THE EFFECT OF SIGNAL COORDINATION ON INTERSECTION SAFETY

BY

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I also wish to thank all the engineers and research assistants who helped me in the data collection phase.

DEDICATION

This dissertation is dedicated to my ***loving parents***,

my ***wife*** and ***children***.

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DISSERTATION ABSTRACT

NAME: **Khalaf Aidhah Mohammad Ali Al-Ofi**

TITLE OF STUDY: **The Effect of Signal Coordination on Intersection Safety**

MAJOR FIELD: **Civil Engineering**

DATE OF DEGREE: **Second Semester 1993-94**

Traffic accidents at urban intersections constitute about 50 percent of all urban accidents. There are only a few research studies about the signal coordination on intersection safety. The main purpose of this research is to study the effect of signal coordination on intersection safety and to develop a methodology by which intersection safety could be optimized besides other measures of effectiveness (stops and delays).

It was hypothesized that signal coordination mainly affects stops and that stops are mainly related to rear-end accidents. An experiment was designed and data were collected to establish the relationship between stops and rear accidents using the Traffic Conflict Techniques (TCT). It was shown that there is a significant relationship between rear-end conflicts and a significant relationship between rear-end conflicts and rear-end accidents. Using these relationships, the direct relationship between stops and rear-end accidents was obtained and used thereafter in the remaining parts of the research.

A signal simulation and optimization model (TRANSYT) was selected and calibrated for the study area so that it simulated the observed number of stops in the field. The cost functions of the optimization model were revised for Saudi Arabian conditions and the costs of rear-end accidents were added as functions of stops and delays. Delays were calculated based on the cost of delay and cost of stops. Furthermore, K values that optimize safety as well as other costs were calculated.

Using the calibrated program and the calculated K values, several investigations were carried out. It was shown that signal coordination may reduce rear-end accidents and operational costs up to 30 percent. Different signal phasing schemes were investigated for different combinations of volumes and intersection spacings and it seems that four phase schemes are generally better than five phase schemes in similar conditions of the study area. It was also shown that shorter than optimum cycle lengths may cause sharp increases in stops, delays, rear-end accidents and operational costs; compared to longer than optimum cycle lengths. Therefore, it is recommended that shorter than optimum cycle lengths be avoided.

Finally practical implications and some recommendations for further research were given.

DOCTOR OF PHILOSOPHY DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
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خلاصة الرسالة

اسم الطالب الكامل : خلف عيضة محمد علي العوفي

عنوان الرسالة : تأثير تنسيق الإشارات المرورية على السلامة في التقاطعات

التخصص : هندسة مدنية .

تاريخ الشهادة : يونيو ١٩٩٤م .

تشكل حوادث المرور في التقاطعات حوالي نصف عدد حوادث المرور في المدن . وليس هناك سوى عدد قليل من البحوث عن تأثير تنسيق الإشارات على السلامة في التقاطعات . والهدف الرئيسي من هذا البحث هو دراسة تأثير تنسيق الإشارات المرورية على السلامة في التقاطعات وتطوير منهج يمكّن المهندس المروري من أخذ السلامة في الإعتبار عند إيجاد الحل الأمثل لخطة توقيت إشارات المرور .

وقد تم إفتراض أن تنسيق الإشارات يؤثر بصورة رئيسية على عدد السيارات التي تضطر للوقوف عند الإشارة وهذا بدوره يؤثر على عدد حوادث التصادم الخلفية بين السيارات . وقد تم تصميم تجربة لمعرفة العلاقة بين عدد السيارات التي تتوقف عند الإشارة وعدد حوادث التصادم الخلفية ، وأوضحت التجربة أن هناك علاقة قوية بين عدد السيارات المتوقفة وبين التعارض بين السيارات من الخلف الذي بدوره له علاقة قوية مع عدد الحوادث الخلفية . وقد تم إستنتاج العلاقة المباشرة بين عدد السيارات المتوقفة وعدد حوادث التصادم الخلفية . وقد أستعملت هذه العلاقة في الجزء المتبقي من البحث .

وقد تم إختيار نموذج تصميم ومحاكاة (TRANSYT) لإيجاد الحل الأمثل لتوقيت وتنسيق الإشارات المرورية بعد معايرته بحيث يحاكي عدد السيارات المتوقفة في منطقة الدراسة . وقد تم مراجعة معادلات التكلفة للنموذج لتمثيل التكلفة في منطقة الدراسة وتم إضافة كلفة حوادث التصادم الخلفية إلى التكلفة الإجمالية . وقد تم حساب معامل التوقف (K) بحيث يأخذ كلفة هذه الحوادث في الحسبان عند إيجاد الحل الأمثل .

وباستخدام البرنامج المعاير ومعامل التوقف تم إجراء العديد من التحقيقات ولوحظ أن استخدام تنسيق الإشارات يمكن أن يخفض الحوادث الخلفية والتكلفة التشغيلية بنسبة ٣٠٪ . وتم كذلك إجراء إختبارات على عدد من خطط ترتيب أطوار الإشارة الضوئية مع عدد من التباديل والتوافيق من أطول المسافات بين الإشارات وكثافة المرور على هذه الشوارع ويبدو أن خطط ترتيب أطوار الإشارة الضوئية ذات الأربع مراحل أفضل من ذات الخمس مراحل في المناطق الشبيهة بمنطقة البحث . كذلك اتضح أن الدورات الزمنية للإشارات التي تكون أقصر من الحل الأمثل تسبب زيادة في التأخير والتوقف والحوادث والكلفة الإجمالية ويجب تحاشيها .

وأخيراً تم ذكر الدلالات العملية المستنتجة من البحث وبعض المقترحات للبحوث المستقبلية في هذا المجال .

درجة الدكتوراه في الفلسفة

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

التاريخ : يونيو ١٩٩٤م .

Chapter 1

INTRODUCTION

Traffic accidents at urban intersections are very serious problem. They constitute about 50 percent of all urban accidents in the U.S.A. (1). In Saudi Arabia, accident rates are four to five times greater than those of the industrialized countries (2), a situation that makes research in the area of traffic safety an urgent priority.

1.1 PROBLEM STATEMENT

Traffic signal coordination is one of the most cost effective management tools available for traffic engineers to reduce delay, stops, and fuel consumption. It has been used for a long time in the industrialized countries. However, there are only very few research studies which have investigated the effect of traffic signal coordination on safety in developing countries (3,4,5) and none in Saudi Arabia. One of the reasons for traffic signal installation is safety. Therefore, when a traffic management scheme (such as signal coordination) is considered, safety should be taken into account.

Several optimization and simulation computer models have been introduced during the last three decades, e.g. TRANSYT, PASSER, and MAXBAND (6). None of these computer models used traffic safety as a measure of effectiveness or considered it as a parameter to optimize when choosing the optimum plan. Most of the computer-based models for arterial or network optimization contain algorithms for computing signal offsets and splits that minimize some combination of delay and stops in the arterial or the network.

1.2 GOALS AND OBJECTIVES

The main goal of this research is to investigate the effect of traffic signal coordination on safety and suggest a methodology by which traffic safety could be incorporated into signal coordination. To achieve this general goal, the following specific objectives are targeted: the following objectives are targetted:

1. Identify and collect data relevant for to study.

2. Investigate the relationship between signal coordination and accidents and accident surrogate measures.

3. Calibrate the selected signal coordination and simulation program for local conditions.

4. Using the calibrated signal coordination program,

investigate the following:

(i) the potential effect of signal coordination on intersection safety.

(ii) the ways of incorporating safety into the objective function of the optimization model.

(iii) recommend values of parameters needed to incorporate safety into the optimization process.

(iv) the effect of alternative signal phasing schemes on safety.

Chapter 2

LITERATURE REVIEW

2.1 INTERSECTION SAFETY

Intersection safety depends on the following factors: 1) Physical Environment, 2) Traffic Parameters, and 3) Traffic Control (1).

2.1.1 Physical Environment

The geometry of an intersection affects intersection safety. As the number of legs of the intersection increases, the conflicting movements increase and, hence the number of accidents experienced at the intersection increases. T and Y intersections usually have less accident rates than cross intersections (7). Left turn channelization enhances the safety of intersections because it segregates different movements and different speeds (8,9). Sight distance is a very important factor for intersection safety, especially for unsignalized intersections. An evaluation of the Federal Highway Safety Program Project indicated that out of 34 different improvement types, the improvement of sight distances at intersections was the most effective (10).

A large portion of intersection accidents take place at night especially at rural intersections. Previous research has shown that the illumination of an intersection reduces night time accidents (11,12). Skiddin is a major cause of accidents especially during wet and icy periods. Special surface treatment within the intersection reduces the accidents, significantly (13).

2.1.2 Traffic Parameters

The most important traffic parameters that affect intersection safety are approach speed, speed distribution and volumes (1). Approach speed and speed distribution are believed to affect safety in the following manner:

(a) Speed affects the driver's response time and the distance required to stop. As the speed increases, the stopping sight distance increases, and, hence, higher speed is an indication of higher accident potential.

(b) Higher speed variation results with a higher potential for accidents because of the greater interaction between vehicles.

(c) Higher absolute speed may cause higher severity of accidents. (2,7)

Traffic volume affects the number of accidents at intersections, by changing the exposure. As the number of vehicles entering the intersection increases, there are more chances of vehicles being involved in accidents. For unsignalized intersections, the conflicting movements are not separated by time. Therefore, the number of accidents is more sensitive to minor street volumes because an increase in this volume affects the number of conflict chances more than an equal increase in the major street volume (14).

At signalized intersections, the conflicting movements are separated by time except those which result from rear-end and lane change conflicts. As a result of this separation, the number of accidents is a function of the total volume entering the intersection. Statistically significant correlations between accidents and total intersection volumes were obtained by Lalani and Walker (15).

2.1.3 Traffic Control

Traffic control measures are used whenever the traffic volumes or conflicts at intersections are sufficiently large to require the management of the flow of individual movements or when the accident rates are relatively high. There are three types of traffic control devices: yield signs, stop signs, and traffic signals.

Yield signs are used to regulate traffic flow at low volume intersections and where accidents are higher than average for comparable intersections . Yield signs have been found to be effective at previously uncontrolled, isolated, urban, low volume intersections (16).

Stop signs are used along major routes to control intersectioning local or collector streets. A study in California of 150 major/local type intersections with 2 way stop control, (17) showed that 2-way stop control is more effective for low volume on minor streets and high volume on major streets.

Other studies showed that four-way stop controls significantly reduce accidents at intersections where entering traffic volumes on all approaches are relatively equal. If the entering volumes are not relatively equal, there will be an increase in the traffic accidents when four-way stop control is applied (1).

The principal function of traffic signals is to permit crossing streams of traffic to share the same intersection by means of time separation. The major criterion for traffic signal installation is traffic volumes entering the intersection and accident experience (18).

A comprehensive review of research done in 1975 (19) led to the following conclusions:

- Signalization leads to the reduction in right-angle accidents and an increase in rear-end accidents.

- Higher accident rates are found in signalized intersections but the severity per accident is less, so the net effect of signalizing intersections is a reduction in accident cost.

Many studies have been conducted on the effect of signal installation in the United States (1) and the results of these studies vary considerably and research has shown situations where total accidents have decreased in some and increased in other situations. However, the above mentioned findings have been confirmed in most of the studies.

