Transportation Engineers.

Chapter 2

LITERATURE REVIEW

2.1 General

Determination of the change interval is a crucial step in signal timing. Whereas other aspects of timing focus on the efficiency of moving traffic through a signalized intersection, the change interval relates directly to safety, specifically those elements associated with reassigning the right-of-way to conflicting traffic streams [5].

2.2 Diagnostic Tools For Assessing Change Interval - Dilemma Zone and Option Zone

During the change interval the decision for a driver to stop depends on the speed of the vehicle, the distance from the stop-line and the driver behavior. In ideal conditions, the decisions of drivers should be exactly the same for all drivers as shown in Figure 2.1. But in reality the decisions are not similar; and there is a

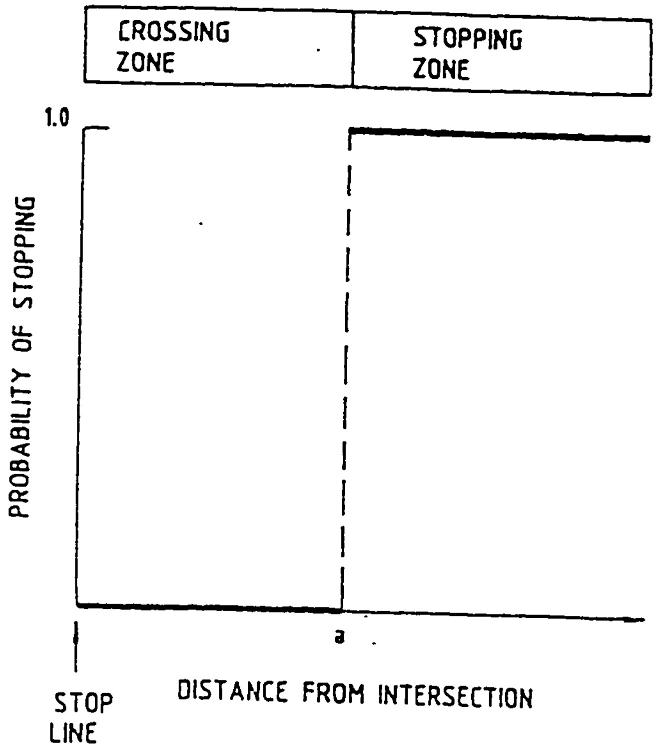


Figure 2.1: An ideal probability function of stopping.

probability distribution of stopping as a function of approach speed and distance from the stop-line as can be seen in Figure 2.2. These probability distribution curves are for United States conditions.

The distance from the stop-line of the intersection is divided into two zones: the *dilemma zone* and the *option zone*. In the dilemma zone, the driver has to make one of the two dangerous decisions: either to stop at a high deceleration rate and take a chance of being hit by a rear-end vehicle, or continue driving and take a chance of being hit by a right angle vehicle. The second zone is the option zone, in which the driver can either stop, or enter the intersection prior to the onset of the red light. The presence of two legitimate options will split the drivers decisions either to stop or go and this confusion may increase the risk of rear-end accidents [8].

The ability of a driver either to cross the stop-line or to stop is based on deterministic normative values. It is usually assumed that a deceleration takes place at a

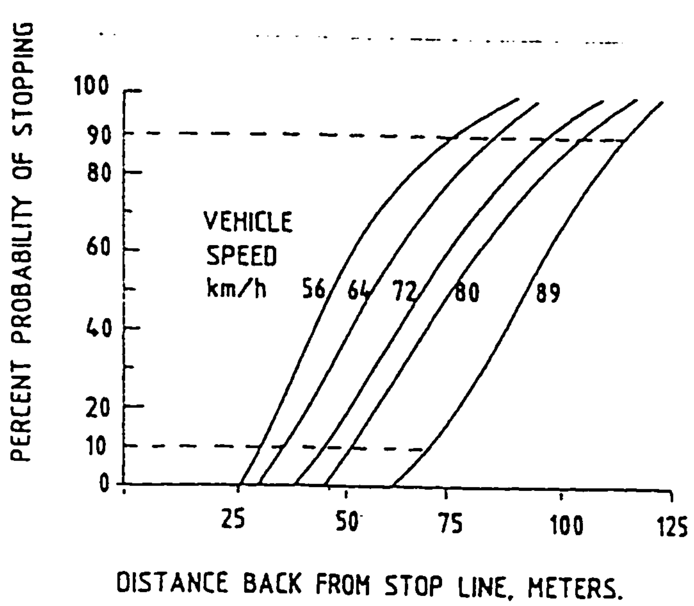


Figure 2.2: The probability of stopping as a function of approach speed and distance from stop-line.

rate of about $10 ft/sec.^2$ and that when there is an attempt to cross the intersection the driver will continue at a constant speed or accelerate at a rate of $5 ft/sec^2$. Figure 2.3 presents the shape of the dilemma and option zones as a function of approach speed and distance from the stop-line [9].

It is important to note that these zones described under normative deterministic assumptions are what a driver can and may do in each zone, but they do not describe what a driver will actually do, not even in the stochastic sense. Thus, it can be concluded that dilemma and option zones are tools for diagnostics; they are not, and they cannot describe, the actual behavior of drivers.

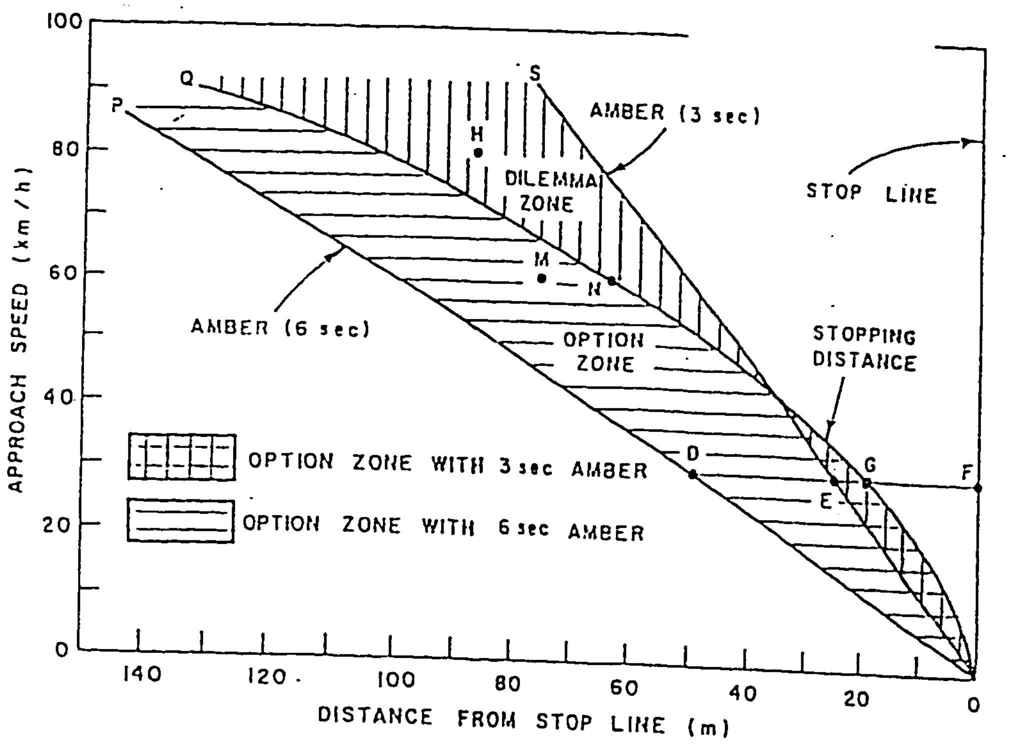


Figure 2.3: Dilemma zone and option zone as a function of approach speed and distance to stop-line.

2.2.1 Quantification of Dilemma Zone Boundary - Gazi's Traditional Equation

The concept of a 'dilemma zone' was introduced in a qualitative form by Gazi et. al. [10] in 1960. Gazi's reported that if the yellow signal time duration is below a threshold value, some approaching drivers can neither stop nor clear the intersection before the red signal onset, such drivers are said to be in the dilemma zone. They calculated the dilemma zone boundary in terms of speed of travel and distance from intersection at yellow signal onset. After quantifying the dilemma zone boundary they calculated the yellow signal time duration threshold at which the dilemma zone disappears. Gazi's equation for determining the required length of yellow interval is given below:

$$Y = t + \frac{v}{2a} \tag{2.1}$$

Where,

Y = Yellow interval.

t = Perception/reaction time of the driver.

v = Vehicle approach speed.

a = Deceleration rate.

The above equation represents the time required for a driver to come to a stop after the yellow interval begins. Gazi suggested a reaction time of 1.0 sec. and deceleration rate of $10ft/sec^2$ to be used in the equation.

The above equation was modified by Parsonson [11] who introduced the grade of the approach 'G' in the equation so as to account for its effect on the decelera-

tion rate. The resulting equation for determining the length of the yellow interval is given below. The following equation is also recommended by the Institute of Transportation Engineers [2].

$$Y = t + \frac{v}{2a \pm 2gG} \tag{2.2}$$

A list of procedures found in literature for quantifying the yellow interval timing are summarized in Table 2.3 under section 2.5.

2.2.2 Elimination of Dilemma Zone and Option Zone

A proper design of the yellow interval will eliminate the dilemma zone and thereby eliminate the risk of right-angled accidents. On the other hand it is difficult to completely remove the option zone and therefore difficult to eliminate totally the rear-end accidents. One way of reducing the rear-end and right-angle accidents is in the use of an actuated traffic signal, where the green phase is extended to allow approaching vehicles to go without a yellow indication.

Green extension systems can also be used in eliminating these zones. In these systems, boundaries of the zones are determined and vehicle detector loops are placed. The presence of vehicles in these zones will delay the termination of green and hence eliminate rear and right angled accidents [8].

2.3 Analysis of Driver Behavior to Change Interval

2.3.1 Traffic Characteristics

In most of the research done on change interval, the driver behavior at the onset of the yellow interval was examined in relation to the distance of the vehicle from the stop-line and its approach speed.

In 1961, Crawford and Taylor [7] observed driver decisions using eight subjects in repeated runs. In this experiment subjects faced the onset of yellow at varying speeds (20-60mph) and at varying distances from the traffic signal (50-350ft). Yellow interval duration was fixed at 3sec. At a given speed, the percentage of drivers that stopped was found to increase linearly with the logarithms of distance from the intersection. Stop-go decisions of drivers free to cross an urban intersection (i.e. drivers whose path were not blocked by other stopping vehicles) were studied by William [6] in 1977 . Logarithmic relationships between approach speed and stopping distance for constant percentages of drivers stopping were found to describe the data adequately.

Chang et. al. [12] found that the probability of drivers stopping or clearing was affected by approach speeds and the distance to the intersection at the yellow onset. Various studies suggest that the percentage of drivers stopping depends on their approach speed and distance from the intersection when the signal changes.

Early literature [6, 10, 7, 13, 12] indicates that the researchers have generally attempted to analyze the behavior of drivers in terms of the distance from the intersection at the onset of yellow interval. However a recent analysis of the first

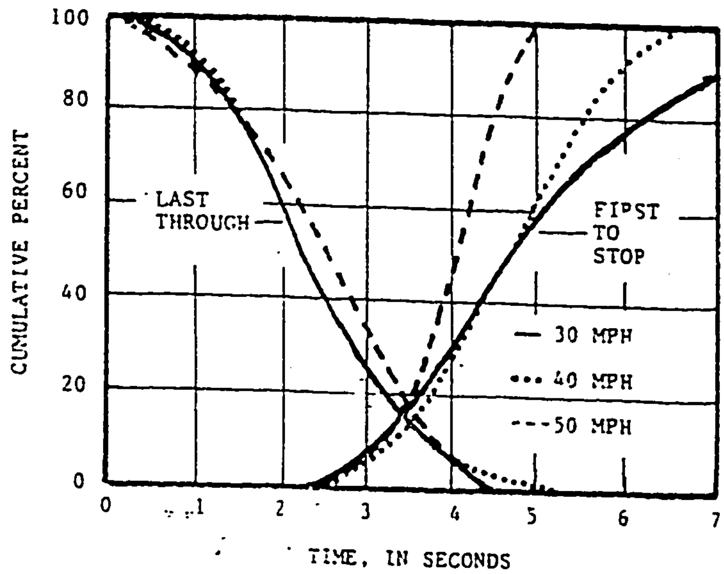


Figure 2.4: Time from intersection at onset of yellow interval: 30, 40 and 50 mph approach speeds.

vehicle to stop at an intersection and the last vehicle to clear the intersection was made by Wortman and Fox [5, 14, 15] at some signalized intersections in Arizona, U.S.A.

A number of analyses involving the time from the intersection were undertaken in an attempt to identify the effect of the approach speeds and intersection geometric conditions on the driver behavior. Figure 2.4 shows the time from the intersection at the onset of the yellow interval for the first vehicles to stop and the last vehicle through the intersection for approach speeds of 30, 40 and 50 mph. The curves are plotted showing the cumulative percent. From field data, the first vehicle to stop at all the approach speeds was approximately 2sec. from the intersection [5].

For the last vehicles through the intersection, the curves for the various approach

speeds show considerable similarity. For signal change interval timing purposes, the critical section of the curve is at the lower percentages. For example, the curves indicate that regardless of the approach speed, approximately 95 percent of the last vehicles through the intersection took 4sec or less from the onset of yellow to clear the intersection. For all approach speeds, the 4sec. value corresponding to the 5th percentile vehicle is quite consistent. Further examination of the lower portion of the curves for the two groups of vehicles reveals a fact that has a major implication in terms of considering the required yellow interval. The time for the last vehicle through the intersection is more critical than that for the first vehicle to stop; thus the determination of the yellow interval should be a function of the time for the last vehicle through the intersection [5].

Lin et. al. [1] using the same concept given by Wortman and Fox [5], determined the yellow interval demand as the time elapsed from the onset of yellow till the last entering vehicle reached the stop-line. Using this yellow interval demand, a uniform yellow interval timing was calculated which satisfied the needs of most of the drivers. Based on field observations, Lin et. al. [1] found that, the yellow interval demand at a particular intersection is a function of vehicle supply (number of vehicles present during the 5sec. of travel time after the onset of yellow), and the vehicle supply is in turn a function of approach volume, signal coordination and type of signal control. He suggested that the yellow interval demand can be modeled as a function of vehicle supply in order to set a non-uniform yellow interval at signalized intersections.

Similarly Chang et. al. [12] found that 95% of the vehicles going through the intersection took less then 4.5 sec to cross the intersection from the onset of yellow. The Texas Transportation Institute (TTI) [16] revealed similar findings as mentioned

by Wortman and Fox, Lin et. al. and Chang et. al. and showed that the 95th percentile time value for all approach speeds is about 4 to 4.5 sec. Furthermore, the results of this analysis done by Wortman and Fox [5], Lin et al and Chang et al along with the reported findings from the TTI study support the concept of a uniform yellow interval which has also been advocated by earlier researchers [6, 13, 12].

2.3.2 Length of the Yellow Interval

It is established in several studies [17, 13, 12, 18] that the driver behavior does not change as a function of amber phase durations, refuting the early notion that the drivers tend to utilize yellow as part of the green when the yellow phase is set too long [19]. The behavior of drivers in response to the length of the yellow interval was studied by several researchers [17, 13, 12, 18]. In a study conducted by May [17] in 1968, in which the percentage of drivers stopping as a function of approach speed and distance from the intersection were determined for two yellow settings (initial and extended) at two intersections (1 urban and 1 rural), both with and without advance signing and additional pavement markings. One of the findings of this study was that the number of cars entering the intersection after red onset was reduced when yellow duration was extended.

Similarly, Chang [12] in his study found that the percentage of drivers stopping after yellow onset does not depend on the duration of the yellow phase, implying that the traffic flow was same during the yellow interval irrespective of the duration. The above results tends to support the findings obtained by Olson and Rothery [13] and Hulscher [18].

Figure 2.5 shows the results of a study [11] where the amber phase was extended from 3 sec. to 5 sec. During the first 3 months, there was a decrease in the number of drivers running on red, but after 18 months of habitation period the drivers adapted to the changes in the intergreen time with a little shift towards running on red, but on the whole a significant long term decrease in the red runners can be noted. From the above finding it can be concluded that the traffic flow does not change with the duration of the yellow interval, but the percentage of vehicles entering on red is reduced when the yellow interval time is extended.

The effect of extending the yellow interval in relation to conflicts and accidents was also studied by several researchers [3, 20, 10]. It was found that potential intersection conflicts (right-angled) could virtually be eliminated with a small increase in the duration of the yellow phase. Zador et. al. [3], after his study at 91 intersections in the United States found that the group of intersections with less adequate average clearance intervals had higher crash rates than those with more adequate average clearance intervals.

It should be made clear that increase in the yellow interval above the required will no doubt decrease the number of vehicles entering on red or the right-angled conflicts but on the other hand it will also increase the rear-end conflicts due to an increased option zone.

2.3.3 Effect of Enforcement

The driver behavior to change interval was studied by many researchers [21, 14] by applying enforcement policies. In one such study the effect of enforcement by deploying a police vehicle at the site was studied [21, 14] and it was found to reduce

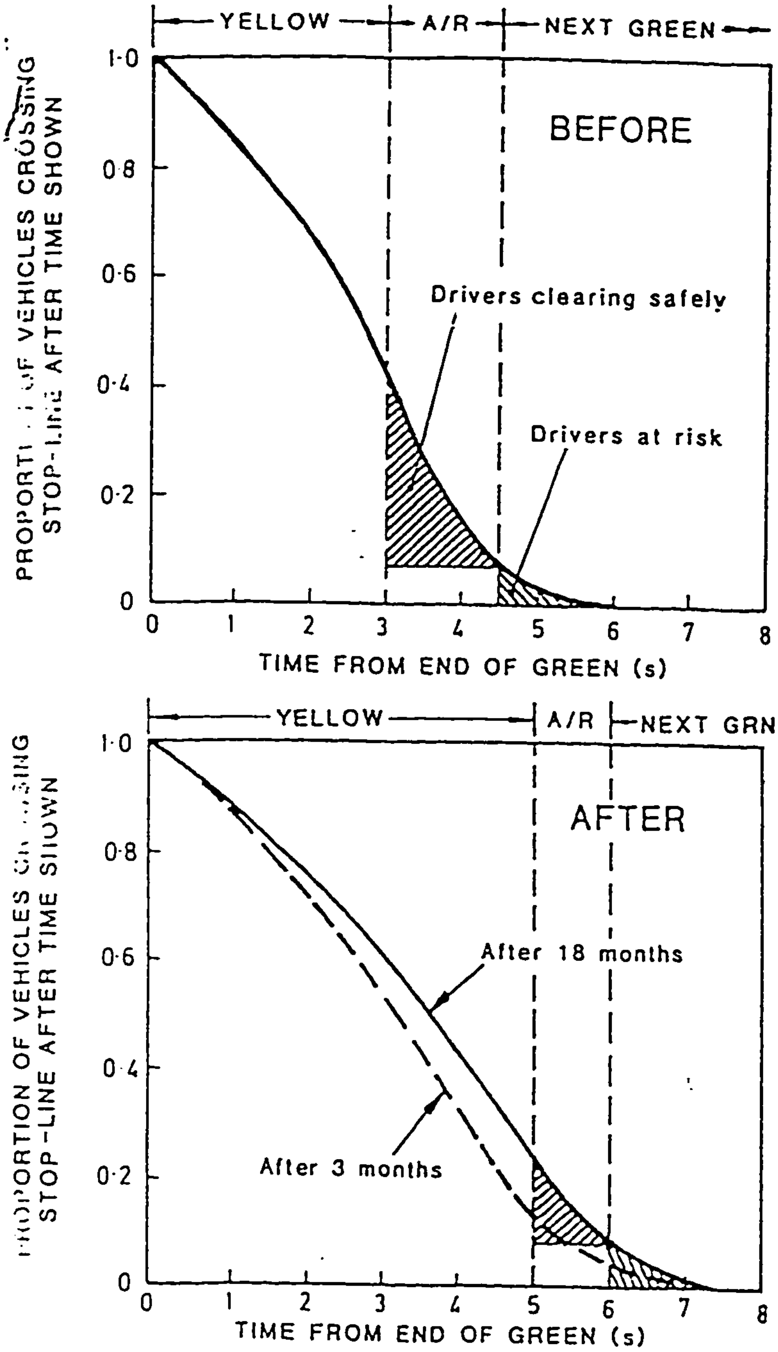


Figure 2.5: Effect of changes in yellow and all-red times on driver behavior.

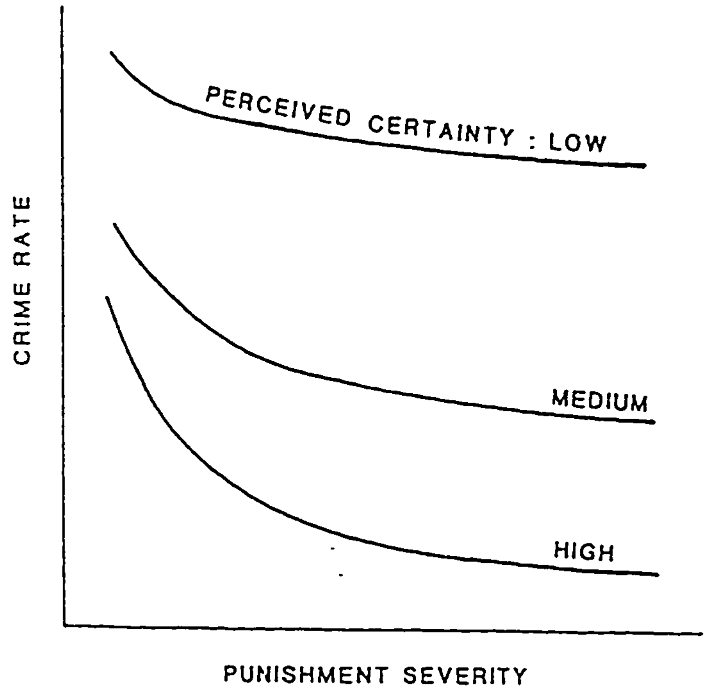


Figure 2.6: Deterrent effects of penalty and perceived risk of apprehension.

the percentages of vehicles entering on the red signal indication. A little extension in the duration of yellow significantly reduces the vehicles entering on red, except some having deviant driver attitudes, so the enforcement policies are in particular relevant for the habitually deviant and recidivist drivers.

Firstly, it is well established in literature that a high perceived risk of apprehension is more effective in promoting compliance with traffic rules than harsh penalties. Figure 2.6 shows the deterrent effects of penalty and perceived risk of apprehension. It is important to note that a high perceived risk of detection has a much greater deterrent effect than severe punishment.

Also evidence from some studies [18, 22] done in England and Australia suggest that the risk of apprehension is seen by drivers as more serious than the risk of an accident, so by increasing the severity of penalties, one cannot successfully modify driver behavior.

Secondly, an enforcement policy will be a success if its prosecution system is good. The on-the-spot enforcement system has the advantage of immediate identification of the offending driver and provides an opportunity for the police to speak to the driver about his breach of the regulation. Also psychological research has confirmed that the celerity of punishment is an important factor to be considered in prosecution systems. That is, the effectiveness of penalties is maximized if the time between apprehension and punishment is kept short.

Long term improvement in the driver behavior can be achieved by means of properly researched communications and propaganda activity at changing the societal attitudes which precipitates deviant action [18].

2.4 Methods For Setting the Change Interval

In this section different methods for designing the change interval as well as their advantages and disadvantages are discussed.

2.4.1 Design of Change Interval - Proposed ITE Practice

The timing of yellow interval as proposed by ITE which is based on the kinematic model of stopping behavior is given below.

$$Y = t + \frac{v}{2a \pm 2gG} \tag{2.3}$$

where,

Y = length of the yellow warning interval, in sec.

t = driver perception/ reaction time, recommended as 1.0 sec.

v = velocity of approach vehicle, in ft/sec^2.

a = deceleration rate, recommended as $10 ft/sec^2$.

G = grade of approach, in percent divided by 100 (downhill is negative grade)

g = gravitational acceleration, ($32.2 ft/sec^2$)

The yellow time calculated by this formula is intended to permit a vehicle to stop at the near stop-line. The derivation of the above formula starts with the equation for stopping distance 'S' in feet as follows:

$$S = V_0 t + \frac{V_0^2}{2a}$$

Where '$V_0 t$' gives the distance traveled at initial speed 'V_o' during braking perception-

reaction time 't', and '$V_o^2/2a$' is the braking distance to a final speed 'V' of zero. When a vehicle is further away from the intersection than the stopping distance at the onset of yellow we can expect the driver to stop, but if the vehicle is at a distance less than the stopping distance, it is reasonable for the driver to decide to clear rather than stop. The minimum required yellow as given by equation 2.3 will carry the clearing vehicle just into the intersection.

The above formula which is derived using the concepts of kinematics is based on a reasonable or ideal driver. There remains an obvious question that should be asked: To what degree is a driver approaching an intersection, capable of a reasonable decision.? That is to say, what is the probability that a driver situated at the stopping distance from the intersection at the onset of yellow will stop.?

Research shows that the vulnerability of the reasonable- driver model lies in low approach speeds. At these speeds the stopping probability (when the driver is at the stopping distance) is comparatively low. In contrast, at high approach speeds, the probability of stopping (when the driver is at the stopping distance) at the onset of the yellow is relatively high. Figure 2.7 shows the probability of stopping at the stopping distance as a function of speed.

The conclusion drawn from above figure is that the model of reasonable driver is substantiated only at high approach speeds. At low approach speeds, this model does not hold for a high percentage of drivers [20].

The above method of determining the change interval is basically deterministic. The method relies on fixed values of deceleration rate and perception-reaction time. Field observations have shown that these variables are random (probabilistic) and not deterministic [23]. Driver behavior varies with individuals, traffic flow condi-

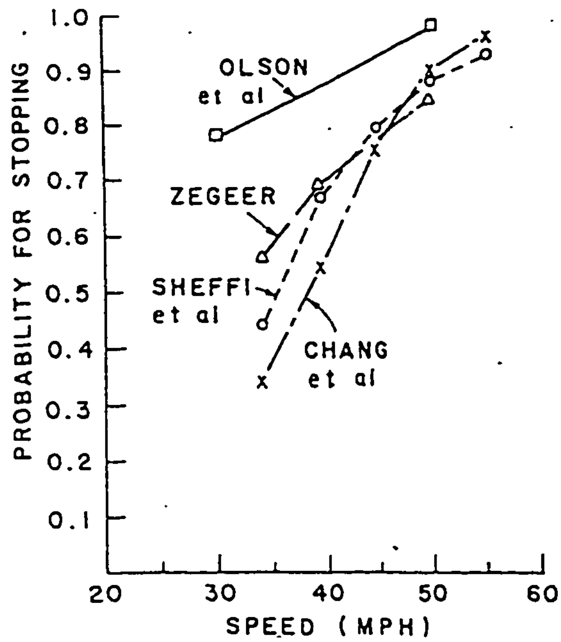


Figure 2.7: Probability of stopping at the stopping distance as a function of speed.

Table 2.1: Reported deceleration rates.

Description	Deceleration (ft/sec^2)	Source
Mean	7.0-13.9	Wortman & Mathias
85th percentile	11.5-18.2	Wortman & Mathias
Mean	8.3-13.2	Wortman & Witkowski
85th percentile	10.8-17.7	Wortman & Witkowski
Mean	7.8-13.4	Chang et al.

tions, geometric design and many other factors, consequently it is doubtful that a single reaction time and a single deceleration rate will allow the determination of a desirable change interval under all circumstances. Also some transportation agencies use equation 2.3 suggested by ITE [2] with different perception and brake reaction times and deceleration rates for different approach speeds. Table 2.1 and 2.2 shows some of the reported deceleration rates and reaction times respectively [1].

It is important to recognize that the equation 2.3 and other similar equations that were presented earlier do not yield consistent results for the situations involving non-

Table 2.2: Reported reaction times.

Description	Reaction time (sec)	Source
Mean	1.4	Jenkins
Mean	1.09-1.55	Wortman & Mathias
85th percentile	1.5-2.1	Wortman & Mathias
Mean	1.1-1.4	Wortman & Witkowski
85th percentile	1.4-2.0	Wortman & Witkowski
Mean	0.7-1.5	Chang et al.
85th percentile	1.0-2.2	Chang et al.

uniform deceleration. In fact the calculated deceleration rates can vary considerably depending on the parameters used to calculate the value. The variation in the calculated values of the deceleration rates increases with increase in the deviation from the linear deceleration profile represented by a constant deceleration. Further studies on the reaction time and the deceleration rate will not make the timing design of the change interval any easier [1].

In the above method the yellow interval timing is linearly related to vehicle approach speeds, but recent studies [1, 5, 24] have raised doubts about the validity of this implied assumption. Based on a study [1], the assumption of assuming that the yellow interval should be lengthened as the approach speed increases was shown to be fallacious. Also field studies do not justify any linear relation between the yellow time and the approach speed as given in equation. Instead, the distance to the stopline was found to be linear with yellow time.

2.4.2 Design of Change Interval Based on the Probability of Stopping or Clearing

In this method of determining change interval the distance of the vehicle at the onset of yellow for different approach speeds is recorded using a video or time lapse photography. The decision whether to stop or not at the onset of yellow for various distances from the stop-line is also noted. Based on these data the probability of stopping can be calculated as a function of the distance of the vehicle to the stop-line at the onset of yellow. The probability of stopping is defined as the proportion of stoppers divided by the total number of vehicles for each distance class (class-width of say 5m). The probability of stopping is plotted for a particular speed category with respect to the distance of the vehicle to the stop-line at the onset of yellow. After plotting the probability curves one might decide that an amber phase should be of such a length (depends on engineering judgement) and that no more than say, 5 percent of the vehicles when faced with amber light do not clear the intersection before the red phase. Thus one could refer to a probability curve for the appropriate speed, determine how far back (distance) from the intersection the 95th percentile point is and use it in the calculation of the yellow interval.

For example, Olson and Rothery [13], developed stopping probability curves for various approach speeds and suggested an equation to be used in conjunction with these curves. The equation for determining the total length of the change interval is as follows:

$$Y = \frac{A + W + L}{V_o} \tag{2.4}$$

Where, 'Y' is the total change interval (yellow + all-red), 'A' is the distance from the intersection at which the desired percentile cutoff occurs (95th percentile in this case and is obtained from the stopping probability curve), 'W', 'L', 'V_o' are the intersection width, vehicle length and approach speed respectively. Using this method we can obtain a different yellow interval for different approach speeds [13].

The main disadvantage of this method is the use of a large sample size to build the stopping probability curves for each speed category in order to determine the dilemma zone boundary and to subsequently determine the required yellow interval.

2.5 Summary

1. The driver behavior at the onset of yellow was first studied by Gazi et. al. in 1960. They put forward a relation based on the principles of kinematics to determine the yellow interval timing.

2. The approach speed and more strongly the distance from the intersection seem to influence the decision to stop at the onset of yellow.

3. Traffic flow was the same with a short or longer yellow interval, but the percentage of vehicles entering on red was reduced with the extension of the yellow interval.

4. ITE's formula is based on the assumption that the yellow interval timing is a positive linear function of approach speed, but recent studies have shown the fallacious nature of assuming the above relation. Also the above formula generated controversy because it uses a constant reaction time and a constant deceleration rate in determining the change interval, contrary to the actual driver behavior which is random or probabilistic. It was also found that the ITE formula for determining change interval fails at low approach speeds.

5. Analysis of the first vehicle to stop at an intersection and the last vehicle to clear the intersection was made by Wortman and Fox at some signalized intersections in Arizona, USA. It was found that the time for the last vehicle through the intersection is more critical than the first vehicle to stop and thus the determination of the yellow interval should be a function of the time for the last vehicle through the intersection.

6. For the last vehicles through the intersection, it was found that the driver behavior did not vary significantly with approach speeds, approach grades, or the duration of the yellow interval.

7. The Manual on uniform traffic control devices (MUTCD) states that the yellow vehicle change intervals should have a range of 3-6sec.

8. Uniform yellow interval is prevalent in many parts of the United States. Several researchers have also recommended the use of a uniform yellow interval. It was also found that most of the transportation agencies use the equation suggested by ITE in determining the change interval.

9. Presence of a police vehicle at the site significantly reduced the percentage of vehicles entering on the red signal indication.

Table 2.3: Proposed timing formulae for yellow duration

No.	Source	Date	Formula	comment
1	Gazi et al	1960	$T = t + \frac{v}{2a} + \frac{W+L}{v}$	velocity and deceleration assumed same for all drivers.
2	Crawford and Taylor	1961	$0.68(\frac{W}{v} + kv^{3/5})$	Constant 'K' depends on proportion of responses
3	Olson and Rothery	1962	$(\frac{A+W+L}{v})$	Where 'A' is the distance from the intersection at which the desired percentile occurs.
4	Olson and Rothery	1962	5.5 sec.	The limits of the applicability of the recommendation are unclear.
5	MUTCD	1971	3 - 6 sec.	Too unspecific to be useful.
6	William's	1977	$t + \frac{v}{2a^{-}_{0.85}} + \frac{W+L}{v_{0.85}} - (t^{*} + \sqrt{\frac{2d}{a^{+}}})$	Cross Street start-up and acceleration time is subtracted.
7	ITE	1980	$T = t + \frac{v}{2a \pm 2gG}$	Grade factor introduced.

Definition of symbols used in Table 2.3.

t, t^* = Driver reaction times for stopping and starting.

v, $v_{0.85}$ = Mean approach speed, 85th percentile of approach speed.

W = Intersection width

L = Vehicle length

A = Distance from stopline at which desired percentile cutoff occurs.

a, $a_{0.85}$, a^+ = Deceleration rate, 85th percentile of deceleration accepted, maximum acceleration of cross-flow traffic.

d = Distance between vehicle and cross-flow stopline.

Chapter 3

Methodology

The study is aimed at evaluating the existing yellow interval timing and validating the hypotheses that an inadequate design of yellow interval will lead to chaos at signalized intersections and will increase the run-red violations and rear-end conflicts.

Also, a new method for designing the yellow interval timing at signalized intersections will be developed. The concept of this method is based on driver behavior at the onset of yellow and is discussed in the subsequent section. Finally, the method developed for yellow timing will be compared with the ITE method for designing the yellow interval timing.

3.1 Research Hypotheses

The analysis of the first vehicle to stop at an intersection and the last vehicle to clear the intersection after the onset of yellow was made by Wortman and Fox [5, 14, 15] at some signalized intersections in Arizona, U.S.A. The results showed that for the last vehicles through the intersection from the onset of yellow, the driver behavior

did not vary significantly with approach speeds, approach grades or the duration of the yellow interval. The results also showed that irrespective of the approach grades, 95 percent of the last through vehicles from the onset of yellow took about 4 sec. or less to clear the intersection, as shown in Figure 2.4. Thus, in this work an attempt will be made to model yellow interval timing based on the time for the last vehicle through the intersection from the onset of yellow.

In order to design the yellow interval timing by this method, *yellow interval demand* 'Y_d' will be measured at the selected signalized approaches. Yellow demand 'Y_d' at a particular signalized approach is defined as the time elapsed from the onset of yellow till the last entering vehicle reaches the stopline. This will give an estimate of the time needed by the clearing drivers to reach the stopline. Based on this, a yellow interval can be set to satisfy the driver behavior and at the same time reduce the number of run-red violations and rear-end conflicts.

In an earlier study [1], it was found that the yellow interval demand at an intersection was found to be a function of the number of vehicles present near the stopline for the first 5 sec of travel time from the onset of yellow, termed as the *vehicle supply*. The vehicle supply at a particular signalized intersection was in turn found to be a function of traffic volume, signal coordination and the type of signal control. Apart from vehicle supply, other variables like approach volume, approach speed and cross-street width will be studied in order to know their influence on yellow interval demand. Hence, the above traffic variables will be measured at the selected signalized approaches and the relationship of these variables with the yellow interval demand will be developed and studied. The general form of the model or relationship will be as follows:

$$Y_d = Y_m + C \tag{3.1}$$

Where,

Y_d = Yellow interval needed to satisfy a specified level of demand at a given intersection, sec.

Y_m = Yellow interval demand needed to satisfy a specified level of yellow interval demand at about 50 percent of the intersections, sec.

C = Y_d - Y_m = Correction factor to be modeled as a function of traffic characteristics, sec.

and

'C' will be modeled as:

$$C = a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 \tag{3.2}$$

Where,

C = Correction factor as discussed above

x_1, x_2, x_3 and x_4 = Traffic characteristics such as approach speed, approach volume, cross-street width and vehicle supply.

a_1, a_2, a_3 and a_4 = Regression coefficients.

3.2 Experimental Design

The design methodology to carry out the study is shown in the flowchart given below. The design methodology as seen in Fig 3.1 is divided into 5 broad categories namely.

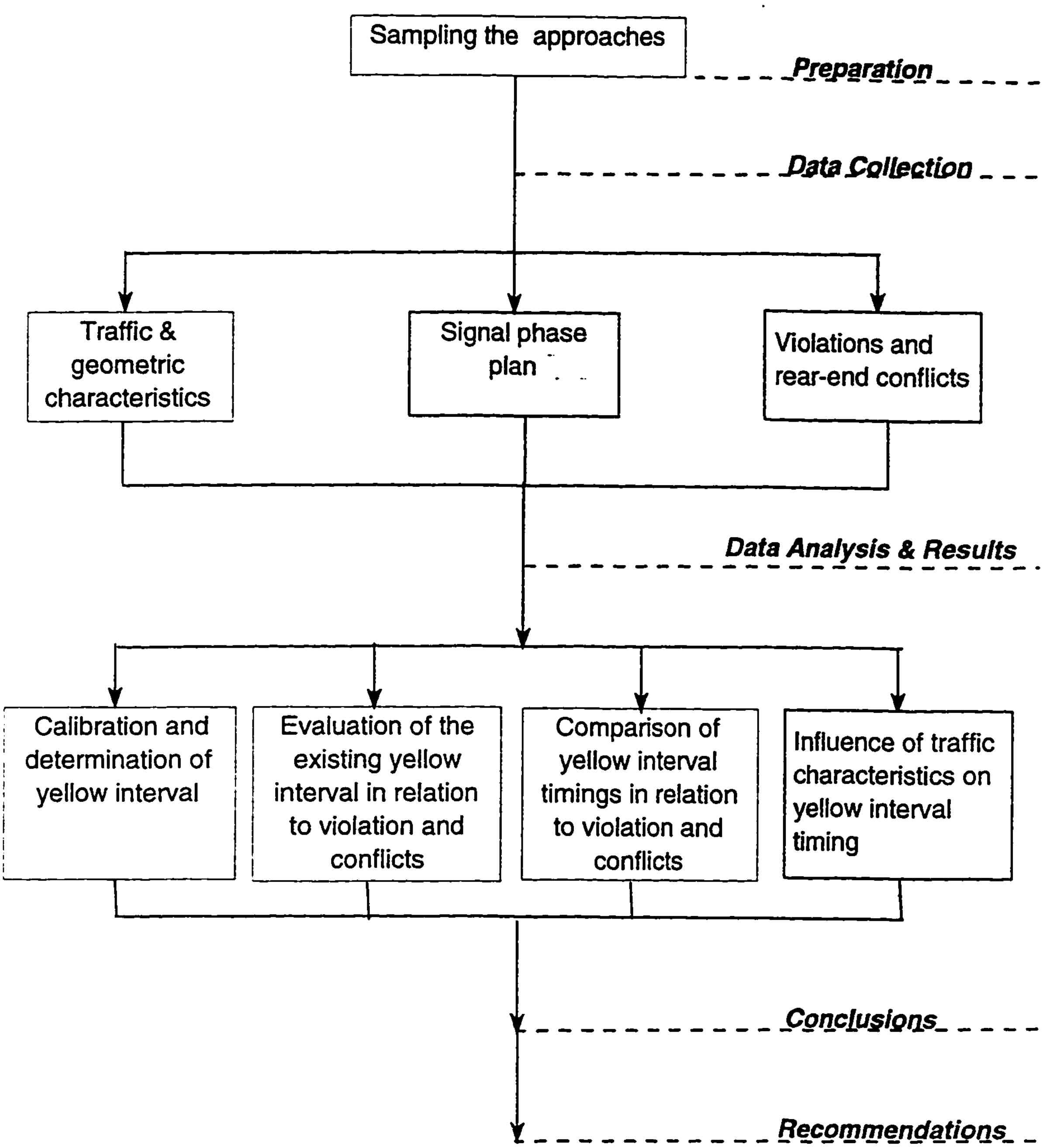


Figure 3.1: Design methodology

1. Preparation

2. Data collection

3. Data analysis and Results

4. Conclusions

5. Recommendations

The above five categories are briefly discussed below:

1. Preparation - Sampling the approaches

   Initially, intersections which satisfy certain criteria will be selected from Khobar, Thuqbah and Dammam region. The set of criteria to select the candidate signalized approaches designed to achieve the objectives of the study are discussed in section 3.3.2. Taking these into consideration, a survey will be conducted and candidate signalized approaches will be sampled. Depending upon the study the required signalized approaches will be randomly selected out of the candidate signalized approaches. The calculation of sample size is discussed in section 3.3.3.