A study by Hakkart and Mahalel (20) showed that, at intersections with a low number of accidents (less than 7) per 38 months, the installation of traffic signals increased the number of accidents, and at intersections with a higher number of accidents, the number of accidents per intersection decreased due to traffic signal installation.

The multiphase traffic signals appear to have a lower percentage of serious and fatal accidents as compared to two-phase traffic signals, as found by a Stanford study in the San Francisco Bay area (7).

Another study by the Kentucky Department of Highways in

1979 (21) also reported a decrease in the severity of accidents as a result of using a multiphase rather than a two-phase operation.

The change interval (amber phase) is a warning for drivers that the green phase is ending and the red phase is starting. This is a very important interval because sometimes the driver has to make a decision whether to stop quickly and take a chance of being involved in rear-end accident or continue and take a chance of crossing the intersection partially in the red phase and hence get involved in a right-angle or other types of accidents.

Engineering solutions for reducing right-angle accidents, such as the proper design of the intergreen interval are well known (22). It is more difficult to eliminate rear-end accidents because it is difficult to eliminate the option zone. One way of reducing read-end accidents is in the case of an actuated traffic signal, when the green phase is extended to allow approaching vehicles to go without yellow indication.

The rear-end accidents at signalized intersections take place because some drivers decide to decelerate; either to stop in response to a yellow or red indication signal, or decrease their speed to turn right or left and the others decide to continue at the same speed or decelerate at a slower rate than the leading drivers. This behavior causes conflicts between vehicles that might lead to rear-end accidents.

The decision to stop when the amber phase starts, 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 exact and the same for all drivers (Figure 2.1). But in reality the decisions are not similar; and there is a probability distribution of stopping as a function of approach speed and distance from the stop line (Figure 2.2). These probability distribution curves are for United States conditions (Kentucky) (22).

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 two dangerous decisions: either to stop at a high deceleration rate and take a chance of being involved in a rear-end accident, or continue driving and take a chance of being involved in a right angle accident. This zone is dangerous, however, a proper design of intergreen interval will practically reduce the risk of involvement in a right angle accident (excluding accidents that involve red signal violation) (22).

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 whether to stop or go and this may increase the risk of rear-end accidents.

Fig. 2.1 An ideal probablity function of stopping.

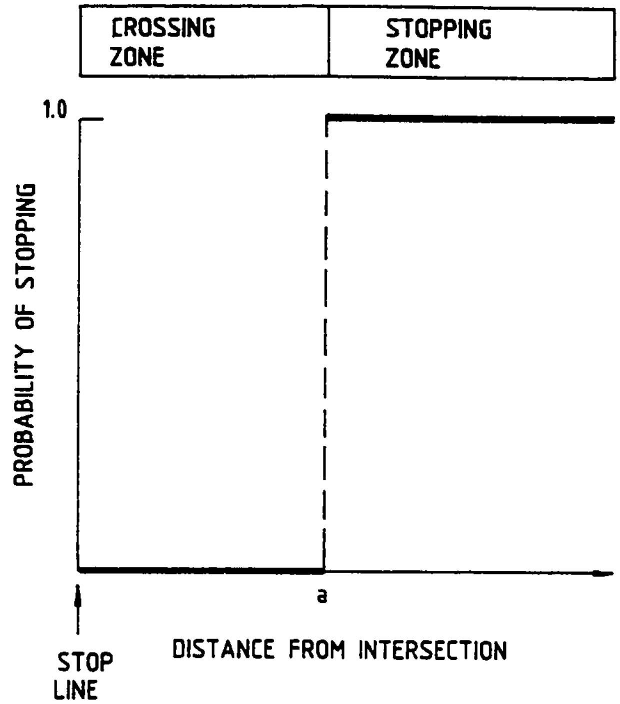
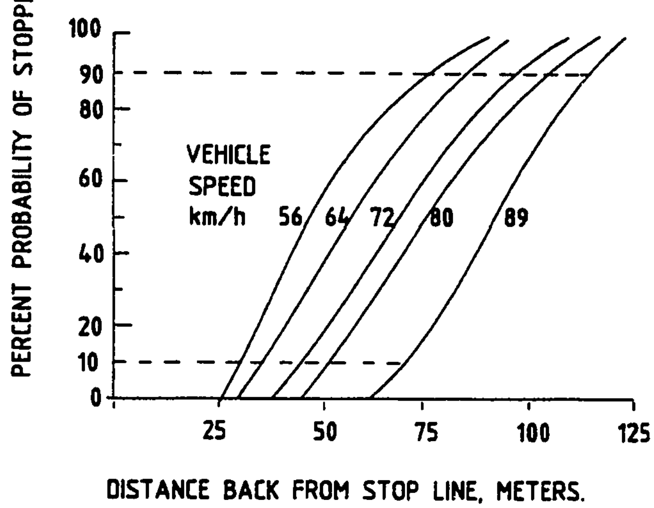


Figure: 2.2 The probability of stopping as a function of approach speed and distance from stop-line. (Ref. 22).



The risk of involvement in a rear-end accident cannot be eliminated but it can be reduced. Figure 2.3 shows the dilemma zone and option zone for signalized intersection approaches as a function of approach speed and distance from the stop line for two cases: an amber phase of 3 seconds and an amber phase of 6 seconds. Referring to Figure 2.3, if a driver doing 80 km/h was at a distance of 80 m from the stopline, he would be in the dilemma zone if the amber phase was 3 seconds. That is, he couldn't stop at a reasonable deceleration and couldn't cross the stop line before the onset of red because his stopping distance would be greater than 80 m and his speed would not enable him to cross the stopline in 3 sec. On the other hand, if the amber was 6 sec, he could cross the stopline before the onset of the red phase. If he was doing only 60 km/hr, and was at a distance of 80 m from the stopline, he would be in the option zone if the amber was 6 sec. He could take one of two decisions: either to stop or to cross the stopline before the onset of the red phase. The dilemma zone is more dangerous than the option zone. The six second amber phase eliminates the dilemma zone, but creates a larger option zone, which is not totally safe itself. Figure 2.3 shows that the amber phase of 3 seconds will create a dilemma zone for an approach speed greater than 50 km/hr, but the amber phase of 6 seconds will eliminate the dilemma zone.

Inspection of Figure 2.3 also shows that no amber period

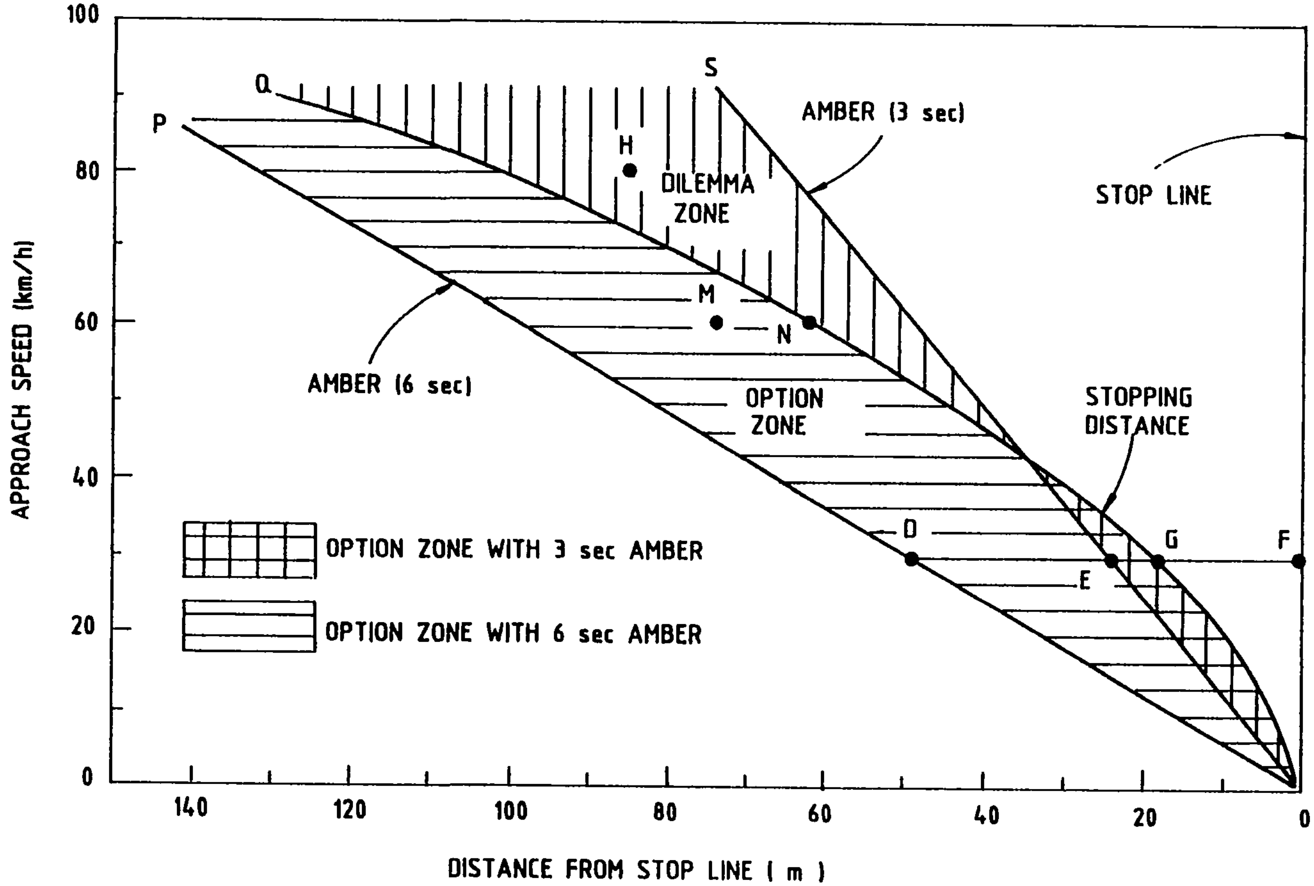


Figure: 2.3 Dilemma and option zones.

Source: Ref. (22).

can eliminate both dilemma and option zones simultaneously. So, the proper design of intergreen period could eliminate the dilemma zone, but cannot eliminate the option zone, which means that crossing accidents can be eliminated, but rear-end accidents cannot be eliminated.

There is also another problem with a long amber phase, that is, after some time, the familiarized drivers tend to treat a long amber phase as a portion of the green phase, and there will be some shift in a driver's behavior that puts drivers at risk. Figure 2.4 shows the results of a study (23) 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, there was a shift towards running on red. Enforcement could be a solution, but it is costly and not practical all the time.