2. Data collection

   As seen in Figure 3.1 the data collection group is composed of three tasks as explained below:

   (i) Traffic and geometric characteristics: This forms the basis of many traffic engineering related projects. In this study traffic and geometric data such as approach volume, approach speed and cross-street width respectively will be

collected for a specified duration at each of the selected signalized approaches. These parameters will be studied in relation to the yellow timing so as to come up with a new methodology for designing the signal change interval. These parameters will also be used to study their influence on driver behavior at the onset of yellow.

The above traffic and geometric parameters are also utilized in calculating the yellow interval by the ITE method, so that a comparison can be made with the developed yellow interval timing. As discussed in earlier sections, the yellow interval demand 'Y_d' and vehicle supply data 'X' will be collected in addition to the above mentioned parameters. The yellow interval demand and the vehicle supply will form the basis for designing the yellow interval satisfying the driver behavior at signalized intersections.

(ii) Different signal plans such as green, yellow and red will be noted at each signalized approach. This will give us an idea about the existing timing, especially the yellow timing in practice

(iii) Violations and rear-end conflicts: In this study, the main objective is to develop a methodology to design the yellow interval timing which accommodates the driver behavior and secondly to evaluate the existing yellow interval timings. Finally, the developed method of timing yellow will be compared with the standard ITE practice. The evaluation and comparison of the yellow interval timing procedures will be done in relation to violations and rear-end conflicts.

Inappropriate design of the yellow interval will cause right-angled and rear-end conflicts and thereby lead to fatal accidents. As mentioned earlier in

section 2.2, right-angled accidents occur because of the increase in the run-red violations. This phenomenon occurs when the yellow interval timing is set less than adequate, leading to the creation of the dilemma zone. Similarly rear-end accidents occur because of the increase in rear-end conflicts. This usually occurs when the yellow is set more than adequate, which leads to the creation of the option zone.

Hence it is better to evaluate or assess the yellow interval timing procedures in relation to the right-angled and rear-end accidents. The above criteria will be helpful in studying the adequacy of the yellow interval timing procedures. Due to unavailability of the accident statistics at the signalized intersections in Saudi Arabia, run-red violations and rear-end conflicts are considered as a potential measure to assess the yellow interval timing procedures, instead of right-angled and rear-end accidents. In addition to run-red violations, vehicles entering on yellow will also be measured.

3. Data analysis and results

Initially the raw data collected will be analyzed and later used for detailed analysis designed to attain the objectives of the study. The preliminary analysis of the raw data is discussed in detail in section 3.4. The detail data analysis designed to achieve the objectives of the study can be classified into 4 subgroups, a brief description of these subgroups is given below:

(i) Calibration and determination of yellow interval.

The design of yellow interval timing which satisfies the driver behavior at signalized intersections is dealt in section 4.2.

(ii) Evaluation of the existing yellow interval in relation to violations and conflicts.

The effect of existing yellow interval timing on violations and conflicts was studied relative to the developed yellow interval timing. The detail analysis and results are discussed under section 4.8.

(iii) Comparison of yellow interval timings in relation to violations and conflicts.

The yellow interval timings obtained by the developed methodology are compared with the yellow obtained by the standard ITE method in relation to violations and conflicts. A detail comparison can be found under section 4.9.

(iv) Influence of traffic characteristics on yellow interval timing.

The influence of traffic characteristics such as the approach speed and approach volume on yellow interval is studied and is discussed under section.4.10.

4. Conclusions

In the light of data analysis, the conclusions will be summarized under section 5.3.

5. Recommendations

Finally suggestions for future work are discussed in section 5.4.

3.3 Data Collection

A database will be built in order to design the yellow interval timing and to evaluate and compare different yellow interval timing procedures. The database built will also be used to study the influence of traffic characteristics on the yellow interval. A list of variables to be collected for the study are mentioned in the subsequent section.

3.3.1 Selection of Variables for Data Collection

The data will be collected for the following selected variables for a specified duration at the required number of signalized approaches.

1. Traffic and Geometric characteristics.

   These include the approach volume (veh/hr), approach speed (km/hr), signal phase plan, yellow interval demand (Y_d), sec., vehicle supply (x), sec., number of lanes and cross-street width

2. Violations

   Number of vehicles entering on yellow per cycle (VEY/cycle) and vehicles entering during all-red per cycle (VER/cycle) will be measured.

3. Rear-end conflicts

   The data for the following four types of rear-end conflicts will be collected :

   1. Left-turn, same direction conflict.
   2. Right-turn, same direction conflict.
   3. Slow vehicle, same direction conflict.
   4. A lane-change conflict.

The definitions of these conflicts are given in Appendix A. The need to collect the data for the above variables is discussed in detail under section 3.2.

3.3.2 Selection of Signalized Approaches

The following criteria will be considered in selecting the candidate signalized approaches.

1. The signalized intersections should be uniform in geometry having 4-legs and with 3 lanes in each direction. Uniform geometry will help remove the extraneous effects of approach volume, speed, cross-street width and turning traffic which will arise if variable intersection geometry is considered.

2. Saturated signalized approaches will be considered in this study. Approaches of this kind will have regular arrival of vehicles during yellow and all-red enabling the quantification of the number of vehicles present near the stopline during yellow and all-red and also to study the behavior of drivers to the yellow interval.

3. In the Eastern Province of Saudi Arabia nearly 95 percent of the intersections have simple four phase plan and very few intersections are installed with multiphase plan. In order to keep homogeneity among the study approaches and also for their easy availability simple four phase intersection approaches will be considered.

3.3.3 Determination of Sample Size

At first, a preliminary survey of candidate signalized intersections present in the area are to be inventoried, their approaches being the sampling units. In order to determine the number of approaches needed in the study, knowledge of the variance in the timing of the yellow interval at approaches in the region is necessary. Once the variance of the yellow interval timing is known the required sample size of signalized intersection approaches is determined by using a statistical formula as shown below [25].

$$N = \frac{Z^2_{\alpha/2}\sigma^2}{E^2} \tag{3.3}$$

where,

N = Required sample size

E = Tolerable error

σ^2 = Variance of yellow interval timing

$Z_{\alpha/2}$ = Normal random variable at 95% significance level.

Variance of yellow interval timing was obtained as $\sigma^2 = 0.931$. The tolerable error 'E' is taken as ± 0.3 sec. with $Z_{\alpha/2}$ at 95% significance level being 1.96. Using equation 3.3, the minimum sample size obtained is forty approaches. To be on the safer side forty four signalized approaches are selected for study. The required number of approaches will be selected randomly from the inventory of available signalized approaches.

The durations for which the data of rear-end conflicts, run-red violations and vehicles entering on yellow to be collected at each site are determined by using the

statistical formula shown below [25].

$$H = \frac{z_{\alpha/2}^2 \sigma^2}{L^2} \qquad (3.4)$$

Where,

H = Required duration of data collection at each signalized approach.

σ^2 = Variance of the variable for which the sample duration is determined.

L = $\frac{\bar{Y}}{P/100}$

$\bar{Y}$ = Hourly mean value of the variable for which duration is being calculated.

p = Percent allowable range ±50%

In order to determine the duration for collecting the rear-end conflicts at each signalized approach, the mean and variance of rear-end conflicts is needed. The hourly mean and variance for rear-end conflicts is obtained from Al-Ofi's work [8]. The variance and mean are 12 conflicts per hour and 5 conflicts per hour respectively. Using the equation 3.4, the minimum duration obtained for collecting the rear-end conflict data is 30 minutes.

Similarly the duration for collecting the data for run-red violations, vehicles entering on yellow and vehicles entering during yellow and all-red were calculated using the hourly mean and variance for vehicles speeding on yellow, which was 6.4 violation per cycle and 19.3 violations per cycle respectively. These values were obtained from a study done in Riyadh [4]. Using equation 3.4, the duration for collecting the run-red violations and vehicles speeding on yellow was obtained as 6.4 minutes. In general a 30 minute period will be spent in collecting the above data at each signalized approach.

3.3.4 Field Work

Before the start of the data collection, lectures were given about the objectives of this study to the observers. Training included the use of equipment and instructions for recording the data on the prescribed forms. For observers of conflicts and violations, literature about the operational definitions of different types of conflicts was given and explained. One day was used for field practice and when satisfied with the performance of the observers, they were assigned to actual data collection jobs.

The violations, traffic conflicts, speed measurements, traffic volume and phasings were observed during the working days of the week i.e saturday through wednesday. The data was collected during the afternoon peak, generally from 4.00 pm to 8.00 pm. The team studying an intersection consists of the following:

1. One conflict observer
2. One violation observer
3. One volume measurer
4. One yellow interval demand observer.

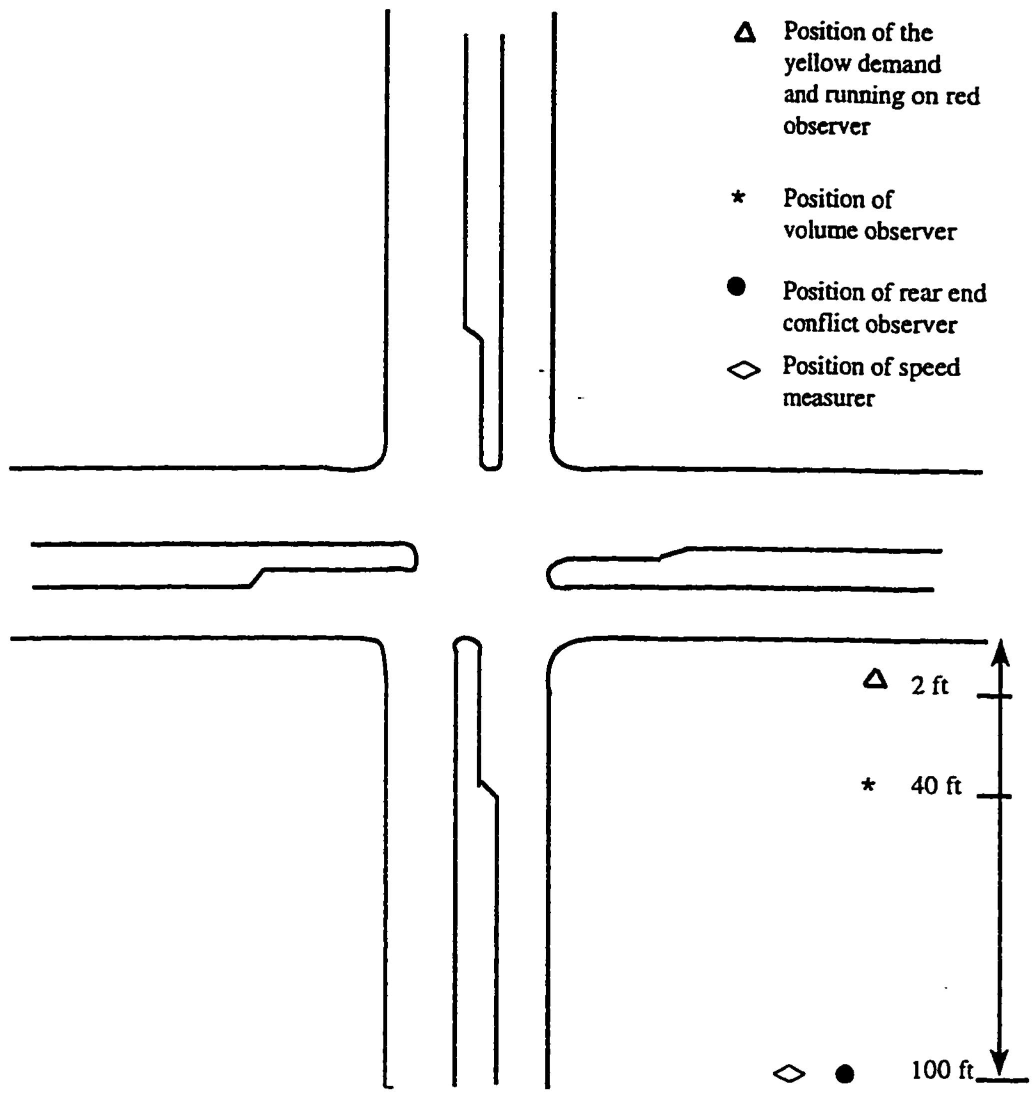
The person counting volume also measured the speed at each approach. The yellow demand observer was the group leader and responsible for all data collecting operations. Generally, data at about 3 approaches was collected daily, starting from 4.00 pm. The data was collected at each approach for the required duration on prescribed forms. After collecting all the required data at a particular intersection the team moved to another approach.

An ideal signalized intersection with the observer positions and phasing is shown in Figure 3.2. The position of volume observer was at a distance of 30-40ft from the stopline and the position of speed measurer was at a distance of 100ft from the

stopline. The rear-end conflict observer was stationed at a distance of 100 ft and the yellow interval demand observer, run-red violations and speeding on yellow observer was stationed near the stopline at about 1-2 ft before the stopline.

The signalized intersections chosen for study were having 4-unidirectional phases as shown in Figure 3.2. Except for speed the data at each approach was taken for a 30 minute period. Thirty speed observations were collected at each approach to determined the spot speed of that approach. The speed was measured using a speed measuring radar, every alternate vehicle was made a target for speed measurement. Approach volume was measured every 5 minute for 30 minute period using a tally board. The conflict observer was taking all the 4-types of rear-end conflicts, every cycle at each approach for 30 minute period.

The violation observer used to count the vehicles entering on yellow and during initial part of red using a tallyboard. The yellow demand observer measured the time taken by the last entering vehicle to reach the stopline from the onset of yellow using an electronic stopwatch. At the end of survey, each observer filled the onsite observation report and also gave his comments.



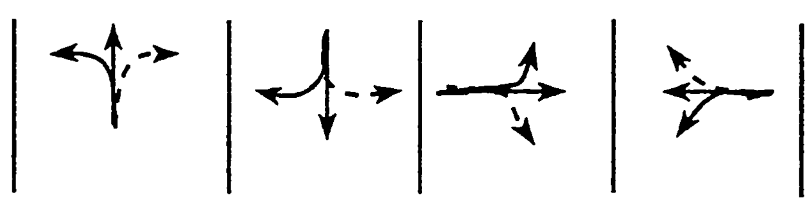


Figure 3.2: An ideal signalized intersection and 4-unidirectional phases

3.4 Preliminary Data Analysis

The raw data obtained was transferred from the forms to the Excel worksheet. The yellow interval demand observations collected at each approach were used to obtain the cumulative frequency distributions. For each approach 85th, 95th and 100th percentile yellow interval demands were obtained. The mean yellow interval demand '(Y_m)' at 44 signalized intersections at 85th and 95th percentile level is calculated to be 3.79 and 4.48 seconds respectively.

The volume data obtained at each signalized approach for a period of 30 minutes was doubled to obtain the approach volume per hour (veh/hr). The conflict and violation data collected at each signalized approach was converted to conflict and violation rates respectively. The spot speed observation taken at each approach were used to calculate the 15th and 85th percentile speeds.

The yellow and all-red signal timing for each signalized approach were calculated by the ITE method [3]. The ITE method for calculating the yellow interval timing is given in equation 2.2. The preliminary data analysis results are shown in Tables B.1, B.2 and B.3 of Appendix B. The variables calculated and tabulated there are:

1. 15th and 85th percentile approach speed, Km/hr.
2. Approach volume, veh/hr.
3. Yellow interval obtained by ITE method.
4. 85th, 95th and 100th percentile yellow interval demand.
5. Existing all-red interval timing and all-red obtained by the ITE method, sec.

6. Ratio of actual yellow interval and the yellow obtained by the ITE method 'Y_a/Y_{ITE}' and the ratio of actual yellow to the 85th percentile yellow interval demand 'Y_a/Y_d'.

7. Violation rates such as vehicles entering on yellow per cycle (VEY/cycle), vehicles entering on all-red per cycle (VER/cycle) and the total vehicles entering during yellow and all-red per cycle (TOTVEYR/cycle).

8. Rear-end conflict rates such as total rear-end conflict per cycle (TOTREC/cycle) and slow vehicle rear-end conflict per cycle (SVREC/cycle).

Chapter 4

Data Analysis and Results

4.1 Introduction

In this chapter, model building will be carried out in order to set the yellow interval timing at signalized intersections in the Eastern Province of Saudi Arabia. This will be followed by cluster analysis which will be used for data reduction. Prior to this, the need for cluster analysis will be discussed. Using the results of cluster analysis, graphical plots will be drawn in order to study the driver behavior at the onset of yellow with respect to violations, conflicts and traffic characteristics.

4.2 Model Calibration for Yellow Interval Demand

The general form of the model for the yellow interval demand is as follows:

$$Y_d = Y_m + C \tag{4.1}$$

Where,

Y_d = Yellow interval needed to satisfy a specified level of demand at a given intersection, sec.

Y_m = Yellow interval demand needed to satisfy a specified level of yellow interval demand at about 50 percent of the intersections, sec.

C = Y_d - Y_m = correction factor to be modeled as a function of traffic characteristics, sec.

and 'C' will be modeled as:

$$C = a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 \tag{4.2}$$

Where,

C = Correction factor as discussed above

x_1, x_2, x_3 and x_4 = Traffic characteristics such as approach speed, approach volume, cross-street width and vehicle supply.

a_1, a_2, a_3 and a_4 = Regression coefficients.

As obtained from chapter 3, the mean yellow interval demand 'Y_m' at 44 signalized intersections at 85th and 95th percentile level is 3.79 and 4.48 sec. respectively. The correction factor will be modeled as a function of the following important variables which are suppose to influence the yellow interval demand.

1. Approach volume
2. Approach speed

Table 4.1: Analysis of variance for the models built

	Estimated variable coefficient (Significance)		
Variable name	Generalized Model	Model1	Model2
Intercept	-1.134 (0.062)	-1.330 (0.001)	-1.194 (0.001)
Volume	0.003 (0.39)	-	-
Speed	-0.0117 (0.27)	-	-
Cross-Street width	0.0032(0.57)	-	-
Vehicle supply	0.43 (0.001)	0.46 (0.001)	0.408 (0.001)
R-square	0.64	0.632	0.50
MSE	7.41	28.87	23.12
F-statistics	18.034	72.031	41.932
Significance	0.001	0.001	0.001

3. Cross-street width
4. Vehicle supply

Using the regression technique of SAS [26], a generalized model of the correction factor at 85th percentile yellow interval demand level was built as a function of the above mentioned variables. The model obtained is as follows:

$$Y_{85} = -1.134 + 0.0003\, x_1 - 0.0117\, x_2 + 0.0032\, x_3 + 0.43 x_4$$

Where,

Y_{85}= Yellow demand at 85th percentile level.

x_1 = Approach volume

x_2 = Approach speed

x_3 = Cross-street width

x_4 = Vehicle supply

The analysis of variance and pearson's correlation coefficient of the generalized model are shown in Table 4.1 and Table 4.2 respectively.

Table 4.2: Pearson's correlation coefficient for the generalized model

Variable	Correction Factor	Volume	Speed	Cross width	Vehicle supply
Correction Factor	1.00 (0.0)	0.507 (0.0004)	-0.075 (0.6276)	-0.0165 (0.9154)	0.795 (0.0001)
Volume		1.00 (0.0)	0.187 (0.2241)	0.0295 (0.8492)	0.571 (0.0001)
Speed			1.00 (0.0)	0.078 (0.6130)	0.0117 (0.9397)
Cross-width				1.00 (0.0)	-0.0884 (0.568)
Vehice Supply					1.00 (0.0)

The Anova table reveals that the independent variables such as approach volume, approach speed and cross-street width were found to be insignificant at $\alpha = 1\%$ significance level, the vehicle supply was the only variable found to be significant at $\alpha = 1\%$ significance level. As can be seen from the correlation matrix there exists a good correlation between the volume and vehicle supply. Since the volume is insignificant at 5% significance level it will not be used in future model building.

In conclusion it can be stated that only the variable vehicle supply influences the correction factor, so the above result suggest that a model should be built between the correction factor 'C' and vehicle supply 'X'.

4.3 Relationship between 85th Percentile Yellow Interval Demand and Vehicle Supply - Model1

The model of the correction factor 'C' at 85th percentile yellow interval demand, 'Y_{85}' was built as a function of vehicle supply 'X'. Procedure Regression of SAS [26] was used to built the model. The model between correction factor and vehicle supply yielded an R^2 value of 0.6317 implying that 63.17% variability in the data is explained by the model. The model is significant at 1% significance level. The analysis of variance is shown in Table 4.1. The parameters, both the intercept and vehicle supply are significant at 1% significance level. The model of the correction factor takes the form as follows:

$$C = -1.33 + 0.46X$$

where, 'X', the vehicle supply takes the positive sign implying that the correction factor increases as the vehicle supply increases, a zero vehicle supply will result in a negative correction coefficient of -1.33. The pearson's correlation coefficient between the correction factor and vehicle supply reflect a strong correlation of 0.79 as can be seen in Table 4.2. The yellow interval demand at any intersection can be obtained by using the relations given below:

$$Y_{85} = 3.79 + C$$

Where,

$$C = -1.33 + 0.46X$$

The final expression of yellow interval demand after substituting the value of correction factor 'C' accounts to:

$$Y_{85} = 2.46 + 0.46X$$

The above relation can be satisfactorily used to determine the 85th percentile yellow interval demand at any signalized intersection. Residual plots were drawn against the fitted value and the regressor variable, the vehicle supply. The plots do not reveal any obvious pattern, reflecting that the assumption of constant variance is satisfied. A Normal probability plot was drawn in order to study the underlying error distribution. The errors align in a straight line thereby satisfying the normality of error assumption.

4.4 Relationship between 95th Percentile Yellow Interval Demand and Vehicle Supply - Model2

A second model with a correction factor at 95th percentile yellow interval demand level, 'Y_{95}' was built as a function of vehicle supply. The Analysis of variance and parameter estimates are shown in Table 4.1. The model is significant at 1% significance level with R^2 value of 0.5, so a 50% variability in the data is explained by the model. The parameter estimates are significant at 1% significance level. The model takes the form as follows:

$$C = -1.194 + 0.41X$$

The pearson's correlation coefficient is shown in Table 4.2. There is a good correlation of 0.71 between the correction factor and vehicle supply. If the vehicle supply at a particular intersection is zero the 'C' takes a negative value as expected. The yellow interval demand at 95percentile level at any signalized intersection can be found by the following relation.

$$Y_{95} = 4.48 + \mathrm{C}$$

where, 'C' is the correction factor which can be obtained from the relation given above. The final expression of yellow interval demand after substituting the value of correction factor 'C' accounts to:

$$Y_{95} = 3.29 + 0.41\mathrm{X}$$

The above relation can be satisfactorily used to determine the 95th percentile yellow interval demand at any signalized intersection. Residual plots were drawn against the fitted value and the regressor variable, vehicle supply. The plots do not reveal any obvious pattern, reflecting that the assumption of constant variance is satisfied. A Normal probability plot was drawn in order to study the underlying error distribution. The errors align in a straight line, thereby satisfying the normality of the error assumption.

4.5 Calculation of Yellow Interval Timing - Application of the Developed Model

The 85th percentile yellow interval demand at any signalized intersection may be obtained by using the following relation:

$$Y_{85} = 2.46 + 0.46X$$

Where 'X' being the vehicle supply

Similarly the 95th percentile yellow interval demand at any signalized intersection may be obtained by using the relation given below:

$$Y_{95} = 3.29 + 0.41X$$

As stated earlier the 85th percentile yellow interval demand means that eighty five percent of the time, the drivers utilize the yellow interval upto 'Y_d' sec. from the onset of the yellow interval. Similarly 95th percentile yellow demand means that ninety percent of the time, the drivers needed 'Y_d' sec. from the onset of yellow for safe clearing during the total change interval period.

Hence, an appropriate yellow interval demand should be set at signalized intersections that should satisfy the needs of drivers and at the same time it should be a balance between safety and efficiency.

The 85th percentile yellow interval demand, will be appropriate in setting the yellow interval timing at signalized intersections. The timing will be a tradeoff between intersection safety and signal timing efficiency. An example calculation for obtaining the 85th percentile yellow interval demand by using the developed model is given below.

Suppose the average vehicle supply at a particular signalized approach is say 3 veh/cycle. The 85th percentile yellow interval demand for that intersection will be:

$$Y_{85} = 2.46 + 0.46X$$

Where, X = 3 veh/cycle

$$Y_{85} = 2.46 + 0.46 * 3 = 3.84 \text{ sec.}$$

A yellow interval time of 3.84 sec. will satisfy the needs of a majority of drivers for safe clearing or stopping at the signalized approach at the onset of yellow.

4.6 Need for Cluster Analysis

One of the main objectives of the study is to evaluate the existing yellow interval timing and to compare the developed methodology of setting the yellow interval with the standard ITE practice.

To evaluate the existing yellow interval timing, it is of interest to explore the trend in violations and conflicts in relation to the existing yellow interval timing. In the present study evaluation of existing yellow interval timing 'Y_a' is done relative to the developed yellow interval 'Y_d'. This implies that the ratio 'Y_a/Y_d' is evaluated in relation to violation and conflicts, doing this will facilitate the evaluation of the existing yellow and also will serve as a relative comparison with the developed yellow interval demand 'Y_d'.

Similarly comparison between the developed yellow interval timing 'Y_d' and the yellow obtained by the ITE method 'Y_{ITE}' is done relative to the existing yellow interval timing 'Y_a'. This implies that 'Y_a/Y_d' and 'Y_a/Y_{ITE}' are compared in relation to violations and conflicts. The need to compare the yellow interval timing procedures relative to the existing yellow interval stems from the fact that the timing developed and those obtained by the ITE method are not implemented on the field. Since it is difficult to the change the timings on the field and thereby difficult to conduct *before* and *after* studies, a good technique is to compare the yellow interval

timing procedures relative to the actual or existing yellow interval timing.

In order to evaluate the existing yellow interval timing, scatter plots between 'Y_a/Y_d' against violations and conflicts were drawn. The plot between 'Y_a/Y_d' and total vehicles entering on yellow and all-red per cycle, (TOTVEYR/cycle) and between 'Y_a/Y_d' and total rear-end conflicts per cycle, (TOTREC/cycle) are shown in Figures 4.1 and 4.2 respectively. As it can be seen in Fig 4.1 the violations seems to decrease with increase in the ratio 'Y_a/Y_d'. But from Figure 4.2, it is difficult to study the underlying behavior between the ratio 'Y_a/Y_d' and total rear-end conflicts.

Also in order to compare the developed methodology of timing the yellow interval with the standard ITE practice scatter plots were drawn between the ratio of yellow interval 'Y_a/Y_{ITE}' against violations and conflicts. Plots between 'Y_a/Y_{ITE}' against vehicles entering on all-red (VER/cycle) and total vehicles entering on yellow and all-red (TOTVEYR/cycle) are shown in Figures 4.3 and 4.4 respectively. By observing the plots it is difficult to interpret the actual behavior between violations and the ratio of yellow interval.

Also, the plot between 'Y_a/Y_{ITE}' and total rear-end conflict shown in Figure 4.5 does not reveal any obvious pattern, so by observing the scatter plots it becomes difficult to interpret the behavior of drivers in relation to conflicts with the variation in the ratio of 'Y_a/Y_{ITE}'.

The above scatter plots will not help in achieving the objectives stated i.e, to evaluate the existing yellow interval and to compare the yellow interval timings. The scatter plots in most cases are difficult to interpret since there exists no obvious pattern. Hence, in order to study the driver behavior in relation to violations and conflicts, cluster analysis will be used. Cluster analysis will basically group ap-

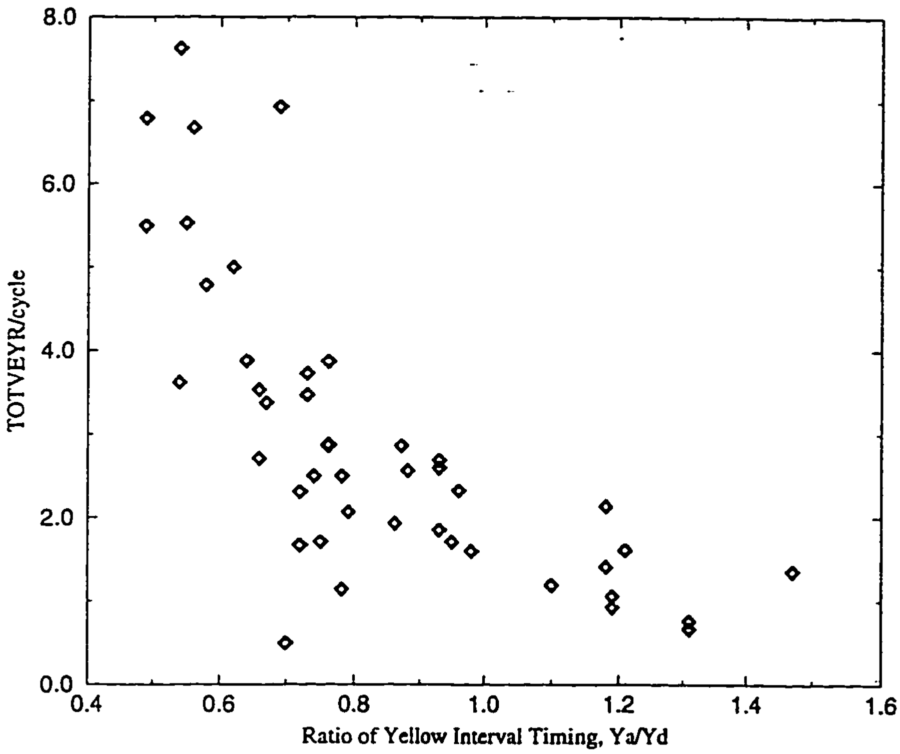


Figure 4.1: Ratio of yellow interval (Y_a/Y_d) as a function of the total vehicles entering during yellow and all-red per cycle, (TOTVEYR/cycle).

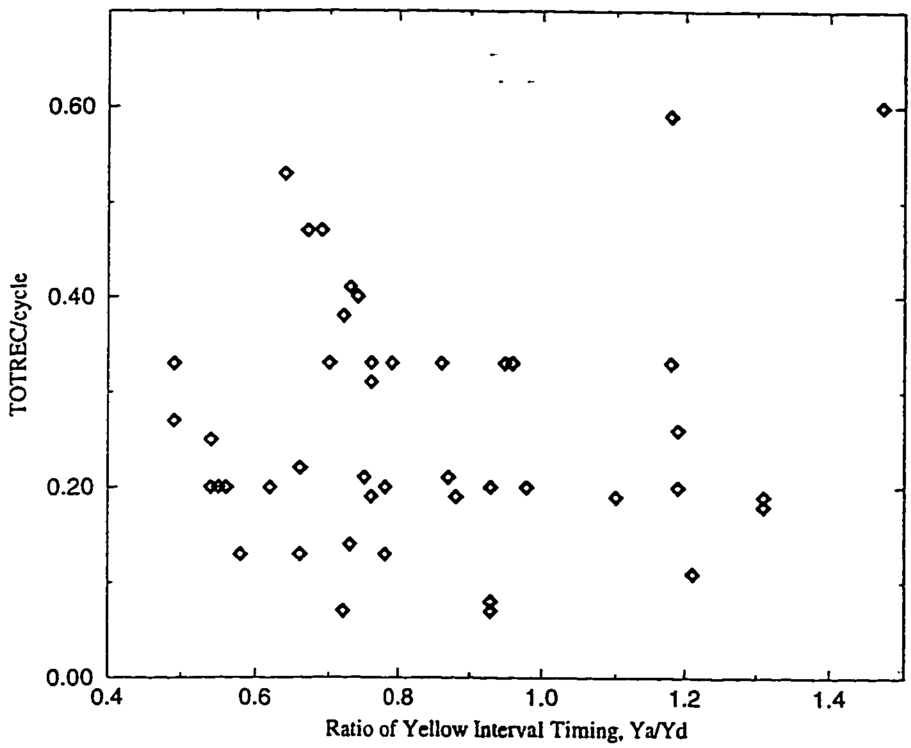


Figure 4.2: Ratio of yellow interval (Y_a/Y_d) as a function of the total rear-end conflicts per cycle, (TOTREC/cycle).

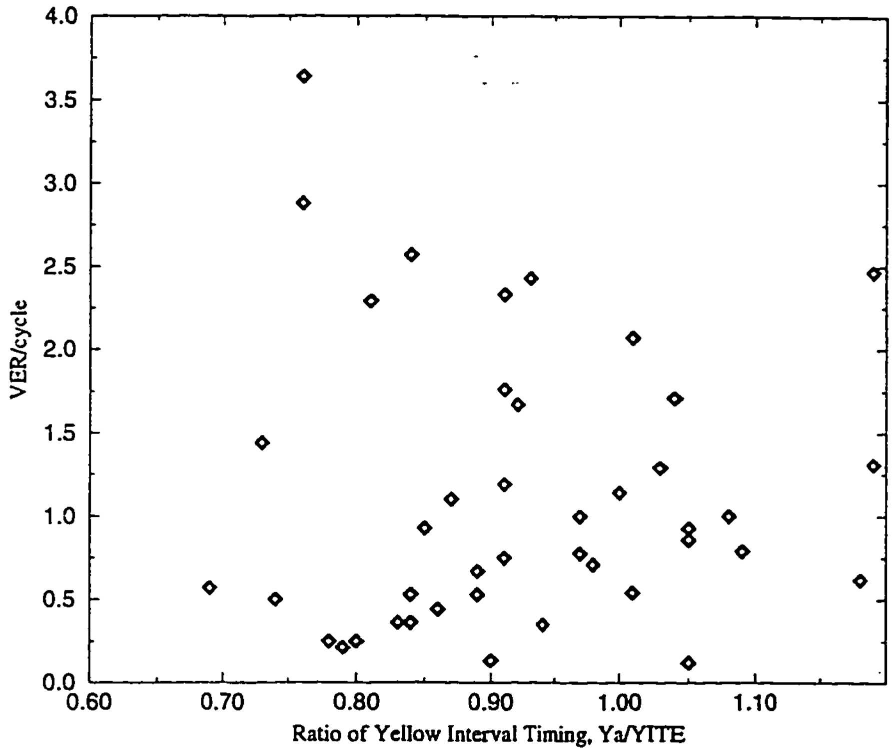


Figure 4.3: Ratio of yellow interval (Y_a/Y_{ITE}) against the vehicles entering during all-red per cycle, (VER/cycle).

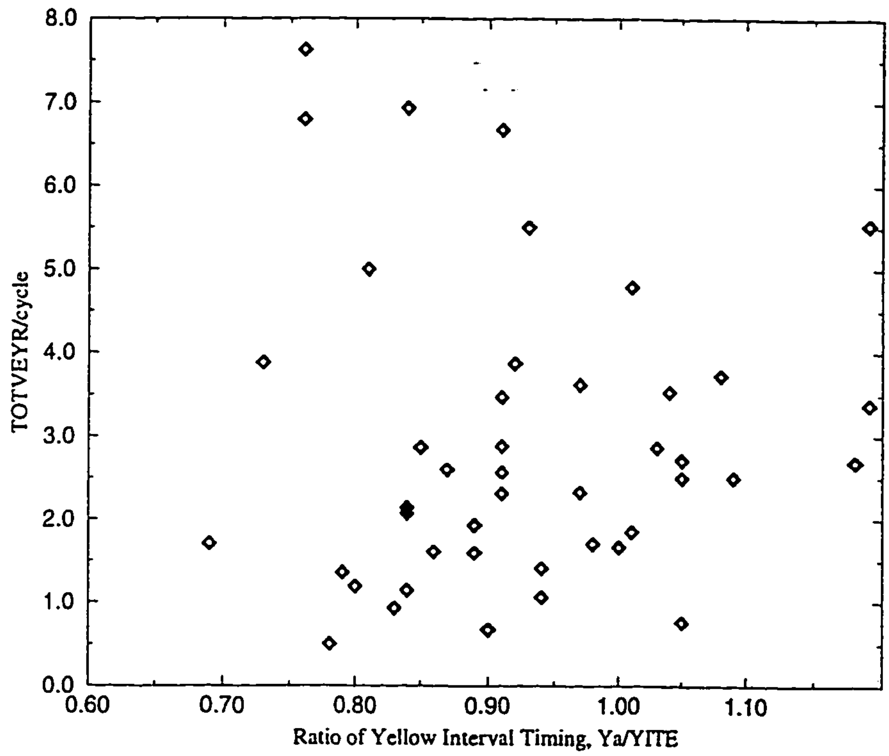


Figure 4.4: Ratio of yellow interval (Y_a/Y_{ITE}) against the total vehicles entering during yellow and all-red per cycle, (TOTVEYR/cycle).

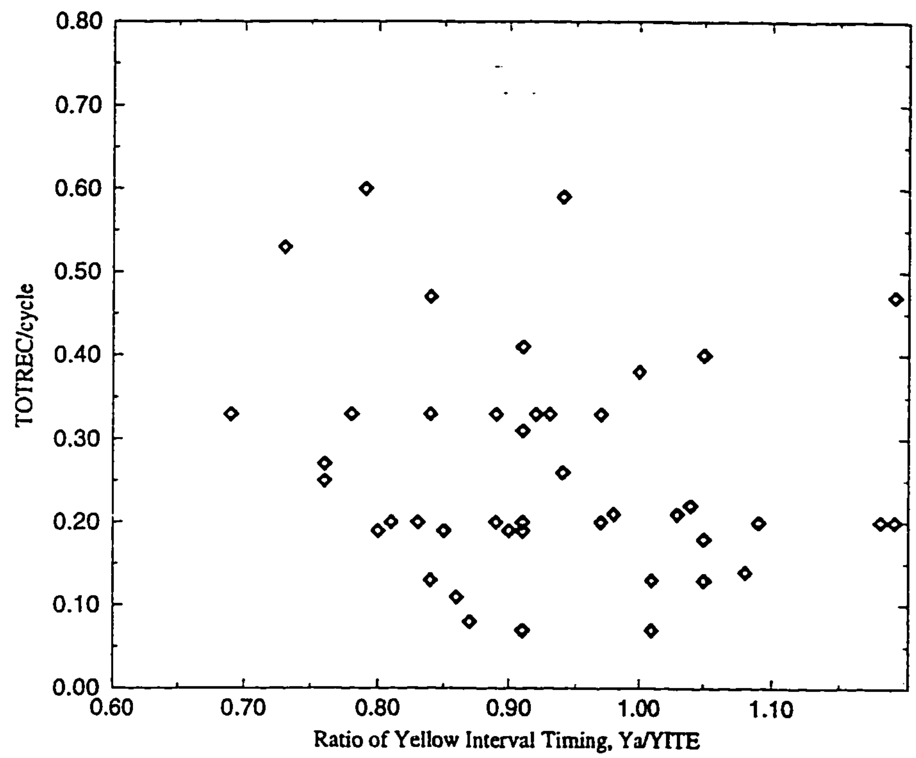


Figure 4.5: Ratio of yellow interval (Y_a/Y_{ITE}) as a function of the total rear-end conflicts per cycle, (TOTREC/cycle).

proaches with similar attributes and thereby helps in evaluating the existing yellow interval timing as well as provide a basis for comparing the yellow interval timing procedures.

4.7 Results of Cluster Analysis

The objective of the study is to evaluate the existing yellow interval timing and also to compare the developed method of timing the yellow with the standard ITE practice. These objectives will be studied in relation to violations and conflicts.