Some intersections have an all-red period, where all the approaches are given red period simultaneously after the termination of the yellow interval of each phase. This is done to allow vehicles that entered the intersection during the yellow interval to clear the intersection before the green is given to the next approach. An all-red period proved to be effective in reducing right angle accidents, but it seemed to increase rear-end accidents (23). Only short intervals of all-red are needed because long

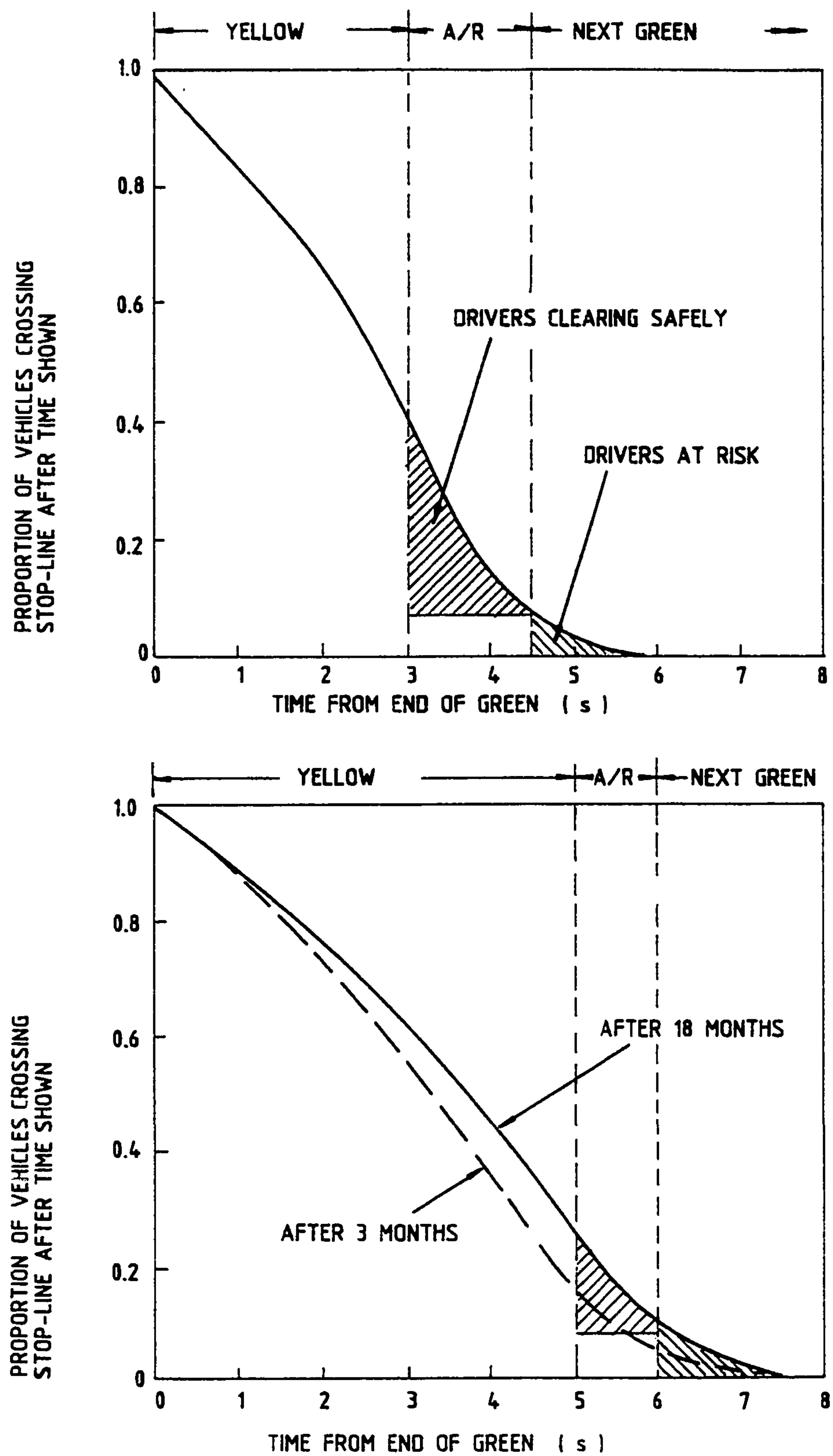


Figure: 2.4 Effect of changes in yellow and all-red times on driver behaviour.

Source: Ref. (23)

intervals would not affect safety.

Generally, allowing right turns on red will not increase right turn accidents as indicated by a study sponsored by FHWA (24).

2.2 TRAFFIC SIGNAL COORDINATION

Traffic signal coordination is defined as the act of developing an optimum signal timing plan (optimum signal offsets and splits), by which the signalized intersections in a given network or arterial are interconnected and operated to optimize a given objective function (25). The objective function could be to minimize some combination of delay and stops, maximize green bandwidth, minimize fuel consumption or minimize operating cost.

Traffic signal coordination has been practiced since the 1920's (26). The signalized intersections have been increasing and as the networks get larger the traffic volumes become much heavier, increasing the need for signal coordination. Traffic signal coordination used to be done manually before the 1950's. As computers and computer programs became available and practical in the 1960's, it became possible to investigate and analyze traffic problems easily, accurately and efficiently. During the last three decades, there was a rapid development in the software and hardware of computers. Many computer models for traffic signal optimization and simulation have been developed, tested and validated. Microcomputers have been developed and have become feasible for use all over the world (25).

2.2.1 Advantages of Signal Coordination

Signal coordination provides significant improvement in service, usually measured in terms of stops and delay. Minimizing delay and stops will provide a more convenient driving environment, improve the network capacity, and reduce excess fuel consumption and user costs (25).

A drop in fuel consumption reduces the user cost and also reduces the air pollution inside cities, which has been a growing concern in recent years. Another benefit of signal coordination is the maintenance of a preferred speed. Slow drivers are expected to increase their speed to catch the green and high speed drivers are expected to slow down to avoid stopping at signals (26).

In the United States, eleven cities optimized a portion of their street networks as part of the National Signal Timing Optimization Project (25). The TRANSYT-7F Program was used to generate signal timing plans. The estimated benefits for an average intersection (based on TRANSYT estimation) were as follows:

1. Each year, 15,470 vehicle-hours of delay were saved.

2. 455,921 vehicle stops were eliminated.

3. 10,524 gallons of fuel were saved.

4. It was reported that driving through urban areas became faster and easier.

Another study in the United Kingdom (26) showed that signal coordination resulted in a 25 percent increase in effective capacity and a 16 percent reduction in travel time.

Another study in California (Garden Grove City) concluded that the use of signal timing plans generated by the TRANSYT program instead of pre-existing plans, yielded a network-wide reduction in total travel time of 5 percent, more than a 10 percent reduction in the number of stops and stopped delay time, and a 6 percent reduction in fuel consumption (26).

Schlappi (26) found that there is a relationship between the concentration of carbon monoxide and the number of vehicle stops. A reduction of 10 percent in vehicle stops reduces the concentration of carbon monoxide by 5 to 7 percent.

Intersection safety was found to be affected by signal coordination. Section 2.3 investigates the past research on the effect of signal coordination on safety.

2.2.2 State-of-Art in Signal Coordination

In this section, a brief review of the state-of-the-art in the models that have been developed for traffic signals coordination for arterials and networks will be presented, with a critical discussion of their advantages and disadvantages in meeting the need for this research.

PASSER II-90 (Progressive Analysis and Signal System Evaluation Routine) (27) is a macroscopic deterministic optimization model designed to develop the optimal signal progression on a linear arterial highway. Macroscopic means that it deals with platoons of vehicles not individual vehicles. Deterministic means that it gives one solution not a set of solutions associated with probabilities. It can be used for isolated intersection analysis or arterial system analysis. For isolated intersection analysis, it can do capacity evaluation and signal timing optimization. For arterial analysis, it can do progression optimization, signal by signal optimization and existing system evaluation. The objective of the optimization process is to maximize the progression bandwidth. It recommends cycle lengths, green split, offsets, and it gives the best phase sequences for individual intersections that maximize the overall progression bandwidth.

The disadvantage of this model, as far as this research is concerned, is that it uses progression bandwidth as a parameter to optimize. The program will not give the optimum solution in terms of stops and delay. (27) The number of stops is the parameter that will be used for approximating safety, as will be explained later.

MAXBAND is an optimization model similar to PASSER II, in that it optimizes the progression bandwidth by varying the offsets. It can optimize progression of two or three intersecting arterials, which is an advantage over PASSER II. The shortcoming of the two models is the same, as far as this research is concerned. They only optimize bandwidths not delay and stops. Delay and stops are taken into account only when the green time is allocated to different phases, but for the whole arterial, they do not minimize delay and stops. (6,28)

SIGOP (Signal Optimization Program) was developed by Peat, Marwick, Livingstone and Company for the U.S. Bureau of Public Roads (25). The latest version of the program (SIGOP III) was developed by KLD Associates, Inc. for the office of Research, Federal Highway Administration. The program is a macroscopic model that can be used for design and evaluation processes. It consists of a traffic flow algorithm and an optimization submodel. The objective function of SIGOP III is a combination of stops, delay and excess queue length realtime to available storage capacity. The major shortcoming of the program is that it cannot deal with intersections having more than four phases (25). The literature review does not show any significant application or validation of the model.

TRANSYT (TRAFFIC Network Study Tool) was written by Robertson in 1967 in the U.K. and was developed substantially after that (25). TRANSYT-7F is an Americanized version of the seventh British version TRANSYT/7. TRANSYT-7F has been developed over the last decade and has been subjected to extensive validation and calibration in many countries including Saudi Arabia (26). The program is macroscopic and a deterministic model. It has two main modules: a traffic simulation model and an optimization procedure. The simulation process is based on simulating the dispersion of platoons of vehicles as they progress along network links (29).

The objective function of TRANSYT 7F is a linear combination of delay and stops. The optimization procedure is an iterative gradient search (hill-climbing) technique that optimizes signal phase lengths and offsets of a signalized network (29). The latest version (TRANSYT-7F Release 6) has many attractive features as compared to other models. These features are:

1. The objective function, which is called the performance index, is very flexible and can be expressed as a linear combination of delay and stops, with a user defined weight

of stops as compared to delay. This weight is the K coefficient in the Performance Index equation:

$$PI = Delay + K\ (stops) \tag{2.1}$$

2. Special weights for specific links could be input into the objective function to reflect the importance of links compared to each other.

3. Fuel consumption can be used as the objective function to minimize instead of delay and stops.

4. The total operating cost can be used as the objective function instead of delay and stops. The total operating cost is a linear function of delay, stops, fuel consumption and user time cost due to excessive delay. The coefficients of cost items in the objective function can be overriden by the user. This feature enables the user to include other cost items such as accident cost and air pollution cost, if the relation between such cost items. and delay and stops is established. By incorporating these cost items in the objective function, they can be optimized online rather than offline.

5. The program can be forced to give good progression along a given arterial by constraining the solution so that it provides a given bandwidth (29).

One of the shortcomings of TRANSYT 7F is that it cannot optimize phase sequence online, but it can be done offline by trying different phase sequences and choosing the one that gives the least performance index. Furthermore, the hill-climbing technique does not always give the global minimum performance index, but generally, the solution obtained by TRANSYT 7F usually gives a good signal timing plan (29).

2.3 TRAFFIC SIGNAL COORDINATION AND SAFETY

Very few studies have been conducted to evaluate traffic signal coordination from a safety point of view. Most of the programs that have been developed for signal coordination try to minimize delay and stops (e.g. TRANSYT 7F) or maximize band width (e.g. PASSER II). So, most of the evaluation studies investigate the success of the programs in optimizing these objectives in the field (25,26).

In 1972, Camkin, H.L. from the New South Wales Department of Motor Transport, Australia (3), presented some accident statistics relating to sections of arterial roads controlled by coordinated traffic signals. The accident statistics showed significant decreases in accidents as a result of signal coordination.

The author showed the effect of signal coordination on the accidents at intersections previously controlled by signals for all systems (Table 2.1). All types of accidents showed reductions due to signal coordination, but only the rear-end type was significant at a level of 5 percent. Table 2.2 shows the statistics of accidents at intersections that were not previously controlled by signals. The effect on accidents shown in this table is a combined effect of signal installation and signal coordination and cannot give any reliable indication about the effect of signal coordination alone.

Berg, W.D. investigated the effect of signal coordination on rear-end accidents (4). He hypothesized that rear-end accidents correlate with the number of stops. He used the accident data available about a high volume urban arterial. He used the TRANSYT model to develop optimized timing plans for a hypothetical time-of-day signal control system. Detailed performance data for both the existing conditions and proposed coordinated signal system were generated using the NETSIM model because there were traffic actuated signals that cannot be simulated using TRANSYT.

Accident records were then analyzed and correlated with the estimated frequency of vehicular stops under existing conditions. An accident prediction model was then used to estimate the safety impacts of the proposed signal coordination.

The output of the analysis showed that there was a small decrease in rear-end accidents due to a decrease in the number of

Table 2.1: The Effect of Signal Coordination on Accidents at Intersections Previously Controlled by Signals

All Reported Accidents:	Before	After	Change %
Pedestrian-involved	9	8	-11
Right-angle	25	17	-32
Rear-end	54	42	-22*
Right-turning	58	56	- 4
Other	31	31	- 0
Total	177	154	-13*
Injury Accidents	42	41	- 2

* Significant @ 5% level on Municipal Control.

Source: Ref. 3.

Table 2.2: The Effect of Signal Coordination on Accidents at Intersections Now But Not Previously Controlled by Signals

All Reported Accidents:	Before	After	Change %
Pedestrian-involved	17	9	- 47*
Right-angle	90	15	- 83*
Rear-end	44	55	+ 25
Right-turning	14	29	+107
Other	11	23	+109
Total	176	131	- 26*
Injury Accidents	41	28	- 32

* Significant @ 5% level on Municipal Control.

Source: Ref. 3.

stops. The prediction model showed significant relationship between number of stops predicted by the NETSIM, which is a microscopic simulation model, model and the accident data. The correlation factor was 0.32, which the author thinks sufficient for such research. The small reduction in the number of stops (instead of a relatively large reduction) may be due to the large distances between the intersections in the study. The effect of coordination decreases due to huge dispersion of platoons, as the distance between intersections increases.

Schlabback, (5) investigated pulsating green wave, which is a control method that varies split, cycle time and offset by a modified gap/density control within a coordinated signal system network. He investigated this coordination system in a study area which had 10 junctions. The results of the experiment showed significant increase in journey speeds, improved journey times for buses, decrease in queue lengths and improvements in traffic safety (especially opposed turns and rear-end collisions).

2.4. THE CONCEPT OF ACCIDENT EXPOSURE

The exposure was defined by Carol et. al. as, "the frequency of traffic events which create the risk of accidents" (30).

The fundamental process of accident occurrence was described as follows (31):

$$A = PE$$

where:

A = The expected number of accidents of a certain type over a specified time period.

E = Exposure or number of opportunities.

P = Probability or propensity of an accident given a unit of exposure.

In order to reduce the number of accidents, at a given intersection , the following methods could be followed (30):

(i) reduce the accident propensity or rate through improved design, new legislation, etc.

(ii) reduce the exposure to accidents by rerouting traffic flows; physically separating the conflicting movements (e.g. channelization) or separating them by time (e.g. signalization).

Chapter 3

METHODOLOGY

In this section first, the research hypothesis about how the traffic signal coordination affects the intersection safety is presented. Then, the research steps are explained and data collection is described in general.

3.1 RESEARCH HYPOTHESIS

The key step in this research is to understand and establish the relationship between signal coordination and intersection safety. Signal coordination is believed to affect the exposure to, and propensity of, certain types of accidents. It is hypothesized that traffic signal coordination reduces first, the exposure to all rear-end and pedestrian accidents and second, the accident propensity of slow vehicle, lane change and pedestrian accidents. The author believes that signal coordination does not affect exposure and accident propensity of right-angle (or cross) accidents. These hypotheses are also supported in the literature cited above (3, 4 and 5). The scope of this research was limited to vehicular accidents. Pedestrian accidents were not studied because of lack of data and resources. The following paragraphs explain how these hypothesis were reached.

3.2 DEVELOPMENT OF HYPOTHESIS

Exposure to rear-end accident exposure is defined as the number of pairs of vehicles travelling in the same direction which are too in a given lane and both vehicles are within the intersection at the same time (31).

Under this definition of exposure, we can explain the effect of signalizing an intersection on rear-end accidents. The literature review showed that when signals are introduced at unsignalized intersections, an increase in rear-end accidents takes place. This can be explained by the increase in exposure to the rear-end accidents because there will be more vehicles that come to complete stops (or slows down to a very low speed) within the intersection area.

Signal coordination creates progressive movements of platoon, where a smaller number of vehicles come to a complete stop or decrease their speed within the intersection area. This decrease in the number of stops is expected to reduce exposure to rear-end accidents and, hence, to reduce rear-end accidents.

For left turns and right turn movements, the exposure to rear-end accidents is expected to be lowered with proper coordination for intersections with left turn lanes. This is expected because a lower number of stops is expected. Lane change exposure is expected to decrease because, the vehicles are travelling at a constant speed and with less obstruction at the intersection that might cause lane change actions. The accident propensity is expected to decrease for slow vehicles and lane change rear-end type accidents because less speed variance is expected.

So, in general, it is expected that a net decrease in all rear-end accidents occurs due to signal coordination and this is attributed to the reduction in the number of stops.

Cross (or right-angle) accidents include those between two vehicles in crossing streams. Most of the previous studies show that signal installation reduces cross accidents especially with multiphase signals, (1) which is the case in Saudi Arabia. This reduction is due to the separation of conflicting movements by time.

These types of accidents could be reduced further with proper design of intergreen interval. This will eliminate the effect of the dilemma zone problem. Cross accidents are usually caused by the dilemma zone and the violation of the red signal. Dilemma zone problem can be eliminated by proper design of the intergreen interval while violation of red signal can be eliminated only by education and enforcement, assuming reasonable cycle lengths.

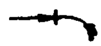
The signal coordination is expected to have no influence on exposure to cross accidents because the exposure to cross accidents depends on the number of vehicles crossing the intersection and the presence of vehicles in the cross approaches. This is not expected to change considerably by signal coordination. With all other variables affecting cross accident propensity being constant, for both a coordinated and an uncoordinated situation, cross accidents are not expected to change with signal coordination.

The exposure to pedestrian accidents is expected to decrease by signal coordination due to less time per vehicle being spent at each intersection. The propensity is also expected to decrease because the pedestrian would not dare to cross the street when a dense platoon is approaching the intersection .

Table 3.1 shows the research hypothesis regarding the effect of signal coordination on accidents at urban signalized intersections.

So, in summary, the expected net effect of signal coordination on intersection safety is believed to be a reduction in rear-end and pedestrian accidents. This hypothesis was tested for the local conditions in the first stage of the research. This was done by establishing and testing the significance of the relationship

Table 3.1: Research Hypothesis for the Expected Effects of Signal Coordination on Accidents At Urban Intersections*

Type of Accident	Diagram	Exposure	Propensity	Net Effect
REAR-END				
Left Turn Same Direction		(-)	No	(-)
Right Turn Same Direction		(-)	No	(-)
Slow Vehicle		(-)	(-)	(-)
Lane Change		(-)	(-)	(-)
CROSS Accidents		No	No	No
PEDESTRIAN		(-)	(-)	(-)

(+) Increase
(-) Decrease
(No) No Effect
* Urban intersections on major multilane divided arterial with multiphase signals and left turn lanes and large turning radial.

between the number of stops and number of accidents (or conflicts).

Cross accidents were not investigated because they are believed to be functions of intergreen interval, rather than signal coordination. There is strong support for this in the literature (3,4,5).

The first step in this research was to establish the relationship between the number of stops and number of rear-end accidents (conflicts) at signalized intersections. Establishing this relationship served two purposes:

(i) It provided further support to the assertion that signal coordination reduces rear-end accidents through the reduction of stops. This is also an indirect test of the research hypothesis. It must be pointed out that there is support for this hypothesis in the literature (3,4). However, this effort may provide further support especially for local conditions.

(ii) The established relationship was used in incorporating safety into obtaining an optimal solution for signal coordination.

3.3 RESEARCH STEPS

The research consists of three stages as shown in the Figure 3.1.

3.3.1 Establishing the Relationship Between Number of Stops and Rear-End Accident (Phase I)

This stage was important for the research because, by establishing this relationship, the effect of signal coordination on safety could be assessed simply by simulating the signal coordination scheme and from the number of stops, the number of rear-end accidents could be estimated. Furthermore, this provided a means for testing the research hypothesis as explained above.

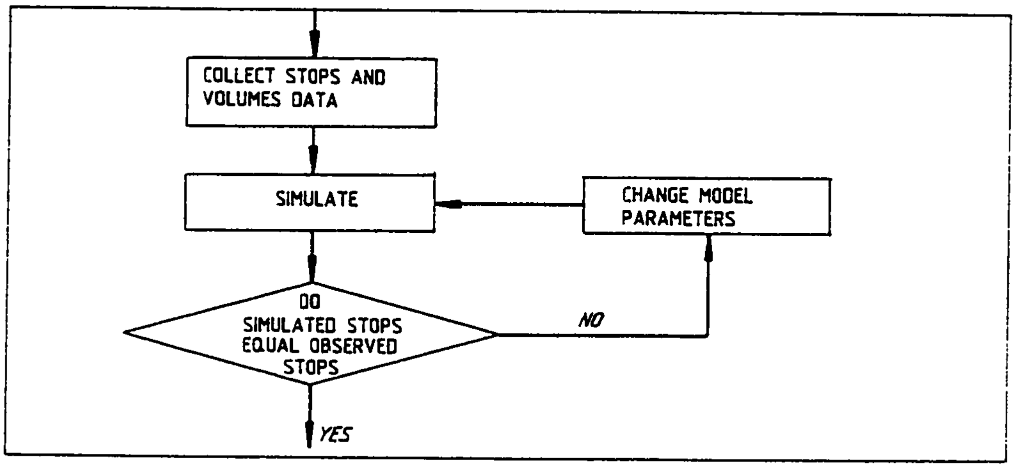
To establish this relationship, two methods were considered as shown in Figure 3.1. The first method was to find the relationship between the number of stops and the number of rear-end accidents directly. The second method was to use Traffic Conflict Technique (TCT) to establish this relationship.

Due to the fact that there was no reliable and complete accident data available for the study area, the traffic conflicts were used as proxy variables for accidents. First, the relationship between the number of stops and number of rear-end conflicts was established. Second, the relationship between the number of stops

Phase I *Establish Relationship Between Stop and Rear - End Accident:*

— Collect stop, volumes and Conflict data.
— Establish the relationstip between stop and conflict.
— Establish the relationship between conflict and accident.
— Obtain the relationship between stop and accidents using the above mentioned relationships.