The data collected at 44 signalized intersections will be used in cluster analysis. The data at four signalized intersections namely Makkah/Dhahran st. N.B and S.B and King Abdul Aziz/28th st. E.B and W.B will be removed from the analysis because of extremely large cross-width, as these data points will distort the real clusters, if they are included in data analysis. The SAS CLUSTER procedure will be used which hierarchically clusters the observations in a SAS data set, using Ward's minimum variance clustering procedure. CLUSTER creates an output data set from which the TREE Procedure can draw a tree diagram also called Dendrogram or Phenogram which can output clusters at a specified level of the tree. It also prints a history of the clustering process, giving statistics useful for estimating the number of clusters in the population from which the data were sampled [26].

4.7.1 The Choice of Variables or Attributes

The column of the data matrix to be used for cluster analysis represents the objects (different signalized intersections in our case) and the rows represent the attributes

or variables (traffic parameters, geometric characteristics and signal timing). The choice of variables is in itself a categorization of the data, it has no mathematical or statistical guidelines, but it should reflect one's judgement of relevance for the purpose of data reduction and of attaining the objectives or hypotheses stated.

Four variables or attributes which are selected for cluster analysis are:

1. Approach speed

2. Approach volume

3. Cross-street width

4.'Y_a/Y_d', Ratio of actual yellow to yellow interval demand. Wherever 'Y_d' is mentioned without any specific notes it will mean 85th percentile yellow interval demand.

The above attributes were chosen so as to form uniform clusters having similar speed, volume, cross-width and 'Y_a/Y_d'. This kind of dissection will consequently make homogeneous clusters each having similar violations and conflicts relative to the above mentioned attributes. The clusters formed in this way will help in studying the effects of yellow interval timing on driver behavior.

4.7.2 Trimming and Standardizing the Data Matrix

Before executing the clustering method, the data matrix will be standardized and trimmed. By standardizing the attributes or data matrix and recasting them in dimensionless units one can remove the arbitrary effects. Also standardization makes attributes contribute more equally to similarities among objects. The procedure Cluster in SAS has an STD option which standardizes the variables to mean zero and unit standard deviation.

The Ward's clustering method which will be used in executing the cluster analysis

is very sensitive to outliers so before using this clustering technique the removal of outliers is a must. The trim option in the cluster procedure of SAS eliminates points with low estimated probability densities. A 10% points will be trimmed from the data which is a reasonable value for many data sets. In the present case, 10% points will be equivalent to 4 objects or intersections out of the total of 40 intersections. So the clustering algorithm will work on 36 objects or intersections and 4 attributes constituting 144 data points.

4.7.3 Deciding on the Number of Clusters

After executing the clustering method and generating clusters and relevant statistics, the real question which arises is to decide on the number of clusters to make from the data matrix. Since we want to make clusters for some specific purpose related to attaining the objectives, we want the clusters to be few in number but well defined.

There are no satisfactory methods for determining the number of population clusters for any type of cluster analysis. It is always a good idea to look at data graphically, if only two or three variables are there, use a plot to make scatter plots identifying the clusters. If the data contains more then 2 variables one can use the procedure Candisc of the SAS package to compute canonical variables for plotting and to infer from that the presence of the number of clusters.

Sarle (1983) used extensive simulations to develop the cubic clustering criterion (CCC), which can be used for crude hypotheses testing and estimating the number of population clusters. In addition to CCC, Pseudo F-statistic and Pseudo t^2 statistic can also be used to determine the number of clusters.

It is advisable to look for a consensus among the three statistics, that is local

peaks of the CCC, pseudo F-statistics with a small value of the pseudo t^2 and a larger value of pseudo t^2 statistic for the next cluster fusion. Also graphical plots between CCC and the number of clusters (NCL), pseudo F-statistic and NCL and PST2 and NCL can be plotted to get a better idea of the presence of the number of clusters.

The hierarchical formation of clusters at each iteration and the three statistics i.e the cubic clustering criterion (CCC), the pseudo F-statistic (PSF) and Pseudo T^2 statistic are shown in Table 4.3. One can observe that cubic clustering criterion have significant peaks at number of clusters(NCL)= 4, similarly pseudo F-statistic have a local peak at NCL=4 and pseudo T^2 statistic have a local trough at NCL=4. So all the three statistics strongly suggest the presence of 4 clusters. Clusters obtained in this way will be well defined and more compact in nature. Graphical plots between NCL and CCC and between NCL and PST2 are a good tool to get an idea about the number of clusters present. The plot between NCL and CCC and an overlay between NCL, PSF and PST2 are shown in Appendix B. These plots also show that CCC and PSF have peak's at NCL=4 and Pseudo T^2 has a local trough at NCL=4. Both the plots and statistics confirm the presence of 4 clusters.

4.7.4 Cluster Membership and Its Statistics

The procedure 'cluster means' is invoked in the SAS program, it generates cluster means, standard deviation for all the four attributes selected in the data matrix for cluster analyses. Simple statistics of the four attributes showing mean, standard deviation etc. are shown in Table 4.4. The cluster means for other variables not included in the cluster analysis can be calculated by knowing the cluster membership.

Table 4.3: Statistics for determining the number of clusters

NCL	clusters Joined	Frequency	Cubic clustering criterion (CCC)	pseudo F-statistic	pseudo T^2 statistic
35	10 & 14	2	.	941.4	.
34	11 & 28	2	.	187.2	.
33	24 & 26	2	.	63.2	.
32	9 & CL34	3	.	46.5	4.4
31	13 & 25	2	.	37.5	.
30	20 & CL33	3	.	32.2	1.7
29	CL32 & 27	4	.	27.8	3.2
28	33 & 34	2	.	25.5	.
27	12 & 30	2	.	23.6	.
26	36 & 37	2	.	22.3	.
25	2 & 41	2	.	21.2	.
24	35 & 38	2	.	20.5	.
23	CL35 & 29	3	.	20.1	119.8
22	CL31 & 21	3	.	18.1	4.2
21	19 & CL30	4	.	16.8	4.6
20	CL24 & CL26	4	.	15.8	2.3
19	CL25 & 39	3	.	15.2	2.2
18	16 & 23	2	.	14.8	.
17	1 & CL20	5	.	14.3	2.1
16	CL27 & CL28	4	.	13.9	3.8
15	CL29 & 22	5	.	13.8	7.8
14	3 & 7	2	.	13.8	.
13	CL22 & 40	4	.	13.9	2.9
12	CL23 & 15	4	.	13.5	9.4
11	CL18 & 17	3	.	13.4	2.2
10	CL17 & 6	6	.	13.4	2.2
9	CL16 & CL13	8	.	13.4	3.9
8	CL9 & CL21	12	.	13.7	3.5
7	CL10 & CL14	8	-1.554	13.8	3.6
6	8 & CL8	13	-2.087	13.2	5.9
5	CL12 & CL11	7	-2.419	13.2	6.1
4	CL6 & CL15	18	-1.963	14.1	5.9
3	CL19 & CL4	21	-3.149	11.7	12.5
2	CL7 & CL3	29	-2.139	10.5	10.1
1	CL2 & CL5	36	0.000	.	10.5

The means of the other variables apart from those used in cluster analysis are shown in Table 4.5. 'Procedure frequency' is invoked to get the name of the objects or intersections present in each cluster. The cluster number, its frequency and cluster membership is shown in Table 4.6.

Procedure Tree also creates a dataset indicating cluster membership at any specified level of the cluster tree. 'Proc tree' draws a tree diagram, also called Dendrogram or Phenogram using output from the cluster procedure. The tree diagram is shown in Appendix 'B' . We have decided on the number of clusters to be equal to 4 i.e, we have cut the tree at NCL=4, which corresponds to a semi-partial R^2 value ranging from 0.05 to 0.15 on the tree diagram shown in the Figure B.3.

The question on where to cut the tree depends on the tradeoff between the desire for detail and the desire for generality. As can be seen from the tree diagram, the cluster membership can easily be read from the tree. Similar objects in a cluster are adjacent to each other. The cluster membership for each cluster is shown in Table 4.6.

Table 4.4: Simple cluster statistics

Cluster No.	Variable	No.of approaches	Mean	St.dev.	Min.	Max.
1	Volume	7	685.71	63.50	592	796
	speed	7	52.16	10.63	40.00	71.10
	cross st. width	7	30.29	1.89	28.00	32.00
	Y_a/Y_d	7	1.18	0.125	0.95	1.31
2	Volume	18	865.89	198.13	516.00	1398.00
	speed	18	46.17	6.80	35.10	58.30
	Cross-st. width	18	30.67	1.08	29.00	32.00
	Y_a/Y_d	18	0.77	0.137	0.49	0.98
3	volume	8	915.00	172.35	640.00	1196.00
	speed	8	42.89	5.71	32.00	51.00
	Cross-st width	8	35.88	1.81	34.00	38.00
	Y_a/Y_d	8	0.73	0.136	0.54	0.93
4	volume	3	1446.00	61.612	1380.00	1502.00
	speed	3	59.50	4.33	54.50	62.00
	cross-st. width	3	30.33	1.15	29.00	31.00
	Y_a/Y_d	3	0.63	0.118	0.49	0.70

Table 4.5: Cluster group average for violations, conflicts and ratio of yellow interval timings

Attributes	Cluster#1	Cluster#2	Cluster#3	Cluster#4
VER/cycle	0.32	1.06	1.29	2.15
VEY/cycle	0.89	1.83	2.11	2.58
TOTVEYR/cycle	1.2	2.92	3.03	4.74
SVREC/cycle	0.14	0.12	0.13	0.17
TOTREC/cycle	0.264	0.22	0.263	0.36
Y_a/Y_d	1.18	0.769	0.728	0.627
Y_a/Y_{ITE}	0.88	0.96	0.99	0.79

Table 4.6: Number of clusters and cluster membership

Cluster No.	Frequency	Name of intersections
1	7	10 4 15 16 17 23 29
2	18	8 9 11 12 13 19 21 22 24 25 26 27 28 30 33 34
3	8	1 3 6 7 35 36 37 38
4	3	2 39 41

4.8 Influence of Yellow Interval Ratio on Violations and Conflicts

In this section the influence of yellow interval ratio 'Y_a/Y_d' on violations and conflicts will be studied. As earlier mentioned,'Y_a/Y_d' is the ratio of actual yellow interval to the 85th percentile yellow interval demand, whenever the yellow interval demand is mentioned in subsequent sections, it will mean the 85th percentile yellow interval demand.

Using the results of cluster analysis, plots will be drawn between the ratio 'Y_a/Y_d' and violations and conflicts. The study of plots will reveal the behavior of drivers in terms of violations and conflicts for varying lengths of the yellow interval. Pearson's correlation coefficients between 'Y_a/Y_d' and violations and conflicts will be determined.

4.8.1 Effect of Yellow Interval Ratio (Y_a/Y_d) on Violations

In order to study the behavior of drivers to varying length of yellow, in terms of violations, plot between vehicles entering on yellow (VEY/cycle), vehicles entering on all-red (VER/cycle) and total vehicles entering on yellow and all-red

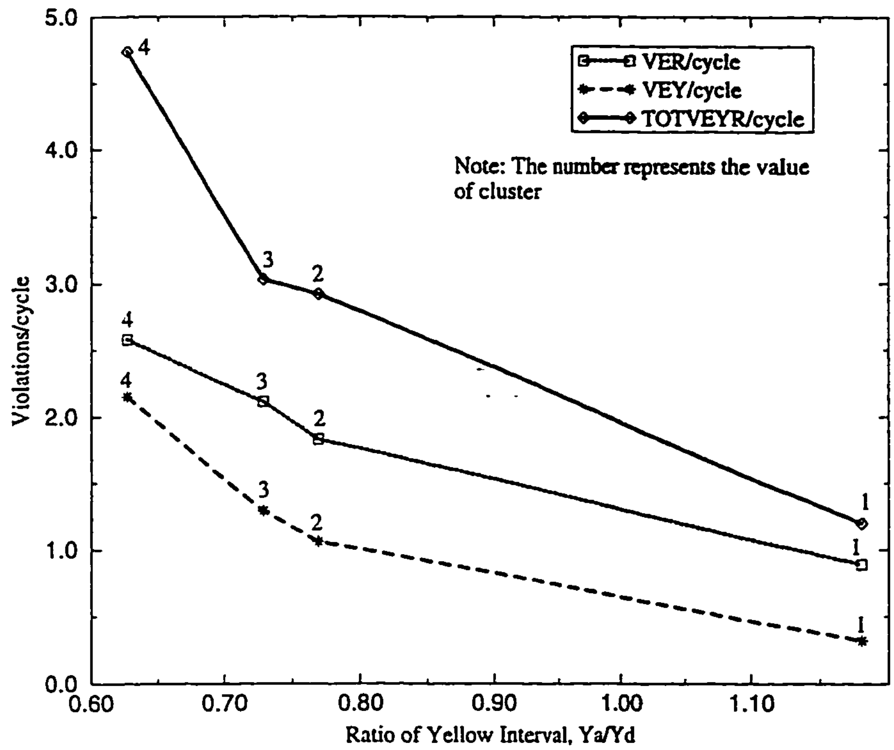


Figure 4.6: Ratio of yellow interval (Y_a/Y_d) as a function of violations.

(TOTVEYR/cycle) against ratio of yellow interval 'Y_a/Y_d' are drawn and are shown in Figure 4.6.

It can be seen that as the ratio of yellow interval increases, the vehicles entering on yellow and all-red decreases sharply. An increase in the ratio of yellow interval implies an increase in the existing yellow interval. This shows that the more the existing yellow interval relative to the observed yellow interval demand, the less are the vehicles that enter on yellow and all-red. So a slight increase of about 10 to 30 percent in the existing yellow will decrease the run-red violations drastically and thereby decrease the risk of cross-street crashes.

Pearson's correlation coefficient were developed between violations and the ratio of yellow timing 'Y_a/Y_d' . A strong negative correlation was found to exists between them and the relationship was significant at 5 % significance level

4.8.2 Effect of Yellow Interval Ratio (Y_a/Y_d) on Rear-End Conflicts

In order to study the behavior of drivers to varying length of yellow interval in terms of conflicts, plots between slow vehicle rear-end conflict (SVREC/cycle) and total rear-end conflict (TOTREC/cycle) are drawn against the ratio of yellow interval timing 'Y_a/Y_d' respectively as shown in Figure 4.7

It can be seen from the plot that the conflicts for both the SVREC/cycle and TOTREC/cycle decreases initially with an increase in the ratio of yellow interval 'Y_a/Y_d' upto a point where the actual yellow interval 'Y_a' equals '$0.77Y_d$', implying a reduction in the dilemma zone. An increase in the ratio of yellow interval 'Y_a/Y_d' above 0.77 will steadily increase both the slow vehicle rear-end conflict and total rear-end conflict implying the creation of the option zone. So an appropriate yellow interval should be based on the transition point between the dilemma zone and the option zone at which the conflicts are minimum. In the figure, the actual yellow of '$0.77Y_d$' corresponds to a minimum number of conflicts

It can be recalled that this kind of behavior is earlier reported in literature [13], and it is a fact that as the actual yellow interval is less than the adequate yellow interval, a dilemma zone exists and the rear-end conflicts steadily increase (Figure 4.7). Similarly if the yellow interval is above the adequate yellow timing, an option zone exists and an increase in the number of conflicts is observed (Figure 4.7).

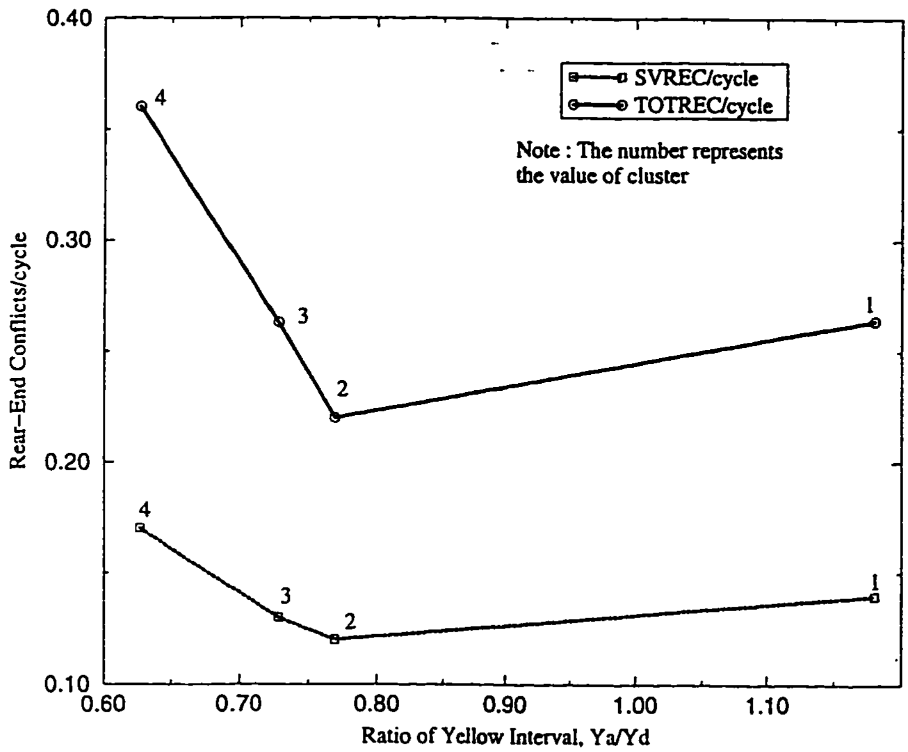


Figure 4.7: Ratio of yellow interval (Y_a/Y_d) as a function of rear-end conflicts.

4.9 Comparison of Yellow Interval Timings in Relation to Violations and Conflicts

In this section, a comparison between yellow interval demand 'Y_d' and the yellow interval obtained by the ITE method, 'Y_{ITE}' will be made relative to the actual yellow interval. The comparison will be done in relation to violations and conflicts.

4.9.1 Comparison between (Y_a/Y_d) and (Y_a/Y_{ITE}) with respect to Violations

Plots between 'Y_a/Y_d' and 'Y_a/Y_{ITE}' are drawn against vehicles entering on yellow (VEY/cycle), vehicles entering on all-red (VER/cycle) and against the total vehicles entering during yellow and all-red (TOTVEYR/cycle) as shown in Figures 4.8, 4.9 and 4.10 respectively. It can be seen in all the plots that as the ratio 'Y_a/Y_d' increases the vehicles entering on yellow, all-red and during both yellow and all-red decreases drastically. This result is supported by earlier researchers [27]. A slight increase in yellow by about 10 to 30% will considerably reduce the run-red violations. It can be observed that nearly 90 percent of the approaches to signalized intersections have a yellow time less than the observed yellow interval demand

An unusual trend is seen in the plot between 'Y_a/Y_{ITE}' vs VEY/cycle, VER/cycle and TOTVEYR/cycle respectively. It can be seen that as 'Y_a/Y_{ITE}' increases the violations decreases initially but as 'Y_a' equals or exceeds '0.88 Y_{ITE}', the violations increase rapidly. This is unusual because as the yellow interval increases the violation should decrease. This unusual behavior seems to occur because the points for which the curve increased (cluster no.2 and cluster no.3), constitutes clusters with 18 and

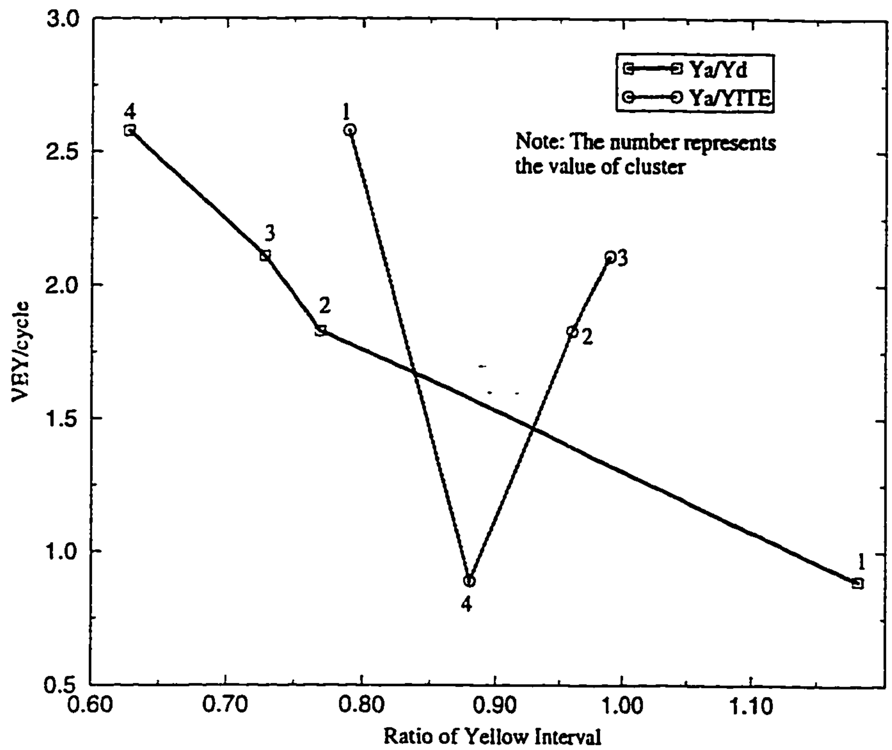


Figure 4.8: Ratio of yellow interval against the vehicles entering during yellow per cycle, (VEY/cycle).