Phase II *Calibrate TRANSYT Model:*



Phase III *Investigate Signal Coordination Effects on Safety:*

— Recive the cost functions.
— Calculate K value for safety inclusion.
— Simulate system to investigate the following:

— Sensitivity of Stop and Delays to K.
— Sensitivity of Stop and Delay to Cycle length.
— Sensitivity of K to accident cost and speed.
— Sensitivity of the total cost to K.
— The effect of signal coordination on safety and costs.
— The effect of signal phasing on Operational Costs.
— The effect of safety inclusion on signal Timing Plans.

Figure: 3.1 Research Steps

and number of rear-end accidents was established using data from another local study (2). And finally, a direct relationship between the stops and accidents was obtained using the first two relationships.

To establish the relationship between accidents and the number of stops using TCT, the following steps were followed:

1. The traffic conflict data was collected for the intersection approaches selected for the study; together with the number of stops and traffic volumes. Graduate students were trained to collect this data.

2. The following equation was used to determine the required duration of study (h) which would add precision to the collected data (32).

$$h = Z^2_{\alpha/v} \frac{\sigma^2}{L^2}$$

where,

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

and $\overline{Y}$ is the hourly mean value of conflicts and σ^2_e is the hourly variance, Z is the statistics that can be obtained from the normal distribution defined by α.

For this study, the hourly mean value of total rear-end accidents is the parameter that is needed. Al-Isa, Ergun and Al-Senan (2) conducted a study on traffic conflicts at signalized intersections in the study area in 1988. The 20 minute average rear-end conflict was 2.650 and the variance was 1.442. So, for one hour, assuming that three 20 min periods are independent:

$$\overline{Y} = 3 \times 2.650 = 7.95 \text{ conflicts/hr.}$$

and

$$\sigma^2 = 3 \times 1.442 = 4.326 \text{ conflicts/hr.}$$

So, the number of hours needed to estimate hourly average rear-end conflict within a range of ± 50% with confidence interval of 95% equals

$$h = 1.96^2 * 4.326^2 \div (7.95^2/0.5^2)$$

$$= 1.05 \text{ hour.}$$

At least, one hour of data collection is needed during day time for each approach. More detail about the collection of this data is presented in Chapter 4.

3. The relation between rear-end conflicts and rear-end accidents for signalized intersections was established using the data collected by Al-Isa et al. in 1988 (2). So, this relation was used to relate accidents to number of stops. More detail about this relation is presented in Chapter 4.

3.3.2 Calibrating the Optimization Model (Phase II)

TRANSYT 7F release 6 was used as a simulation and optimization model for this research. Besides the attractive features that were discussed in the literature review part, TRANSYT 7F was subjected to validation and calibration studies in several countries including Saudi Arabia (25).

Starting with the parameters and constants obtained by Ratrout, (25) in his study to calibrate TRANSYT Model for the cities of Al-Khobar and Dammam, it was possible to calibrate the model so that it gives satisfactory results in simulating number of stops as explained in detail in Chapter 5.

3.3.3 Investigation of the Effects of Signal Coordination on Safety (Phase III)

After calibrating the simulation model, it was used to simulate traffic in order to investigate the tasks specified in phase III of Figure 3.1. These tasks included the following:

1) Sensitivity analysis of stops and delays to K in the

performance index.

2) Sensitivity analysis of stops and delays to cycle length.

3) Revision of cost function.

4) Calculation of K value.

5) Suggested K values for different speeds.

6) Sensitivity of K value to accident cost.

7) Sensitivity of total cost to K.

8) The effect of signal coordination on safety and cost.

9) The effect of signal phasing on operational cost.

10) The effect of safety inclusion on signal timing plans.

These tasks are explained in detail in Chapter 6.

Chapter 4

ESTABLISHING THE RELATIONSHIP BETWEEN STOPS AND ACCIDENTS

4.1 INTRODUCTION

The relationship between stops and accidents has to be investigated and established in order to study the effect of signal coordination on safety. In the previous chapter, the theoretical relationship between signal coordination, stops and accidents was discussed and it was concluded that rear-end accidents were expected to be correlated to the number of stops at the intersection approaches. The aim of this chapter is to establish the relationship between stops and accidents by studying stops and accidents in the field through the proper experimental design, data collection and statistical analysis.

4.2 METHODOLOGY

Two methods were suggested earlier in this research to establish this relationship. The first method was to establish the relationship directly between stops and accidents; through the collection of data about stops, at the selected intersections through field study and about accidents that took place at the same sites during the recent two years from police files. This method was excluded because of the difficulties faced in the collection of accident data from the police accident form. These accident forms were found unclassified by time, had missing forms and there were difficulties in reading and recognizing the accident sites. Another difficulty was that the accident forms of all the accidents that took place in Eastern Province were stored unclassified in one room. The process of going through more than 100,000 forms with incomplete data and missing forms was not feasible because of lack of resources. Furthermore, a large part of accident reports was missing due to the transfer of the reports between the municipality and the police headquarters. The extracted data would have been incomplete and unreliable.

The second method was to use the traffic conflict technique (TCT) to establish the relationship indirectly between stops and accidents. The TCT was used first, to establish the relationship between stops and conflicts and second, to establish the relationship between accidents and conflicts. These two steps are explained in the following sections.

4.3 ESTABLISHING THE RELATIONSHIP BETWEEN STOPS AND CONFLICTS

The goal of this step was to investigate and establish the relationship between stops and rear-end conflicts at signalized intersections. The objectives of this step include the following:

1. Prepare the experimental design.
2. Train the graduate students on TCT and stops data collection.
3. Collect data about rear-end conflicts and number of stops at the selected intersections.
4. Establish the relationship between rear end conflicts and stops using appropriate techniques and assess the relationship through statistical tests.

4.3.1 Experimental Design and Data Collection

This part of data collection was conducted in the summer of 1992. The first step was to make an inventory survey of all signalized intersections in Khobar, Thogbah, Agrabiyah and Dammam cities having the following characteristics:

1. The approach must be on a cross type signalized intersection.

2. The approach must be separated from the opposing approach by a raised median with at least two lanes.

3. The approach must have left turn lanes.

The size of the sample was calculated so that it gives a margin of error not greater than ±1.5 conflicts according to the following equation (32).

$$n = \frac{\left(z_{\alpha/2}\right)^2 V^2}{E^2}$$

where E = error

V = variance of conflicts per hour {obtained from Al-Isa, et. al. Study (2)}

n = sample size

$z_{\alpha/2}$ = Normal Random Variable

Allowable error was chosen to be ± 1.5 conflict per hour, which is about ± 18 percent.

$$n^2 = \frac{\left(z_{\alpha/2}\right)^2 \sigma^2}{E^2} = \frac{1.96^2(4.326)^2}{E^2}$$

$$n = \frac{1.96^2(4.326)^2}{(1.5)^2}$$

$$n = 32$$

Thirty eight (38) approaches was considered large enough and would give a margin of error of ±1.375.

The approaches of all intersections satisfying the criteria listed above were numbered and 38 approaches were selected randomly. The numbers were written on small pieces of paper and were put in a box and drawn randomly. After each draw the box was shaken to insure an equal chance for each approach to be selected. This random selection resulted in the following number of approaches:

		No. of Lanes 2	3
Combined Movement Phase (CMP)	0	9	21
	1	0	8

The Combined Movement Phase (CMP) means that there are two movements on the approach (e.g. green signal for through traffic and red signal for left turning movement). The dummy variable of CMP can take the value of 0 or 1. CMP = 0 means that the approach has one signal at a time for all movements, while CMP = 1 means that the approach may have more than one signal for the different movements. This dummy variable is used in regression analysis later. Most of the observations were in the cell of 3^+ lanes with CMP = 0 because most of the major arterials that are candidates for signal coordination were in this category. The fourth cell of 2 lanes with CMP = 1 had zero observation because there were no such cases in the approach population.

The conflict and stop data were collected by trained personnel who were given written information about definitions of conflicts and stops. Then they were trained in the field to collect such data. The definition of a stop is: "Any vehicle that comes to a complete stop within the intersection area due to red signal or obstruction by a queue of vehicles still discharging at the beginning of a green signal". Drivers who attempt to avoid stopping by slowing down to a very low speed (less than 10 km/hr) while they are approaching the signal or a queue were considered stopped because the data collector would have missed counting other vehicles should he watch these slow vehicles and determine whether they come to a complete stop or not. Those slowing vehicles encounter relatively long delays and the TRANSYT model simulates them coming to a complete stop. So it was justified to count them as stopped vehicles.

A simple test was done in the field where the two students and the researcher counted stopped vehicles for 15 minutes on the same approach. The results were as follows:

Observer 1 : 236

Observer 2 : 241

Observer 3 : 237

These results show good agreement between the three data collectors and this indicates that the definition of stops is well established and understood. The nonstop vehicles were counted by the same person in the same form.

A similar test was done to assess the reliability of conflict data collection. Two observers (Abed and Khalaf) watched eight 15 minute periods at different approaches. Table 4.1 shows the results of this test. Since there were only two observers, it was not possible to run the formal reliability test suggested by NCHRPR 219 (33). The correlation between the two observers, which is a measure of reliability, was (0.959), which the author considered satisfactory. Abed collected conflicts data of all approaches. Khalid and Khalaf collected the stops data. Data about each intersection were collected by the researcher, such as number of lanes, phases, etc.

4.3.2 Analysis

The means and standard deviations of conflicts per stopped vehicle and conflicts per vehicle are listed in Table 4.2. Now a simple statistical test can be done to see if there are statis-

Table 4.1: Test Data for Conflicts

Intersection	Period (min)	Number of Conflicts	
		Abed	Khalaf
King Abdulaziz by 10th Street	15	2	2
King Abdulaziz by 18th Street	15	0	0
King Abdulaziz by 18th Street	15	1	1
Dhahran by 4th Street	15	1	1
Dhahran by 4th Street	15	2	2
Dhahran by 4th Street	15	0	0
King Abdulaziz by 28th Street	15	0	0
Dhahran Street by Prince Homoud Street	15	2	3
Dhahran Street by Prince Homoud Street	15	2	2

Table 4.2: Means and Standard Deviations of Rates of Conflicts

			Number of Lanes	
		Variable	**2**	**3+**
CMP[1]		$\frac{\text{Conflict}}{\text{Stops}}$	0.0141(0.00793)	0.01167(0.00526)
		$\frac{\text{Conflict}}{\text{Volume}}$	0.00876(0.00389)	0.00788(0.00351)
		$\frac{\text{Conflict}}{\text{Stops}}$	*	0.01052(0.00665)
		$\frac{\text{Conflict}}{\text{Volume}}$	*	0.00546(0.00237)

1. Combined Movement Phase

tical differences among the rates of conflicts among different cells. The t-test given by the following formula was used for this test {see (32) for the explanation of the test}.

The null hypothesis: $H_o : \mu_1 = \mu_2$

$H_A : \mu_1 = \mu_2$

$$t = \frac{\overline{X}_1 - \overline{X}_2}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

$$S_p^2 = (n_1 - 1)\, S_1^2 + (n_2 - 1)\, S_2^2$$

$$\nu = n_1 + n_2 - 2$$

where μ_i is the true mean of conflict/stop and conflict/volume for the two tested cells.

$\overline{X}_i$ is the sample mean of the ith cell.

$S^2{}_i$ is the sample variance of the ith cell.

n is the sample size

ν is the degree of freedom.

Table (4.3) shows the results of the t test.

Table 4.3: Test of Differences Among Cells

Tested Differences*	$T_{cal}(T_{table}$ at $\alpha = 0.05)$	
	Conflict/Stops	Conflict/Volume
Between Cells 1 and 2	0.4896 (1.703) (Difference is not significant)	1.790 (1.703) Difference is significant
Between Cell 2 and 3	0.904 (1.701) (Difference is not significant)	0.6097 (1.701) (Difference is not significant)
Between Cells 1 and 3	0.751 (1.753) (Difference is not significant)	1.559 (1.753) (Difference is not significant)

* Cells are shown in page 45

1: CMP = 0, No. of lanes = 2

2: CMP = 0, No. of lanes = 3+

3: CMP = 1, No. of lanes = 3+

The rates of conflict per stop show no significant difference among the cells at $\alpha = 0.05$. The rate of conflict per vehicle shows no significant difference between three cells for $\alpha = 0.05$, except between cell 1 and 2 which are only significantly different at $\alpha = 0.10$. Therefore, the data from the three cells can be lumped together.

In order to establish the relationship between the conflicts and stops, various regression models were calibrated. Regression model is a technique which expresses a dependent variable as a linear function of various independent variables. An explanation of the technique can be found in Walpole and Mayers(32).

For the regression models, number of conflicts was used as the dependent variable. The independent variables were as follows:

Stops

Volume

No. of Lanes

Overlapping phase (OLP) (0-1 variable)

Before running the regression models, correlations among all the variables were obtained, as shown in Table 4.4, using the SAS program (34). The table shows that there is a high correlation between stops and volume (0.85). Since these are both inde-

Table 4.4: Pearson Correlation Coefficients N = 38

	Conflicts	Stops	Volume	No.of Lanes	Signal Over lapping (OLP)
Conflicts	1.00000* 0.0	0.79624 0.0001	0.70771 0.0001	0.29861 0.0686	-0.10011 0.5498
Stops	0.79624 0.0001	1.00000 0.0	0.84889 0.0001	0.43794 0.0060	0.02700 0.8722
Volume	0.70771 0.0001	0.84889 0.0001	1.00000 0.0	0.53977 0.0005	0.13556 0.4171
No. of Lanes	0.29861 0.0686	0.43794 0.0060	0.53977 0.0005	1.00000 0.0	0.28768 0.0799
CMP	-0.10011 0.5498	0.02700 0.5498	0.13556 0.8722	0.28768 0.4171	1.00000 0.0

* The figure on top is correlation and the figure at the bottom is the significance of the correlation.

pendent variables, they should not both be used in the same model because using both would causes multicollinearity. The other independent variables have low correlation between each other and can be used in the same model. The table also shows that stops has the highest correlation with the dependent variable (conflict) (0.796). Volume also has a high correlation with conflict (0.71). It is expected that the regression models include either of these independent variables to have significant relationship, but stops are expected to have stronger relationship.

The SAS program was used to build various regression models with the dependent variable as the number of conflicts per hour. Table 4.5 shows a summary of these models. The first five models included number of lanes and overlapping phasing as independent variables beside other independent variables. However, neither number of lanes nor overlapping phasing proved to be significant in any models. Therefore, they were discarded from the subsequent analysis. Model #3, Model #5, Model #1 and Model #4 have R^2 of 0.664,0.659. 0.649 and 0.628 respectively. Model #2 has a lower R^2 of 0.542. Model #5 includes both volumes and stops, despite their high correlation and shows that volume doesn't add significantly to the explanation of variance in conflicts if added to stops in the model. Model #3 and #4 include $stops^2$ and stops * volume as independent variables respectively, but they add

Table 4.5: Regression Models for Conflicts

Model # [1]	Parameter Estimates and Significances							Model Statistics		
	Intercept	Stops	Volume	$Stops^2$	Stops*Volume	No. of Lanes	OLP	R^2	F	(Significance)
1	0.410 (0.6713)	0.0116 (0.0001)	*	*	*	−0.220 (0.85)	−1.173 (0.287)	(0.649)	20.97	(0.0001)
2	0.141 (0.903)	*	0.0087 (0.0001)	*	*	−0.597 (0.670)	−1.892 (0.133)	0.542	13.44	(0.0001)
3	2.555 (0.005)	*	*	0.00001 (0.0001)	*	−1.080 (0.316)	0.0783 (0.944)	0.664	22.42	(0.0001)
4	2.507 (0.0085)	*	*	*	0.0000081 (0.0001)	−0.236 (0.845)	−1.25 (0.27)	0.628	19.17	(0.0001)
5	0.127 (0.90)	0.0094 (0.002)	0.0023 (0.337)	*	*	−0.567 (0.633)	−1.298 (0.244)	0.659	15.94	(0.0001)
6	0.0844 (0.917)	0.0114 (0.0001)	*	*	*	*	*	0.634	62.36	(0.0001)
7	*	0.0115 (0.0001)	*	*	*	*	*	0.869	24.5	(0.0001)

[1] The dependent variable is number of rear-end conflicts.
* Variable not used in the model.

little to R^2 and F value of Model #1. It was decided that Model #1 without number of lanes or CMP would be adequate for this research since it constitutes a logical relationship between stops and conflicts in view of the exposure concept explained in Chapter 2. Stops in this case could be exposure or number of chances of conflicts and they are expected to be related linearly with conflicts. Removing number of lanes and CMP from Model #1 gives Model #6, which is a linear relationship between conflicts and stops with R^2 of 0.634 and F value of 62.36. The change in R^2 due to removing the two variables was very small. The intercept of Model #6 was not significantly different than zero and Model #7 shows a linear relationship between conflicts and stops that passes through the origin. The estimate of the coefficient changes very slightly from 0.0114 to 0.115 as a result of the removal of the intercept. R^2 is higher for no intercept model, not because the model fits the data better than the model with intercept, but because R^2 is calculated differently (36). For the model with intercept, R^2 is the proportion of the variability measured by the sum of squares about the mean $\bar{y}$ accounted by the regression, while for the model without intercept, R^2 measures the proportion of variability in y about the origin, explained by regression. For this reason, F value for the no intercept model is much higher than the intercept model.

R^2 and F are not good statistics to compare the two models, but since the intercept is very small (0.0844) and the change in b is also very small, the no intercept model is expected to have a comparable fit to the intercept model.

The following relationship between conflict and stops will be used in the following stages of the research:

$$\text{CONFLICT} = 0.01154 \text{ Stops} \qquad (4.1)$$

4.4 ESTABLISHING RELATIONSHIP BETWEEN ACCIDENTS AND CONFLICTS

The relationship between accidents and conflicts is needed in this research as an intermediate step in the development of the relationship between stops and accidents, which is the main goal of the first stage of this research.

4.4.1 Data

Before 1987, Al-Khobar traffic police department used to collect accident data for Al-Khobar and Thogbah cities that provided the required information, namely, location, date and type of accident. Al-Isa et. al. (2) extracted information from these reports about accidents at signalized intersections in 1405H and 1406H (1985-6G). This information, which also included the collision diagrams, was available for this research. It is assumed that the relationship between the conflicts and accidents at that period is still the same for the present time.

There were seven signalized intersections about which data were collected. These intersections were:

1. King Abdulaziz Street (major) by 28th street (major) in Al-Khobar.
2. King Abdulaziz Street (major) by Dhahran street (major) in Al-Khobar.
3. Makkah Street (major) by 20th street in Al-Khobar.
4. Twenty-eighth (major) by Prince Homood Street in Al-Khobar.
5. King Abdulaziz Street (major) by 22nd street in Al-Khobar.
6. King Abdulaziz Street (major) by 10th street in Al-Khobar.
7. Dhahran Street (major) by Makkah Street (major) in Thogbah.

Dhahran Street by Makkah Street underwent some geometric and traffic changes in the years 1405H and 1406H (1985-6G) where the north approach was closed and the traffic was directed through the adjacent approach. These changes caused disturbances in the traffic flow and could have affected the accidents.

It was decided to exclude this intersection because the accident data doesn't reflect the safety of this intersection. It was also decided to include approaches that are on major streets only in order to get homogeneous data. Table 4.6 shows the data that will be used to establish the relationship between accidents and conflicts. It includes the rear-end conflicts collected by Al-Isa et. al. (2) for 40 min. in morning peak and 40 min. in afternoon peak.

4.4.2 Analysis and Results

The conflict data were multiplied by 0.75 to convert them into conflicts per hour. Means, standard deviations, minimum and maximum of the rear end accident and rear-end conflicts are shown in Table 4.7. Figure 4.1 is a scatter plot between conflicts and accidents. It shows that a reasonable relation between conflicts and accidents is either quadratic or linear.

Various regression models were calibrated between the accidents and conflicts as shown in Table 4.8, using the SAS program. As mentioned before, the model with intercepts cannot be compared to the models without intercepts by comparing R^2 and F value because these parameters are calculated differently. However, Mean Squares of Errors (MSE) can be compared. Model 4 seems to be the best fit because it has the highest R^2 and lowest MSE. Furthermore, the curve is passing through the origin which

Table 4.6: Accident Vs Conflict Data (Source: Al-Isa et al.)

Intersection*	Approach	Rear-end Accidents (2 years)	Rear-end Conflicts (80 min)
1	E	5	4
1	N	19	7
1	W	5	6
1	S	17	8
2	E	16	7
2	N	19	9
2	W	9	5
2	S	11	5
3	N	10	5
3	S	3	5
4	E	2	4
4	W	0	3
5	N	7	7
5	S	6	4
6	N	7	5
6	S	7	4

1. King Abdulaziz Street by 28th Street (Al-Khobar)
2. King Abdulaziz Street by Dhahran Street (Al-Khobar)
3. Makkah Street by 20th Street (Thogbah)
4. Prince Homoud Street by 28th Street (Al-Khobar)
5. King Abdulaziz Street by 22nd Street (Al-Khobar)
6. King Abdulaziz Street by 16th Street (Al-Khobar)

Table 4.7: Simple Statistics for Rear-End Accidents and Conflicts

Variable	N	Mean	Standard Deviation	Minimum	Maximum
Rear-end Accident	16	8.94	5.98	0	19
Rear-end Conflicts	16	4.125	1.35	2.25	6.75