8 approaches having low approach speeds of 46.17 and 42.89 km/hr respectively, as shown in Table 4.4. In earlier studies [20], it was found that the probability of stopping by drivers at the onset of yellow is less at low approach speeds. The study also shows that the yellow timing formula given by ITE *fails* to give a correct yellow timing for approaches to intersections with *low approach speeds.* So the yellow interval timing obtained by the ITE method can only be substantiated at high approach speeds [20]. This seems to be the possible reason for a sudden increase in violations with the increase in the 'Y_a/Y_{ITE}' ratio.

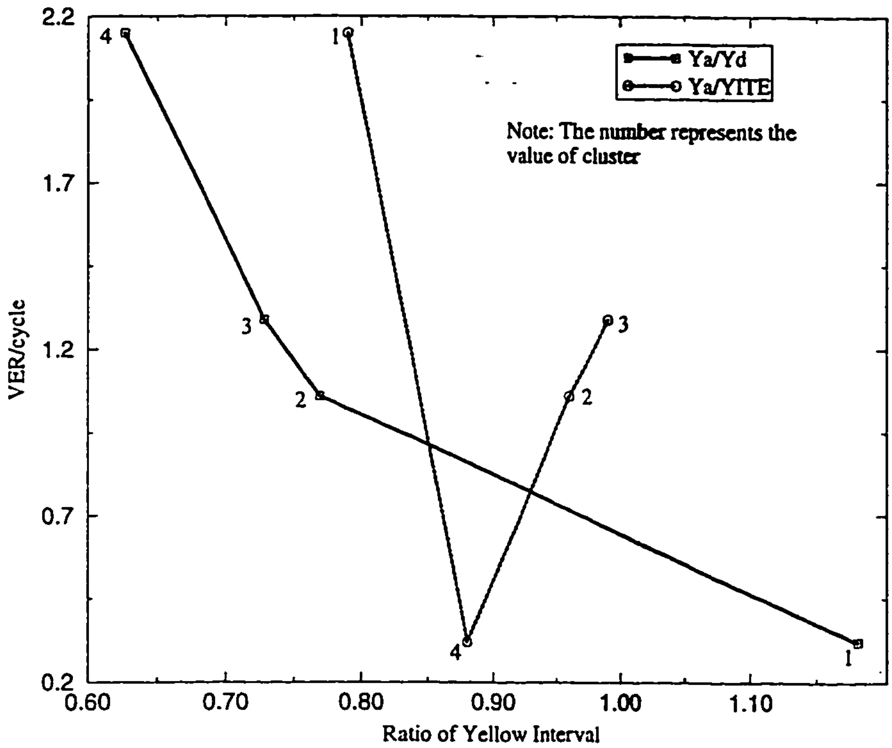


Figure 4.9: Ratio of yellow interval against the vehicles entering during all-red per cycle, (VER/cycle).

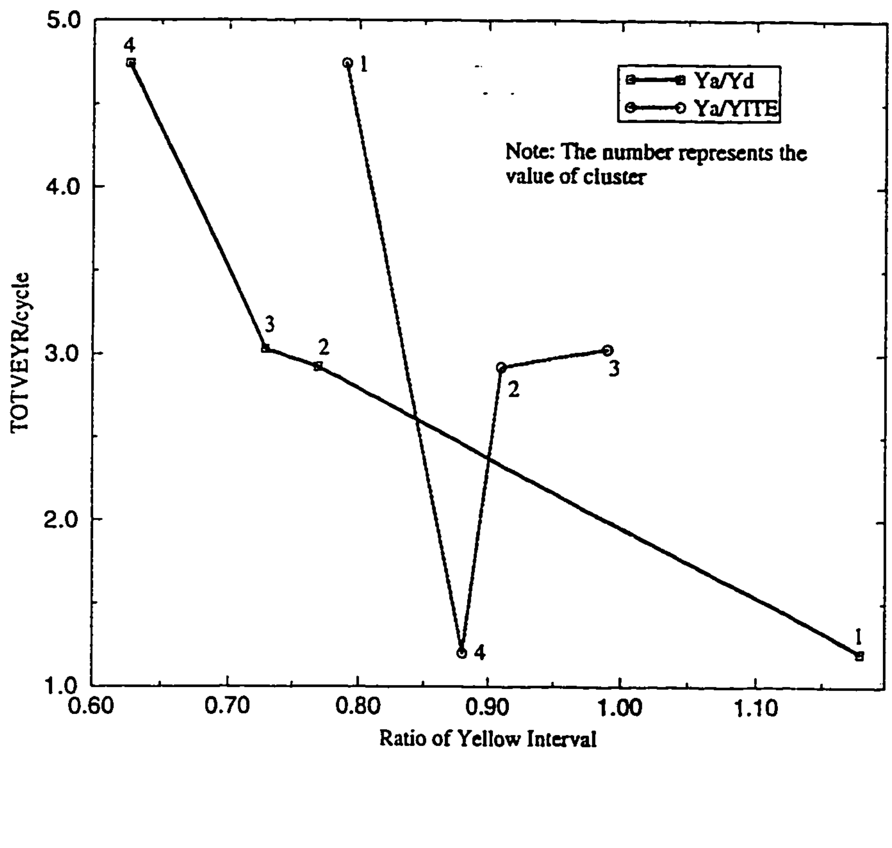


Figure 4.10: Ratio of yellow interval as a function of the total vehicles entering during yellow and all-red per cycle, (TOTVEYR/cycle).

4.9.2 Comparison between (Y_a/Y_d) and (Y_a/Y_{ITE}) in relation to Rear-end Conflicts

In order to compare the yellow interval demand and the yellow interval timing obtained by the ITE method in relation to conflicts, plots were drawn between 'Y_a/Y_d' and 'Y_a/Y_{ITE}' against slow vehicle rear-end conflict (SVREC/cycle) and total rear-end conflict (TOTREC/cycle) as shown in Figures 4.11 and 4.12 respectively.

From figure 4.11, it can be seen that the slow vehicle rear-end conflict decreases as the ratio of yellow interval increases due to a reduction in the dilemma zone. However, after reaching a point where '$Y_a = 0.77\ Y_d$' on the 'Y_a/Y_d' curve and '$Y_a = 0.95\ Y_{ITE}$' on the 'Y_a/Y_{ITE}' curve respectively, the slow vehicle rear-end conflict (SVREC/cycle) increases with an increase in the ratio of yellow interval implying the creation of an option zone leading to increase in rear-end conflicts.

Similarly from Figure 4.12, it can be seen from both the curves 'Y_a/Y_d' and 'Y_a/Y_{ITE}' that as the ratio of the yellow interval increases or actual yellow increases the total rear-end conflicts decreases due to reduction in the dilemma zone. But after reaching a point where '$Y_a = 0.77\ Y_d$' on the 'Y_a/Y_d' curve and an '$Y_a = 0.95\ Y_{ITE}$' on the 'Y_a/Y_{ITE}' curve, the total rear-end conflicts increases with an increase in the ratio of the yellow interval, signifying an increase in the option zone.

In conclusion it can be said that the two timings, the yellow interval demand 'Y_d' and the yellow interval timing obtained by the ITE method, the 'Y_{ITE}' timings are safe in terms of both violations and conflicts, but from the efficiency point of view, the yellow interval obtained by the ITE method is on the conservative side as compared to the yellow interval demand.

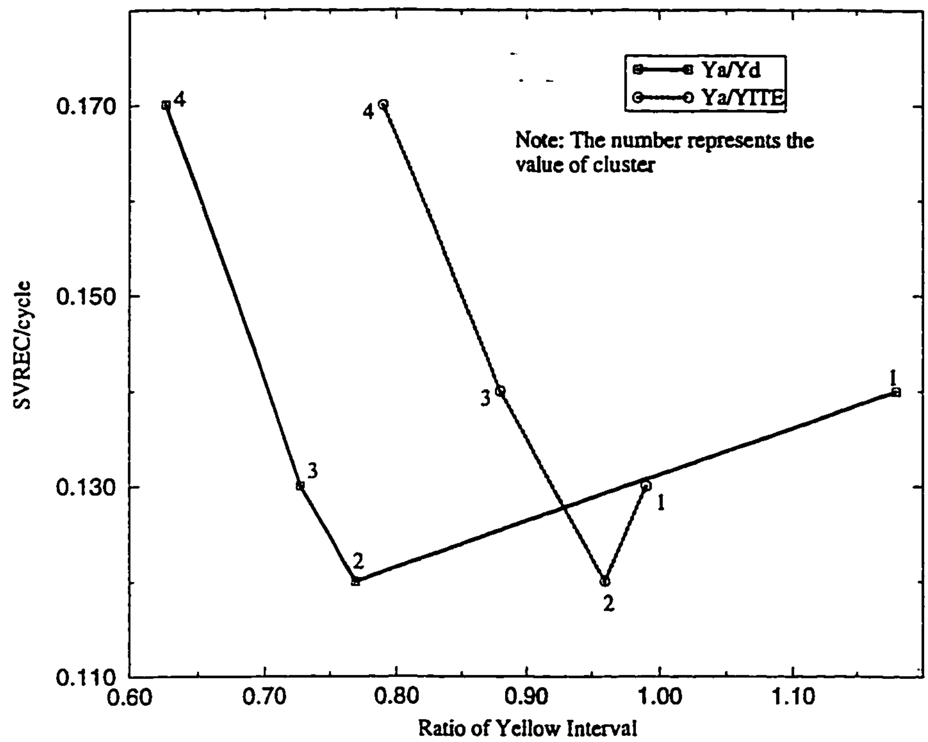


Figure 4.11: Ratio of yellow interval against the slow vehicle rear-end conflicts per cycle, (SVREC/cycle).

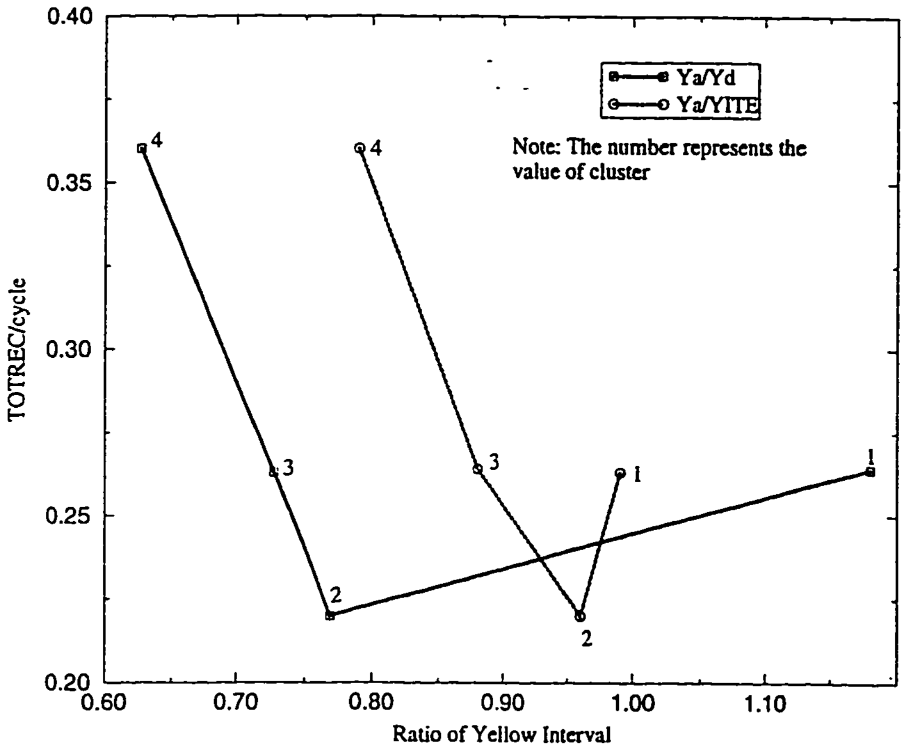


Figure 4.12: Ratio of yellow interval against the total rear-end conflicts per cycle, (TOTREC/cycle).

4.10 Influence of Traffic Characteristics on Violations and Conflicts

We believe that there are certain extraneous effects on violations and conflicts which have to be taken care of, even if the driver behavior is accounted for in the design of the yellow interval. These factors are normally the geometric and traffic characteristics. In this section the behavior of drivers at the onset of yellow was studied by understanding the influence of traffic characteristics on violations and conflicts. Plots were drawn between the traffic characteristics, speed and volume against violations and conflicts. Pearson's correlation coefficients were established between the traffic characteristics and violations and conflicts.

4.10.1 Effect of Volume and Speed on Violations

As can be seen from the Figure 4.13 when the approach volume increases, the vehicles entering on yellow, all-red and during yellow and all-red increases drastically. In a similar study [4] done in Riyadh it was found that the frequency of violations seems to increase with the increase in traffic volumes.

Figure 4.14 shows the plot between speed and violations. It can be seen that for the vehicles entering on yellow, all-red and during both yellow and all-red the violations decrease with increase in speed, but it can also be observed that at high speeds of 58 to 60 kmph the violations increases rapidly. Hence it can be concluded that when the approach speeds are low, the headway is less and the violations are more. This finding is supported in literature [20]. Also when the speeds are very high i.e greater than or equal to 58 to 60 kmph the violations seem to increase

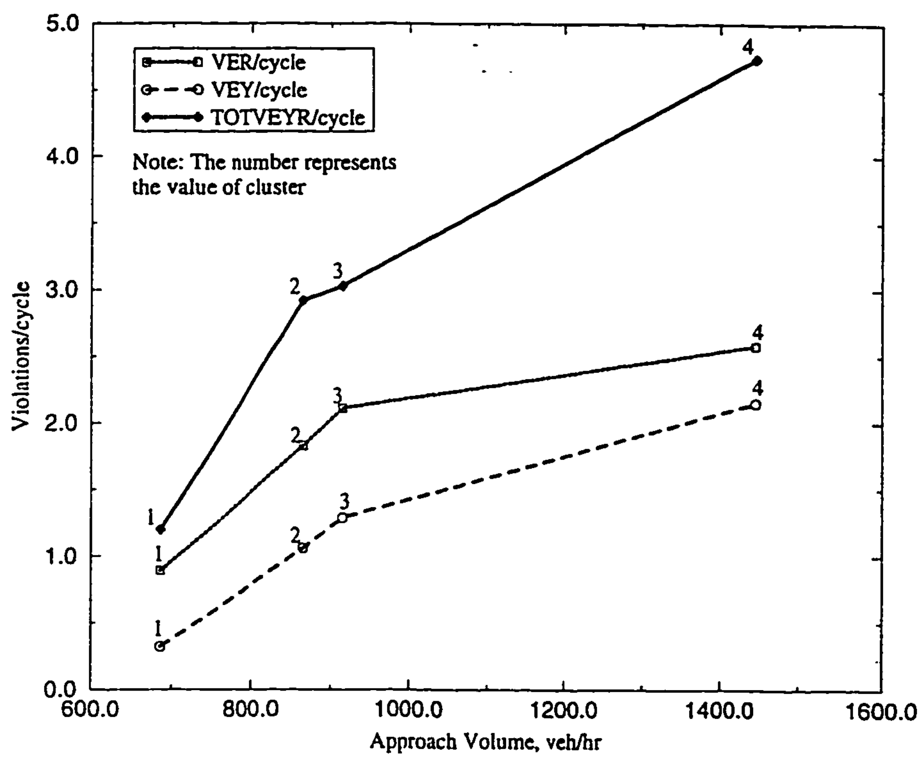


Figure 4.13: Plot of approach volume against Violations.

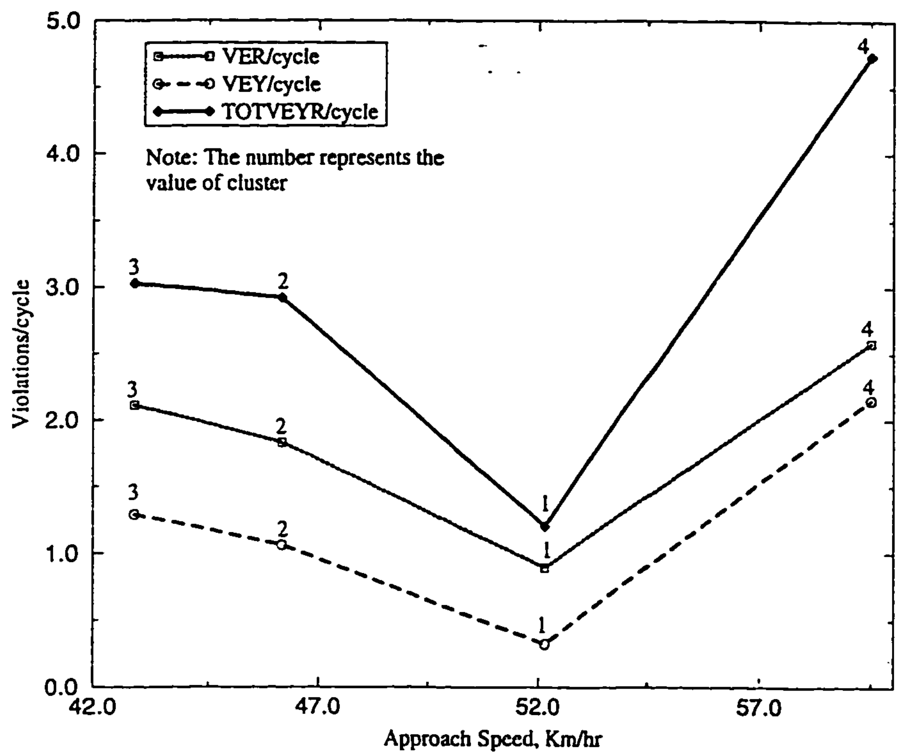


Figure 4.14: Plot of approach speed against Violations.

drastically.

Pearson's correlation coefficient were calculated betweeen violations and volume and they were found to have a strong positive correlation and the relationship between them was found to be significant at 5% significance level.

4.10.2 Effect of Volume and Speed on Rear-End Conflicts

Figure 4.15 shows the plot between total rear-end conflicts (TOTREC/cycle), slow vehicle rear-end conflict (SVREC/cycle) and volume. It can be observed that as the volume increases, the rear-end conflicts decrease initially but as the approach volume exceeds 800 veh/hr the conflicts increase, indicating that more the vehicles present near the stopline at the onset of yellow, the more will be the vehicles caught in the option or dilemma zone leading to rear-end conflicts.

Plots are drawn between rear-end conflicts and approach speed (km/hr) as shown in Figure 4.16. It can be observed that as the approach speed increases, rear-end conflicts decrease initially, but as the approach speed reaches or exceeds 45km/hr both total and slow vehicle rear-end conflict increase steadily, indicating that speed in addition to volume influences rear-end conflicts at signalized intersections. The relationship was found to be significant at $\alpha = 10\%$ significance level.

Pearson's correlation coefficient was calculated between volume and rear-end conflicts. A positive correlation was found to exists between them as expected. Also the relationship between approach volume and rear-end conflicts was statistically significant at $\alpha = 1\%$ significance level.