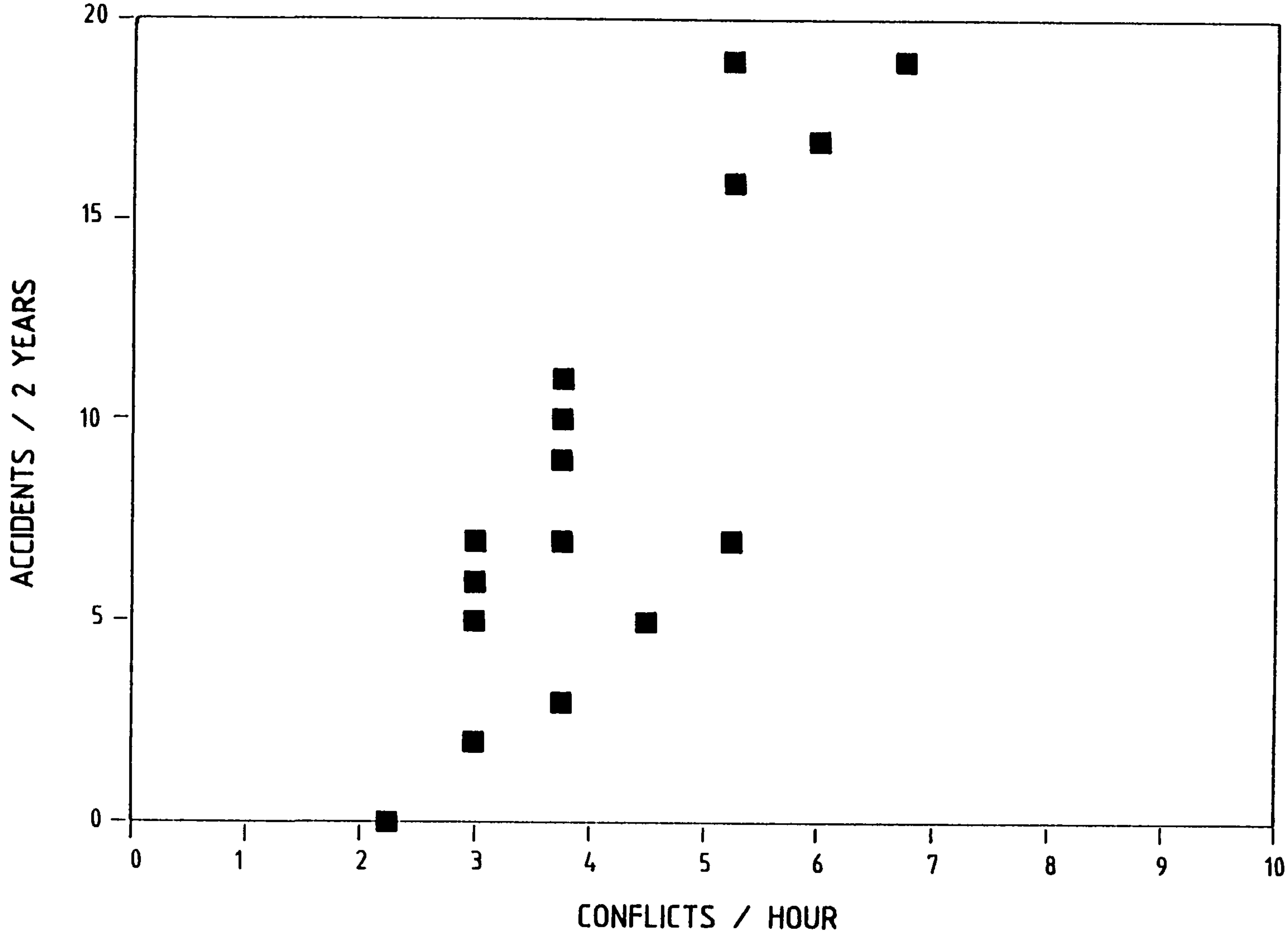


Figure 4.1, Scatler Diagram of Conflict vs Accidents.

Table 4.8: Regression Models for Accidents

	Parameters Estimates (Significance)			Model Statistics			
Model[1]	Intercept	Conflict	$Conflict^2$	R^2	MSE	F	Sig.
1	-7.366 (0.031)	3.952 (0.0001)	*	0.687	3.46	30.78	0.0001
2	*	2.309 (0.0001)	*	0.869	3.977	99.8	0.0001
3	0.932 (0.599)	*	0.433 (0.0001)	0.673	3.54	28.81	0.0001
4	*	*	0.470 (0.0001)	0.901	3.457	136.91	0.0001

1. Dependent variable: Number of Accident

is also logical because when there are no conflicts there should be no accidents. So the best model is given below:

$$\text{Accident} = 0.47\ (\text{Conflict})^2 \qquad (4.2)$$

On the other hand, assuming a linear relationship between accident and conflicts which is Model #2, would facilitate the incorporation of safety into a TRANSYT model. Because there is not much difference between Model #2 and Model #4 in terms of their R^2 and MSE values, Model #2, which is given below, will be used in this research.

$$(\text{Accident}/2\ \text{years}) = 2.309\ (\text{Conflict}/\text{hour}) \qquad (4.3)$$

4.5 RELATIONSHIP BETWEEN ACCIDENTS AND STOPS

The relationship between stops and accidents can now be derived easily from the two relationships developed above and given below again:

$$\text{Conflict} = 0.01154\ \text{stops} \qquad (4.1)$$

$$\text{and Accident}/2\ \text{years} = 2.309\ \text{conflicts}/\text{hour} \qquad (4.3)$$

Substituting Eq. 4.1 into Eq. 4.3:

$$\text{Accidents} = 2.309 * 0.01154\ \text{stops}$$

$$\frac{\text{Accident}}{\text{2 years}} = 0.02665 \ \frac{\text{Stops}}{\text{hr}} \qquad (4.4)$$

The accidents are per two years and the stops are per peak hour. The next stage is to make the relation per hour for both variables. In other words, the relationship should be independent of time. In order to do so, the stops per hour should be expanded to stops per two years. It is very difficult, if not impossible to count number of stops for two years continuously for so many approaches.

However, since there is a high correlation between stops and volumes, the ratio between the peak hour stops to total yearly stops will be assumed to be the same as the similar volumes ratio. To obtain the volume ratio, traffic counters were used to collect daily traffic statistics on ten different major approach lanes in King Abdulaziz Street in Al-Khobar. These lanes included Thru, Right and Left lanes. The traffic counters produced volume histograms that shows the volume every 20 or 25 minutes. From these counts, the volumes during the periods (7:00 - 9:30 A.M. and 4:00 - 6:30 P.M.) and the average hourly volume were calculated. The average hour volume was then divided by the total daily traffic volume to get the percentage of hourly volume from the total daily traffic. Table 4.9 shows the data extracted from the histograms.

Table 4.9: Estimation of Percentage of Average Morning and Afternoon Peak Hour from Daily Traffic Volume

Obs.	16:00-18:30	7:00-9:30	Day Volume	Average Vol/hr	Ratio
1	714	425	3660	228.0	6.22
2	291	96	1254	77.4	6.17
3	1092	735	6383	365.4	5.72
4	804	456	3863	252.0	6.52
5	840	537	4698	295.0	6.29
6	765	687	4756	290.0	6.11
7	468	328	2763	159.0	5.76
8	1041	921	5852	392.4	6.88
9	372	309	2175	136.0	6.26
10	564	360	2788	145.0	6.63

The average ratio between the hourly volume and the daily volume was 6.236% with a standard deviation of 0.325 %. The results show that the ratio is fairly stable and doesn't change much from lane to lane and from approach to approach. The factor to expand one hour's volume (or stops) to daily volume (or stops) can be calculated as follows:

$$\text{Daily Volume Factor} = \frac{1}{0.06236} = 16.04$$

Assuming that volume remains the same throughout the year, the factor to convert one day's volume to two years' volume will be as follows:

$$\text{Two years factor} = 354 * 2 = 708 \text{ days}$$

where the 354 is the number of days in one Hijri year.

To convert one hour's volume to two years' volume the factor will be 16.04 * 708 = 11,353.

The relationship between number of stops and accident will be as follows:

$$\text{Accident} = \frac{0.0265}{11353} \text{ stops}$$

$$\text{Accident} = 2.347 * 10^{-6} * \text{stops} \qquad (4.5)$$

4.6 SUMMARY OF RESULTS

The results of this chapter can be summarized as follows:

1. Relationship between rear-end conflicts and stops:

   Rear-end conflicts = 0.01154 * stops

2. Relationship between rear-end accidents in 2 years and rear-end conflicts in the peak hour:

   Rear-end accidents = 2.309 * conflicts.

3. The relationship between accidents and stops was calculated as follows:

   Rear end accidents = $2.347 * 10^{-6}$ * stops

Chapter 5

CALIBRATION OF TRANSYT MODEL

5.1 INTRODUCTION

Before using the model to simulate the traffic flow, it has to be calibrated so that it gives a good estimate of the number of stops. Ratrout (25) calibrated a TRANSYT model for the study area (Khobar and Dammam). He showed that the model simulates the real platoon dispersion behavior; and suggested the platoon dispersion factors for different kinds of links in the study area. The number of stops were not checked against field stops in Ratrout's study because it was beyond the scope of his work. For this study, the number of stops is the most important measure of effectiveness (MOE) because it was found to be directly proportional to the number of accidents. In order to estimate the number of accidents correctly, the model should be able to estimate the number of stops correctly.

The TRANSYT model assumes that every delayed vehicle is stopped. In reality, this is not true because some vehicles avoid stopping by slowing down. Figure 5.1 shows the time space diagram of the vehicles approaching the intersection. The vehicles that are delayed for a relatively long period of time are forced to

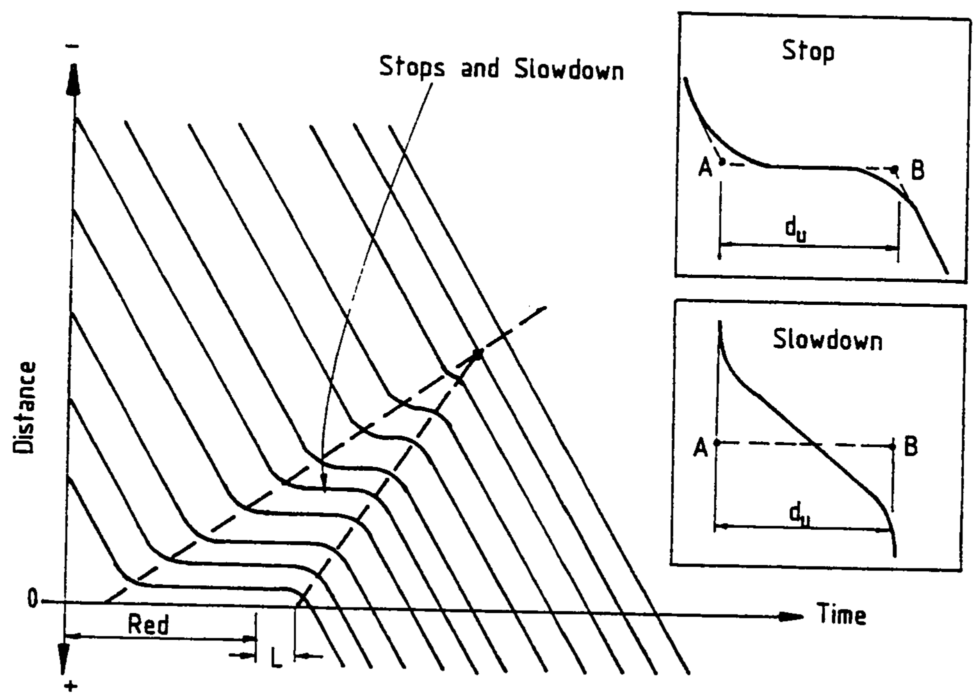


Figure: 5,1 Stop vs Slowdown

Source: TRANSYT Manual (Ref. 29)