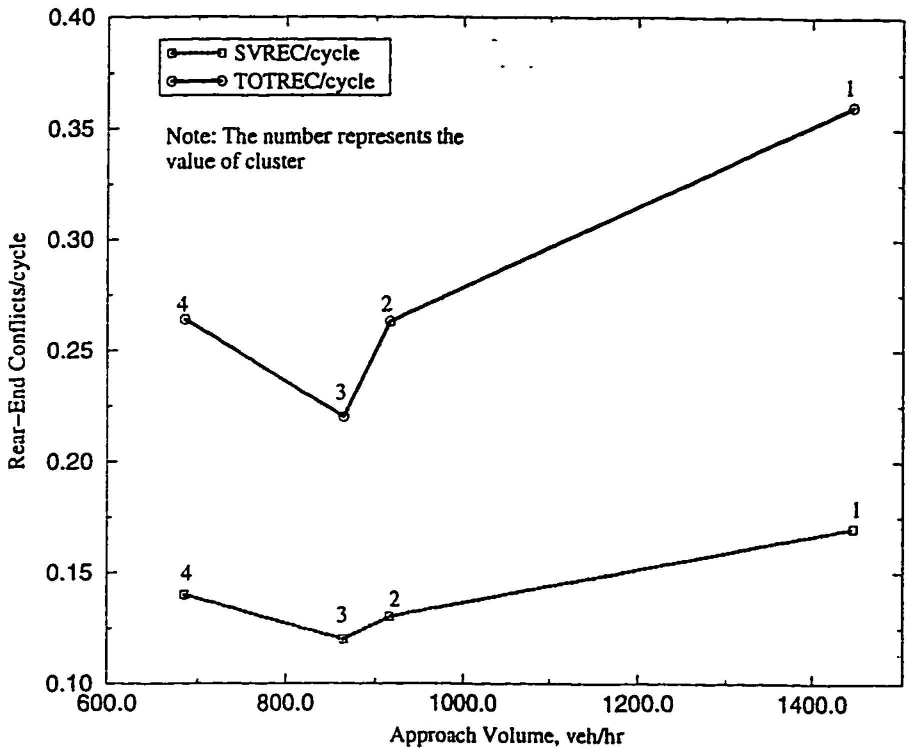


Figure 4.15: Plot of approach volume as a function of rear-end conflicts.

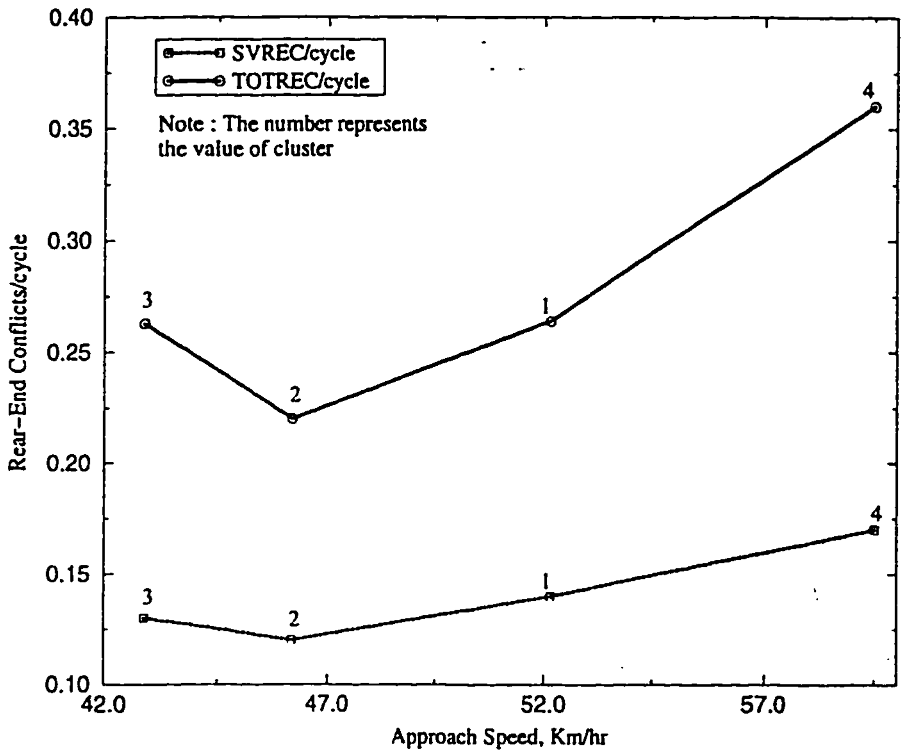


Figure 4.16: Plot of approach speed as a function of rear-end conflicts.

Chapter 5

Conclusions and Recommendations

5.1 Summary

One of the main objective of this study was to develop the yellow interval timing at signalized intersections in the Eastern Province of Saudi Arabia. The reason for developing a new method based on driver behavior stems from the observation that the current or existing yellow interval timing is below adequate, thereby leading to an increase in violations and conflicts. The existing yellow interval timing is based on a rule of thumb and there is no standard method behind timing the yellow interval. The formula given by the Institute of Transportation Engineers may be used in setting the yellow interval. It is based on the principles of kinematics and states that the yellow interval duration should be increased as the approach speed increases, this underlying assumption of ITE was criticized by recent researchers [3].

A new method based on the time for the last vehicle to enter the intersection after

the onset of yellow was designed so as to take care of driver behavior at signalized intersections. Data for the yellow interval demand 'Y_d' (time elapsed between the onset of yellow till the last entering vehicle reaches the stopline), vehicle supply (vehicles entering during yellow and all-red), approach speed, approach volume and cross-street width was collected at 44 signalized intersections at Khobar, Thuqbah and Dammam region. The study was made for a period of 30 minutes during the afternoon peak at all intersections. Initial results of regression analysis showed that out of 4 independent variables (approach volume, approach speed, cross-street width and vehicle supply), only vehicle supply was found to influence the yellow interval demand and the relationship between them was found to be significant. Hence, the models for the yellow interval demand were built as a function of Vehicle supply. The general form of the model is given as under:

$$Y_d = Y_m + \mathrm{C}$$

where,

$$\mathrm{C} = \mathrm{AX} + \mathrm{B}$$

Combining the above two relations will result in

$$\mathrm{C} = Y_m + \mathrm{Ax} + \mathrm{B}$$

Where,

Y_d = Yellow interval needed to satisfy a specified level of demand at a given intersection, sec.

Y_m = Yellow interval demand needed to satisfy a specified level of yellow interval demand at about 50 percent of the intersections, sec.

C = Y_d - Y_m = correction factor to be modeled as a function of the traffic characteristics, sec.

The 85th and 95th percentile yellow interval demands 'Y_{85}' and 'Y_{95}', respectively were calculated from the sample of observations for each intersection. For example, the 85th percentile yellow interval demand at a particular intersection means that about 85 percent of the time, the drivers were entering the intersection for upto 'Y_d' sec from the onset of yellow. The model for 85th percentile yellow interval demand takes the form as follows.

$$Y_{85} = 3.79 + C$$

where 'C' is modelled as;

$$C = - 1.31 + 0.46X$$

The model developed for the correction factor 'C' was significant at $\alpha = 1\%$ significance level and the parameter estimates were also significant at 1% significance level. The model yielded an R^2 value of 0.63. The final expression of the yellow interval demand after substituting the value of correction factor 'C' accounts to

$$Y_{85} = 2.46 + 0.46X$$

The above relation can satisfactorily be used to determine the 85th percentile yellow interval demand at any signalized intersection. The 85th percentile yellow

interval demand is suggested for setting the yellow interval because it is a tradeoff between safety and efficiency.

Similarly the model for 95th percentile yellow interval demand takes the form as follows

$$Y_{95} = 4.48 + \mathrm{C}$$

where 'C' is modelled as follows;

$$\mathrm{C} = -1.19 + 0.41\mathrm{X}$$

The model and parameter estimates for the correction factor at 95th percentile yellow interval demand are significant at $\alpha = 1\%$ significance level. The final expression for 95 percentile yellow interval demand after combining the above two relations accounts to the following relation.

$$Y_{95} = 3.29 + 0.41\mathrm{X}$$

The above relation can satisfactorily be used to set the 95th percentile yellow interval demand at signalized intersections.

5.2 Driver Behavior at the onset of Yellow Interval

In order to study the driver behavior at the onset of yellow , the data for violations, conflicts, traffic and geometric characteristics were collected at 44 signalized intersections. Using cluster analysis, the data was reduced to 4 clusters, the Ward's

minimum variance algorithm was used in data reduction. Cluster means were obtained for the variables used for clustering such as cross-street width, volume, speed and ratio of yellow interval 'Y_a/Y_d'.

Plots were drawn between violations such as vehicles entering on yellow (VEY/cycle), vehicles entering on all-red (VER/cycle) and vehicles entering during yellow and all-red (TOTVEYR/cycle) and approach volume. In all the cases an increase in volume resulted an increase in violations. Pearson's correlation coefficient were calculated for violations and volume, a significant correlation was found at $\alpha = 1\%$ significance level. A plot between rear-end conflicts and volume revealed an initial decrease in conflicts with an increase in volume, but for the major part of the curve the rear-end conflicts increases as the approach volume increases. Pearson's correlation coefficient was obtained which indicated a significant relationship between volume and rear-end conflicts at $\alpha = 5\%$ significance level.

Plots between violations and approach speed reflect that as the speed increases the violations decrease, but as the speed exceeds 58km/hr the violations seem to increase rapidly. Similarly plot between conflicts and approach speeds indicate that as the speed increases, conflicts tend to increase linearly.

Ratio of yellow interval 'Y_a/Y_d' was plotted against violations and conflicts. It was observed that as the ratio increases, the violations decrease rapidly. It implies that a slight increase of about 10 to 30 % in the existing yellow will reduce the violations significantly. Pearson's correlation coefficient were calculated between violations and 'Y_a/Y_d'. The relationship for all the violations such as vehicles entering on yellow (VEY/cycle), vehicles entering on all-red (VER/cycle) and total vehicles entering during yellow and all-red (TOTVEYR/cycle) was found to be significant

at $\alpha = 5\%$ significance level

Comparisons between ratio of yellow interval timings in relation to violations were studied. Plots between 'Y_a/Y_d' , 'Y_a/Y_{ITE}' and violations such as vehicles entering on yellow (VEY/cycle), vehicles entering on all-red (VER/cycle), and total vehicles entering during yellow and all-red (TOTVEYR/cycle) were drawn. The plots reflect that as the ratio of yellow interval demand increases the violations decrease as is usual in the case of 'Y_a/Y_d'. The curve for 'Y_a/Y_{ITE}' decreases initially but suddenly increases at '$Y_a = 0.99\ Y_{ITE}$'. This unusual behavior seems to occur because the points for which the curve increases constitute clusters (cluster #2 and cluster #3), with 18 and 8 approaches respectively having low approach speeds (46.17 and 42.89 km/hr) and as indicated in earlier studies, the ITE method *fails* to give correct yellow interval timing at *low approach speeds.* It is found in literature [20], that the stopping probability is less at low approach speeds and the yellow interval timing obtained by ITE method can be substantiated only at high approach speeds. This seems to be the reason for a sudden increase in violations with an increase in the 'Y_a/Y_{ITE}' ratio.

plots were drawn between ratio of yellow interval 'Y_a/Y_d' and 'Y_a/Y_{ITE}' against rear-end conflicts. In both the plots a decrease in conflicts was indicated by a slight increase in the ratio, indicating the reduction of dilemma zone, but after a certain point was reached there seems to be an increase in the rear-end conflicts indicating the creation of an option zone. Hence, the yellow timing should be set at this transition point where the rear-end conflicts are a minimum.

5.3 Conclusions

In the light of the above findings the following conclusions can be drawn.

1. Model of 85th percentile yellow interval demand can be used to set the yellow interval timing at signalized intersections.

2. For most of the study sites, a uniform yellow interval of 3.8 sec will virtually guarantee that at least 85th percentile yellow interval demands are satisfied.

3. The existing yellow interval timing is significantly less than the observed yellow interval demand.

4. Yellow interval timing obtained by the ITE method gives a slightly conservative estimate compared to the observed yellow interval demand.

5. Field studies showed that the yellow interval duration is not linearly related to approach speeds contrary to what is suggested by the ITE method.

6. Increase in the volume indicate an increase in violations.

7. Low and high speed approaches have more violations compared to moderate speeds. The violations seems to be minimum for vehicles travelling at the posted speed of 50 km/hr.

8. Rear-end conflicts increase linearly with an increase in approach speeds and approach volumes respectively.

9. An increase in the yellow interval timing by 10 to 30% will drastically decrease the run-red violations.

10. At low approach speeds, the ITE method fails to give the correct yellow interval timing.

11. Approach speed in addition to approach volume influences the rear-end conflicts and violations at signalized intersections.

5.4 Recommendation

The following recommendation is made for future study:

The data for the yellow interval demand and vehicle supply was collected for a duration of 30 minutes during the afternoon peak. It is recommended that the above data be collected for other times of the day. The model subsequently built will be comprehensive and will reflect drivers demand for different times of the day.

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Appendix A

Definitions of Traffic Conflict

A.1 General Definition of a Traffic Conflict

One excellent generalized definition was generated at the International conference in Oslo [36].

"A traffic conflict is an observable situation in which two of more road users approach each other in space and time to such an extent that there is a risk of collision if these movements remain unchanged."

A.2 Specific Traffic Conflict Definitions

1. Left-turn, Same Direction

A left-turn, same direction conflict situation occurs when an instigating vehicle slows to make a left turn, thus placing a following, conflicted vehicle in jeopardy of a rear-end collision. The conflicted vehicle brakes or swerves, then continues through the intersection.

2. Right-turn, Same Direction

A right-turn, same direction conflict situation occurs when an instigating vehicle slows to make a right-turn, thus pacing a following, conflicted vehicle in jeopardy of a rear-end collision. The conflicted vehicle brakes or swerves, then continues through the intersection.

3. Slow Vehicle, Same Direction

A slow vehicle, same direction conflict situation occurs when a instigating vehicle

slows while approaching or passing through an intersection, thus placing a following vehicle in jeopardy of a rear-end collision. The following vehicle brakes or swerves, then continues through the intersection. The reason for the vehicles slowness may or may not be evident, but it could simply be a precautionary action, or as the result of some congestion or other cause beyond the intersection.

4. Lane Change

A lane change conflict situation occurs when an instigating vehicle changes from one lane to another, thus placing a following, conflicted vehicle in the new lane in jeopardy of a rear-end or side swipe collision. The conflicted vehicle brakes or swerves, then continues through the intersection.

Appendix B

Tables and Figures

No.	Approach Name	D	Type	Lanes	Bay	Cross-width(m)	15th% Speed(kmph)	85th% Speed (kmph)	Vol(veh/hr)
1.00	King Abdul Aziz/18th St.	NB	4-leg	3.00	W	35.00	33.00	51.00	908.00
2.00	King Abdul Aziz/18th St.	EB	4-leg	4.00	W	31.00	47.00	62.00	1456.00
3.00	King Abdul Aziz/11th St.	NB	4-leg	4.00	W	38.00	35.00	43.00	952.00
4.00	Makkah/Dhahran St.	NB	4-leg	3.00	W/o	110.00	30.50	42.50	894.00
5.00	Makkah/Dhahran St.	SB	4-leg	3.00	W/o	110.00	39.70	54.40	956.00
6.00	King Saud/11th St.	NB	4-leg	3.00	W/o	38.00	28.40	41.30	640.00
7.00	King Saud/11th St.	SB	4-leg	3.00	W/o	38.00	20.00	32.00	1196.00
8.00	King Saud/11th St.	EB	4-leg	3.00	W/o	31.00	22.20	35.10	1398.00
9.00	King Saud/11th St.	WB	4-leg	3.00	W/o	31.00	25.50	38.90	780.00
10.00	Mecca/20th St.	NB	4-leg	3.00	W	32.00	24.80	45.60	686.00
11.00	Mecca/20th St.	SB	4-leg	3.00	W	32.00	28.80	39.90	720.00
12.00	Mecca/20th St.	EB	4-leg	3.00	W	30.00	28.80	44.50	860.00
13.00	Mecca/15th St.	NB	4-leg	3.00	W	32.00	30.80	46.80	688.00
14.00	Mecca/15th St.	SB	4-leg	3.00	W	32.00	27.50	45.10	672.00
15.00	Riyadh/15th St.	NB	4-leg	3.00	W	28.00	28.00	40.00	592.00
16.00	Riyadh/15th St.	SB	4-leg	3.00	W	28.00	38.40	53.30	652.00
17.00	Meqrin/28th St.	EB	4-leg	3.00	W	29.00	48.30	71.10	728.00
18.00	Meqrin/28th St.	WB	4-leg	3.00	W	29.00	39.90	57.80	938.00
19.00	Amir Fahad/11th St.	NB	4-leg	3.00	W/o	30.00	40.80	58.30	1062.00
20.00	Amir Fahad/11th St.	SB	4-leg	3.00	W/o	30.00	37.60	54.90	984.00
21.00	Amir Fahad/11th St.	EB	4-leg	3.00	W/o	30.00	31.80	54.50	612.00
22.00	Amir Fahad/11th St.	WB	4-leg	3.00	W/o	30.00	21.50	38.30	516.00
23.00	Amir Fahad/18th St.	NB	4-leg	3.00	W/o	31.00	35.80	60.50	674.00
24.00	Amir Fahad/18th St.	SB	4-leg	3.00	W	31.00	35.80	51.70	1034.00
25.00	Amir Fahad/18th St.	EB	4-leg	3.00	W/o	31.00	29.50	47.60	826.00
26.00	Amir Fahad/18th St.	WB	4-leg	3.00	W	31.00	36.40	50.30	1032.00
27.00	King Khaled/11th St.	NB	4-leg	3.00	W/o	32.00	25.20	41.60	844.00
28.00	King Khaled/11th St.	SB	4-leg	3.00	W/o	32.00	29.00	37.90	760.00
29.00	King Khaled/11th St.	EB	4-leg	3.00	W/o	32.00	36.00	49.50	796.00
30.00	King Khaled/11th St.	WB	4-leg	3.00	W/o	32.00	26.00	41.00	922.00
31.00	King Abdul Aziz/28th	EB	4-leg	3.00	W	65.00	39.50	54.50	872.00
32.00	King Abdul Aziz/28th	WB	4-leg	3.00	W	65.00	41.40	64.50	912.00
33.00	King Saud/18th St.	NB	4-leg	3.00	W	29.00	33.30	49.50	914.00
34.00	King Saud/18th St.	SB	4-leg	3.00	W	29.00	39.00	51.70	766.00
35.00	King Saud/18th St.	EB	4-leg	3.00	W	34.00	31.50	46.70	992.00
36.00	King Saud/18th St.	WB	4-leg	3.00	W	34.00	28.30	46.10	818.00
37.00	King Khaled/18th St.	NB	4-leg	3.00	W	35.00	23.50	39.00	772.00
38.00	King Khaled/18th St.	SB	4-leg	3.00	W	35.00	32.70	44.00	1042.00
39.00	King Khaled/18th St.	EB	4-leg	3.00	W/o	29.00	33.80	54.50	1502.00
40.00	King Khaled/18th St.	WB	4-leg	3.00	W	29.00	28.80	48.50	868.00
41.00	king Khaled/28th St.	NB	4-leg	3.00	W/o	31.00	42.00	62.00	1380.00
42.00	king Khaled/28th St.	SB	4-leg	3.00	W	31.00	21.00	33.00	1636.00
43.00	king Khaled/28th St.	EB	4-leg	4.00	W/o	41.00	33.50	62.90	1736.00
44.00	king Khaled/28th St.	WB	4-leg	3.00	W	41.00	53.40	70.00	1268.00

Table B.1: Traffic and geometric characterstics of selected signalized intersections.

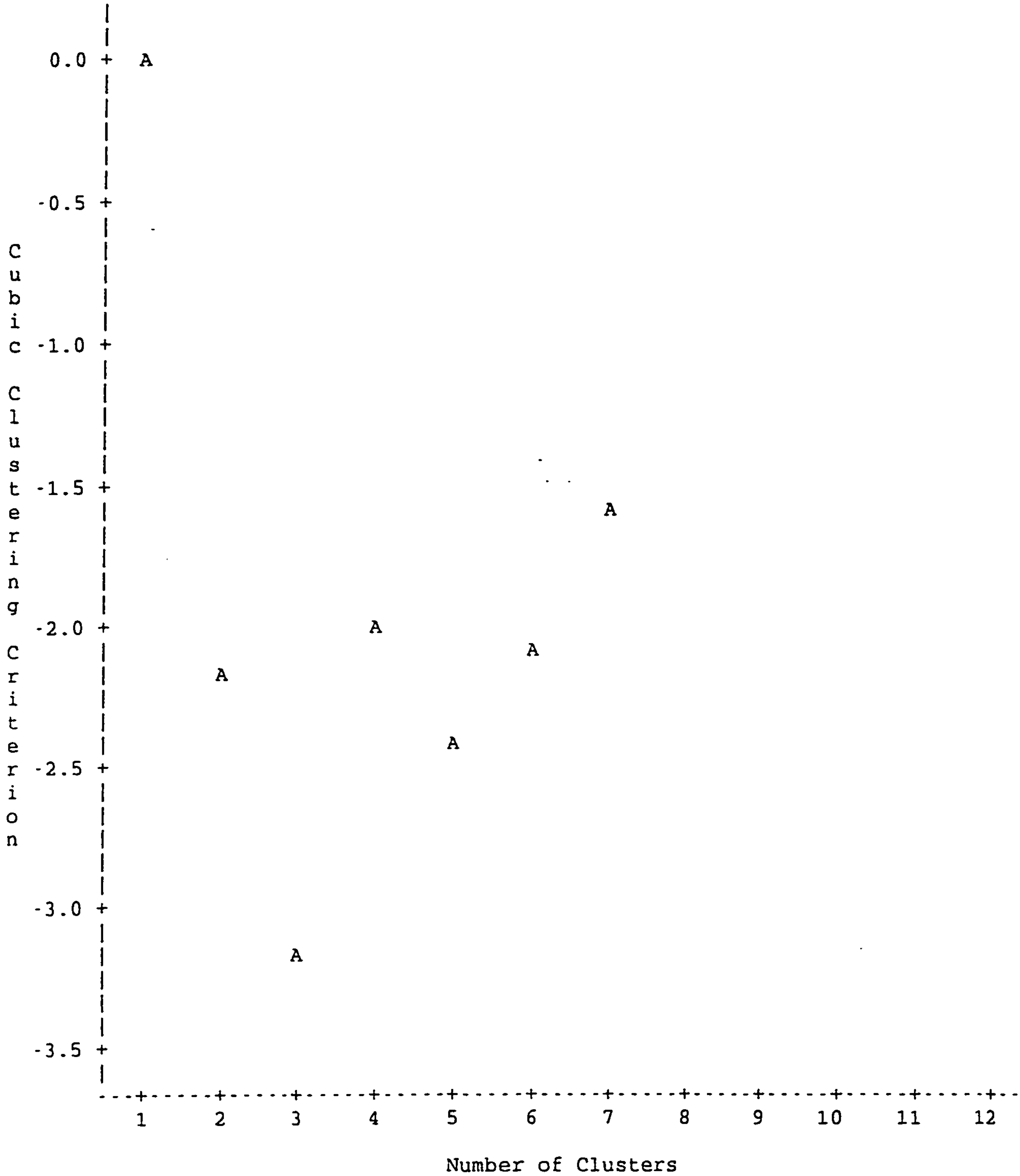
No.	Green(A)	Yell(A)	Yell(ITE)	YD(85)	YD(95)	YD(max)	AR(A)	AR(ITE)	TOTCI(A)	TOTCI(ITE)
1.00	25.11	2.89	3.32	3.10	4.79	5.50	2.06	3.66	4.95	6.99
2.00	29.00	2.98	3.83	4.25	5.12	5.50	2.06	2.16	5.04	5.98
3.00	20.04	2.86	2.96	5.25	6.75	7.50	0.32	4.17	3.18	7.13
4.00	18.00	2.94	2.94	4.08	4.75	5.50	4.09	13.15	7.03	16.09
5.00	17.96	2.95	3.48	3.88	4.75	5.50	4.09	9.86	7.04	13.33
6.00	25.00	2.98	2.88	3.42	4.75	5.50	2.13	5.00	5.11	7.88
7.00	24.84	2.93	2.46	4.37	5.12	5.50	2.13	7.39	5.06	9.85
8.00	24.80	3.06	2.60	3.29	3.75	4.50	2.13	5.43	5.19	8.03
9.00	24.93	2.99	2.77	4.08	4.75	5.50	2.13	4.63	5.12	7.40
10.00	23.02	2.89	3.08	2.44	2.12	3.50	2.17	4.58	5.06	7.66
11.00	19.83	2.93	2.82	4.46	5.12	5.50	2.17	4.26	5.10	7.07
12.00	19.77	2.93	3.03	3.05	3.35	3.50	2.17	3.80	5.10	6.82
13.00	20.02	2.84	3.13	3.88	4.75	5.50	2.09	3.72	4.93	6.86
14.00	25.06	2.89	3.06	2.42	3.12	3.50	2.09	4.18	4.98	7.24
15.00	20.06	2.95	2.82	2.25	3.75	4.50	2.03	3.84	4.98	6.66
16.00	15.07	2.96	3.43	2.44	4.12	4.50	2.03	2.52	4.99	5.95
17.00	35.05	2.94	4.24	3.08	3.75	4.50	2.11	1.78	5.05	6.02
18.00	35.05	2.86	3.63	1.94	2.31	2.50	2.11	2.35	4.97	5.98
19.00	31.21	2.96	3.66	4.75	5.25	5.50	2.69	2.39	5.65	6.04
20.00	30.92	2.95	3.50	3.75	4.25	4.50	2.69	2.67	5.64	6.17
21.00	24.45	2.94	3.48	3.75	4.25	4.50	2.69	3.05	5.63	6.53
22.00	23.34	3.01	2.75	3.88	4.75	5.50	2.69	5.28	5.70	8.02
23.00	22.88	3.02	3.76	2.75	3.25	3.50	2.08	2.60	5.10	6.36
24.00	22.83	3.06	3.36	4.05	4.35	4.50	2.08	3.01	5.14	6.36
25.00	23.03	2.90	3.17	4.05	4.35	4.50	2.08	3.70	4.98	6.87
26.00	23.00	3.01	3.29	3.44	5.12	5.50	2.08	3.03	5.09	6.33
27.00	24.77	2.93	2.90	5.08	5.75	6.50	1.97	4.69	4.90	7.59
28.00	24.89	2.88	2.73	4.37	5.12	5.50	1.97	4.32	4.85	7.05
29.00	30.85	2.94	3.26	2.25	3.75	4.50	1.97	3.19	4.91	6.45
30.00	31.08	2.90	2.87	3.13	3.38	3.50	1.97	4.59	4.87	7.46
31.00	24.72	2.90	3.48	2.44	3.12	3.50	2.40	5.79	5.30	9.28
32.00	24.64	2.91	3.94	2.46	3.12	3.50	2.40	5.13	5.31	9.07
33.00	24.92	2.91	3.26	3.37	4.12	4.50	2.36	3.06	5.27	6.31
34.00	25.00	2.98	3.36	3.05	3.34	3.50	2.36	2.66	5.34	6.02
35.00	24.99	2.85	3.13	5.05	5.35	5.50	2.36	3.89	5.21	7.02
36.00	30.04	2.84	3.10	3.75	4.25	4.50	2.36	4.29	5.20	7.39
37.00	25.03	2.92	2.78	3.94	4.31	4.50	1.12	5.59	4.04	8.37
38.00	25.03	2.94	3.00	3.94	4.31	4.50	1.12	4.01	4.06	7.01
39.00	29.75	2.93	3.48	4.25	4.75	5.50	1.12	2.79	4.05	6.28
40.00	25.05	2.98	3.21	6.05	6.35	6.50	1.12	3.49	4.10	6.70
41.00	19.96	2.92	3.83	5.94	6.31	6.50	2.02	2.27	4.95	6.09
42.00	24.04	2.97	2.50	5.40	5.75	6.50	2.02	5.81	5.00	8.31
43.00	25.00	2.93	3.87	5.44	6.12	6.50	2.02	3.72	5.00	7.59
44.00	20.12	3.06	4.19	4.75	5.25	5.50	2.02	2.42	5.09	6.61

Table B.2: Existing signal timing and observed yellow interval demand at selected signalized intersections.

No.	YA/YITE	YA/Y85	VEY/Cycle	VER/Cycle	TOTVEYR/Cycle	SVREC/Cycle	TOTREC/Cycle
1.00	0.87	0.93	1.50	1.10	2.60	0.00	0.08
2.00	0.78	0.70	0.25	0.25	0.50	0.25	0.33
3.00	0.97	0.54	2.62	1.00	3.62	0.07	0.20
4.00	1.00	0.72	2.43	1.14	1.67	0.06	0.38
5.00	0.85	0.76	1.93	0.93	2.86	0.06	0.19
6.00	1.03	0.87	1.57	1.29	2.86	0.14	0.21
7.00	1.19	0.67	2.06	1.31	3.38	0.27	0.47
8.00	1.18	0.93	2.08	0.62	2.69	0.20	0.20
9.00	1.08	0.73	2.73	1.00	3.73	0.14	0.14
10.00	0.94	1.18	1.06	0.35	1.41	0.29	0.59
11.00	1.04	0.66	1.82	1.71	3.53	0.17	0.22
12.00	0.97	0.96	1.56	0.78	2.33	0.11	0.33
13.00	0.91	0.73	1.71	1.76	3.47	0.24	0.41
14.00	0.94	1.19	0.71	0.35	1.06	0.05	0.26
15.00	1.05	1.31	0.65	0.12	0.76	0.12	0.18
16.00	0.86	1.21	1.17	0.44	1.61	0.06	0.11
17.00	0.69	0.95	1.14	0.57	1.71	0.27	0.33
18.00	0.79	1.47	1.14	0.21	1.36	0.07	0.60
19.00	0.81	0.62	2.71	2.29	5.00	0.13	0.20
20.00	0.84	0.79	1.53	0.53	2.07	0.13	0.33
21.00	0.84	0.78	0.79	0.36	1.14	0.07	0.13
22.00	1.09	0.78	1.71	0.79	2.50	0.07	0.20
23.00	0.80	1.10	0.94	0.25	1.19	0.19	0.19
24.00	0.91	0.76	1.69	1.19	2.88	0.25	0.31
25.00	0.91	0.72	1.56	0.75	2.31	0.00	0.07
26.00	0.91	0.88	1.81	0.75	2.56	0.13	0.19
27.00	1.01	0.58	2.71	2.07	4.79	0.00	0.13
28.00	1.05	0.66	1.86	0.86	2.71	0.07	0.13
29.00	0.90	1.31	0.53	0.13	0.67	0.00	0.19
30.00	1.01	0.93	1.31	0.54	1.85	0.00	0.07
31.00	0.83	1.19	0.57	0.36	0.93	0.00	0.20
32.00	0.74	1.18	1.64	0.50	2.14	0.17	0.33
32.00	0.89	0.86	1.27	0.67	1.93	0.20	0.33
34.00	0.89	0.98	1.07	0.53	1.60	0.00	0.20
35.00	0.91	0.56	4.33	2.33	6.67	0.13	0.20
36.00	0.92	0.76	2.20	1.67	3.87	0.13	0.33
37.00	1.05	0.74	1.57	0.93	2.50	0.13	0.40
38.00	0.98	0.75	1.00	0.71	1.71	0.14	0.21
39.00	0.84	0.69	4.36	2.57	6.93	0.13	0.47
40.00	0.93	0.49	3.07	2.43	5.50	0.20	0.33
41.00	0.76	0.49	3.14	3.64	6.79	0.13	0.27
42.00	1.19	0.55	3.07	2.47	5.53	0.13	0.20
43.00	0.76	0.54	4.75	2.88	7.63	0.13	0.25
44.00	0.73	0.64	2.44	1.44	3.88	0.20	0.53

Table B.3: Ratios of change interval and violation rates.

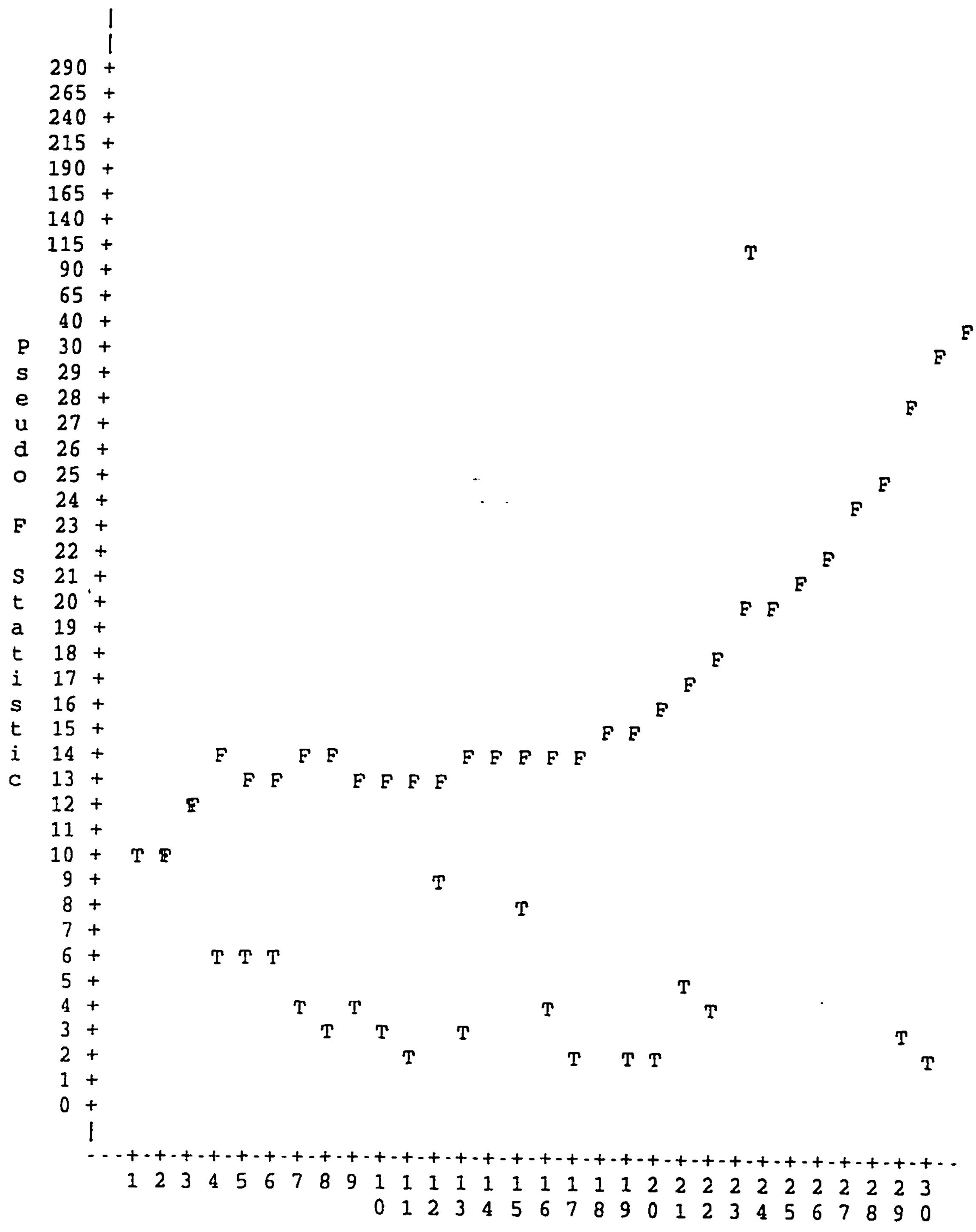
Plot of _CCC_*_NCL_. Legend: A = 1 obs, B = 2 obs, etc.



NOTE: 5 obs had missing values. 63 obs out of range.

Figure B.1: Plot between cubic clustering criterion and number of clusters.

Plot of _PSF_*_NCL_. Symbol used is 'F'.
Plot of _PST2_*_NCL_. Symbol used is 'T'.



NOTE: 9 obs had missing values. 88 obs out of range.

Figure B.2: An overlay between CCC, PST2 and NCL.

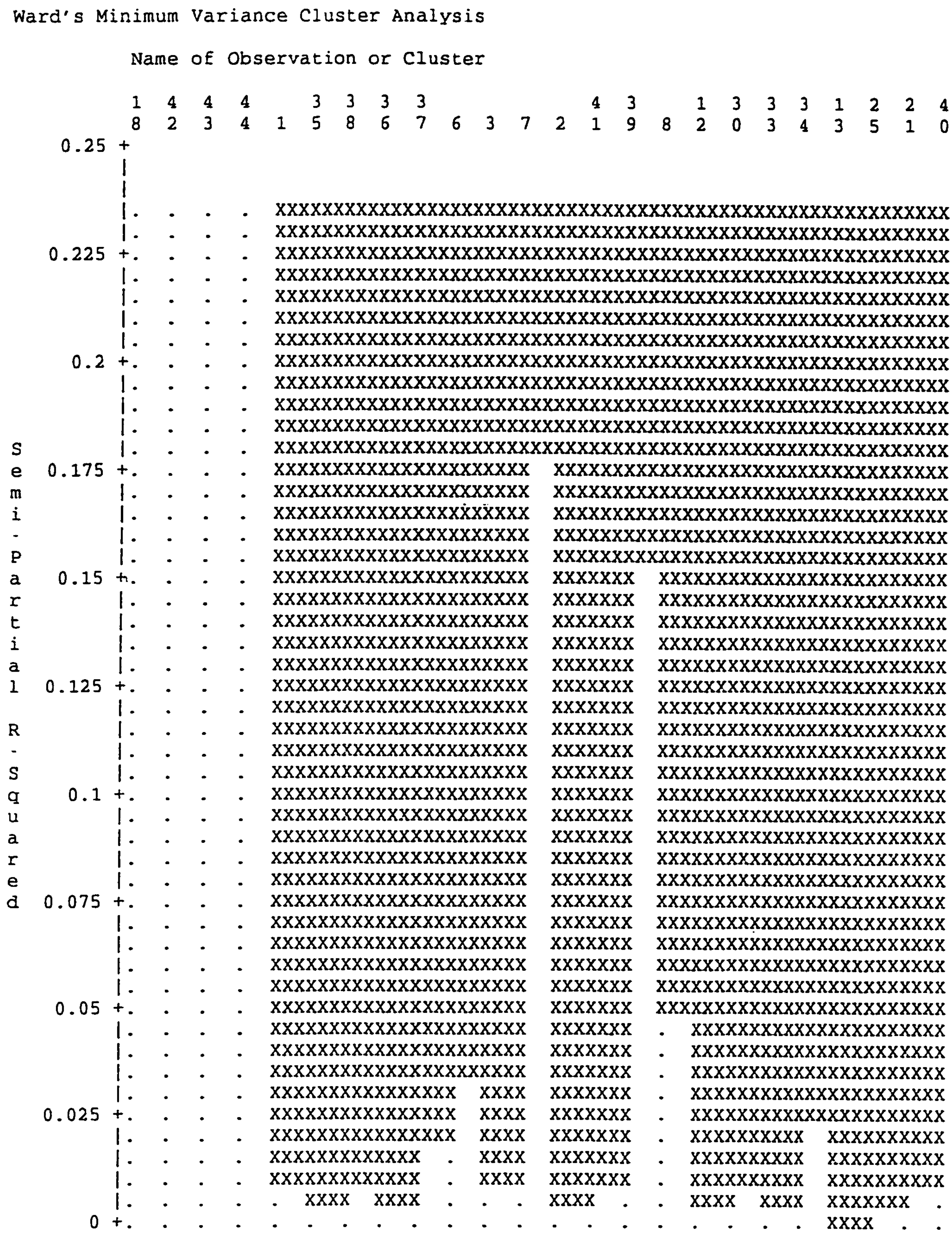


Figure B.3: Tree diagram

Ward's Minimum Variance Cluster Analysis

Name of Observation or Cluster

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  1  2  2  2     1  2  2  2  1  1  2  1  1  2  1
  9  0  4  6  9  1  8  7  2  0  4  9  5  6  3  7


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Figure B.3: Tree diagram continued.