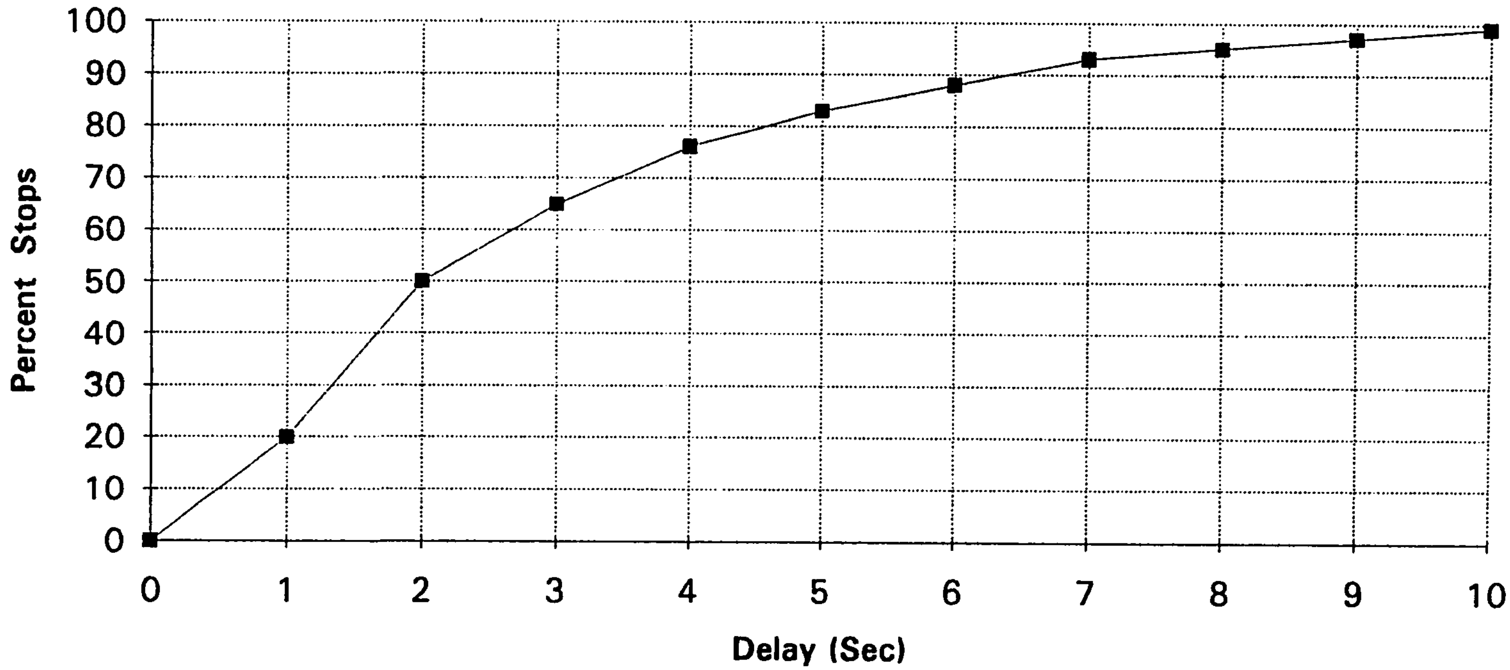
stop, while the vehicles that are delayed for a short period of time actually avoid stopping by slowing down before reaching the back of the queue.

Since the model usually overestimates the actual number of stops, a filtering algorithm is used by the model to reduce the stops as a function of length of delay. Figure 5.2 shows the curve used in the TRANSYT program to reduce stops as a function of delay. For example, if a group of vehicles is delayed for 4 seconds, about 80% of them are expected to come to a complete stop while the other 20% are expected to avoid stopping. This relationship was obtained from empirical studies by Transport and Road Research Laboratory (TRRL) in the United Kingdom (29). However, this relationship represents a behavioral relationship and could be different from country to country.

In order to calibrate the model, the traffic conditions were simulated using the TRANSYT model and the percentage of stops obtained from the model is compared to the percentage of stops obtained from field studies. If the model did not simulate the real condition, the stop reduction algorithm was revised until a good simulation of stops was obtained.

The study area that was chosen, (King Abdulaziz Street in Al-Khobar City, in the Eastern Province of Saudi Arabia), to

Figure 5.2 TRANSYT Default Stop Reduction Curve



calibrate the model, was the same study area chosen by Ratrout in 1988 to calibrate his model. Ratrout concluded that the model simulates the flow profile and the platoon dispersion correctly. He suggested some measured model parameters (e.g. saturation flow and Platoon Dispersion Factor (PDF) for each link in the study area), that ensured correct simulation. These parameters are assumed not to have changed significantly and were used in this study.

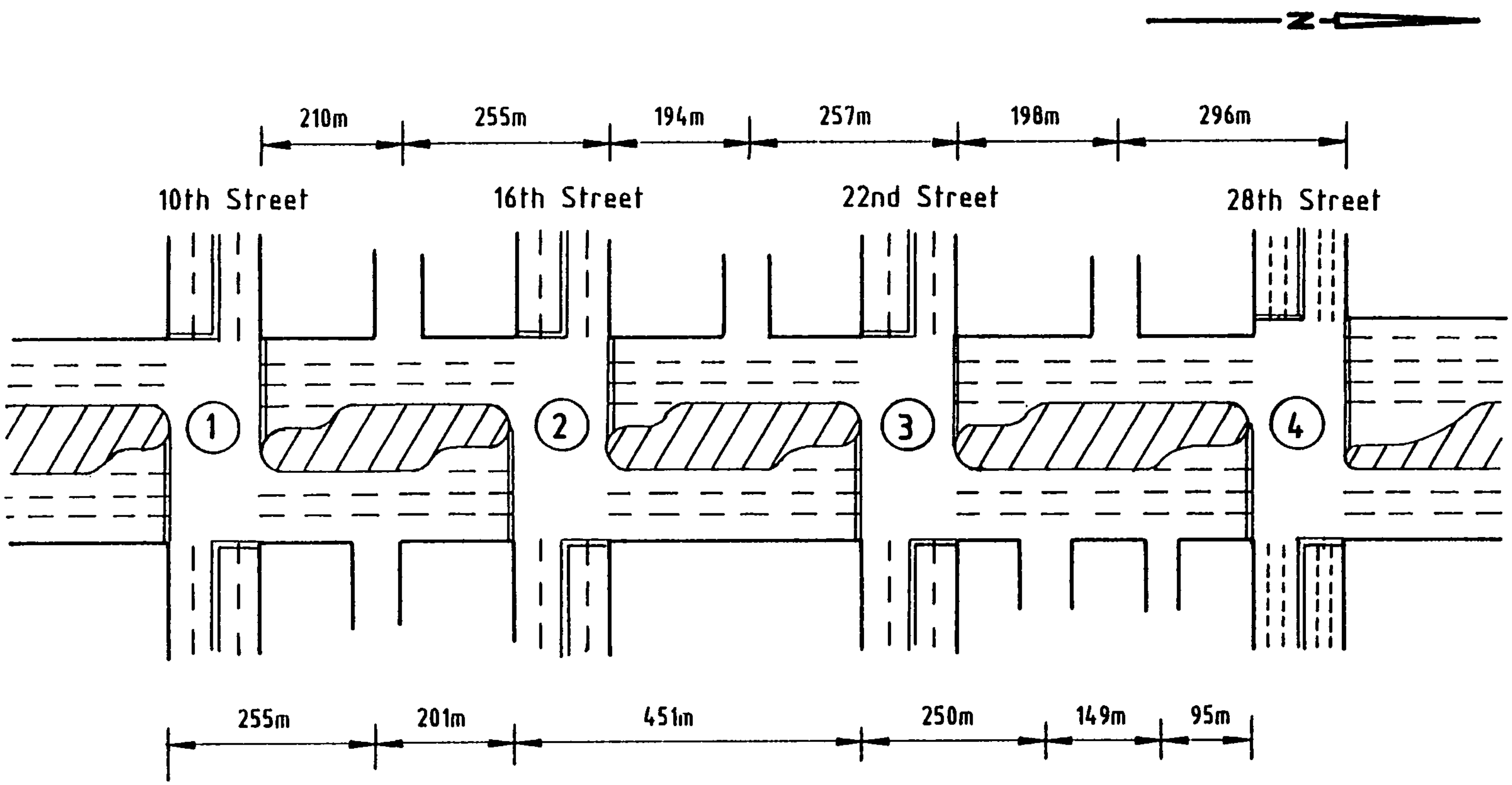
5.2 DATA COLLECTION FOR CALIBRATION

The data required for the simulation are grouped into four general categories:

1. Physical Description of the Arterial
2. Volume Data at each Intersection
3. Signal Timing Plan
4. Driver Performance Characteristics data.

5.2.1 Physical Descrtiption of the Arterial

This category of data includes number of lanes and link lengths. The physical features of the arterial have not changed since 1988. Figure 5.3 shows the physical layout of the arterial links and intersections. It is a divided arterial with three lanes in



NOTE:

This drawing is not to scale and Curb Parking is allowed.

Figure: 5.3, Plan Sketch of King Abdulaziz Street.

each direction and left turn lanes and short right turn lanes along the major arterial. There are four signalized intersections with crossing streets ranging from six lane divided arterial to two lane undivided collector streets. The arterial is a mixed commercial and residential area, with parking allowed along the arterial except near the intersections, where the parking lanes change to right turn lane. The intersections have good sight distances, where drivers can see the signal long before the intersection. The number of lanes will be estimated using the model by dividing the saturation flow of the link by the nominal lane saturation flow and rounding to an integer number.

5.2.2 Volume and Speed Data

The volumes at each intersection classified by movement and any midblock source of traffic greater than 10 percent of the total link volumes are needed for the model. These data were collected by four graduate students and technicians who were trained to use manual tally boards. The time that was chosen for data collection was between 09:30 to 11:40 of a weekday morning. During this time none of the intersections were saturated and volume/capacity (V/C) ratios were all less than 0.95. Oversaturated periods were avoided intentionally because the TRANSYT model is not reliable when intersections are near saturation.

The link-to-link volumes were estimated using a procedure explained in the TRANSYT Manual (29). This procedure is explained by the example, using the section of an arterial shown in Figure 5.4, where there is an upstream and downstream node. There are three links on the south bound approach between the two nodes: the south bound thru movement, the right turn movement at the downstream node and the left turn at the downstream node. The link-to-link volumes denote the source of the volumes at the downstream movement from the upstream node. As suggested by TRANSYT manual (29), the turning movement volumes at the downstream node is assumed are assumed to be from the upstream thru movement only, while the thru movement at the downstream node to be from the upstream turning movements. Figure 5.4 explains this idea graphically. The turning lanes on the main arterial are considered to be separate links while the three through lanes are considered to be one link. Figure 5.5 shows the coding scheme that was used in the TRANSYT model. Two sets of data for two consecutive hours were collected. Tables 5.1 and 5.2 show the volume data for the two hours.

The speed along the links was collected using the floating car technique suggested in the TRANSYT Manual. The car was driven along the links ten times and then the maximum speed attained in each run was recorded and the ten values were

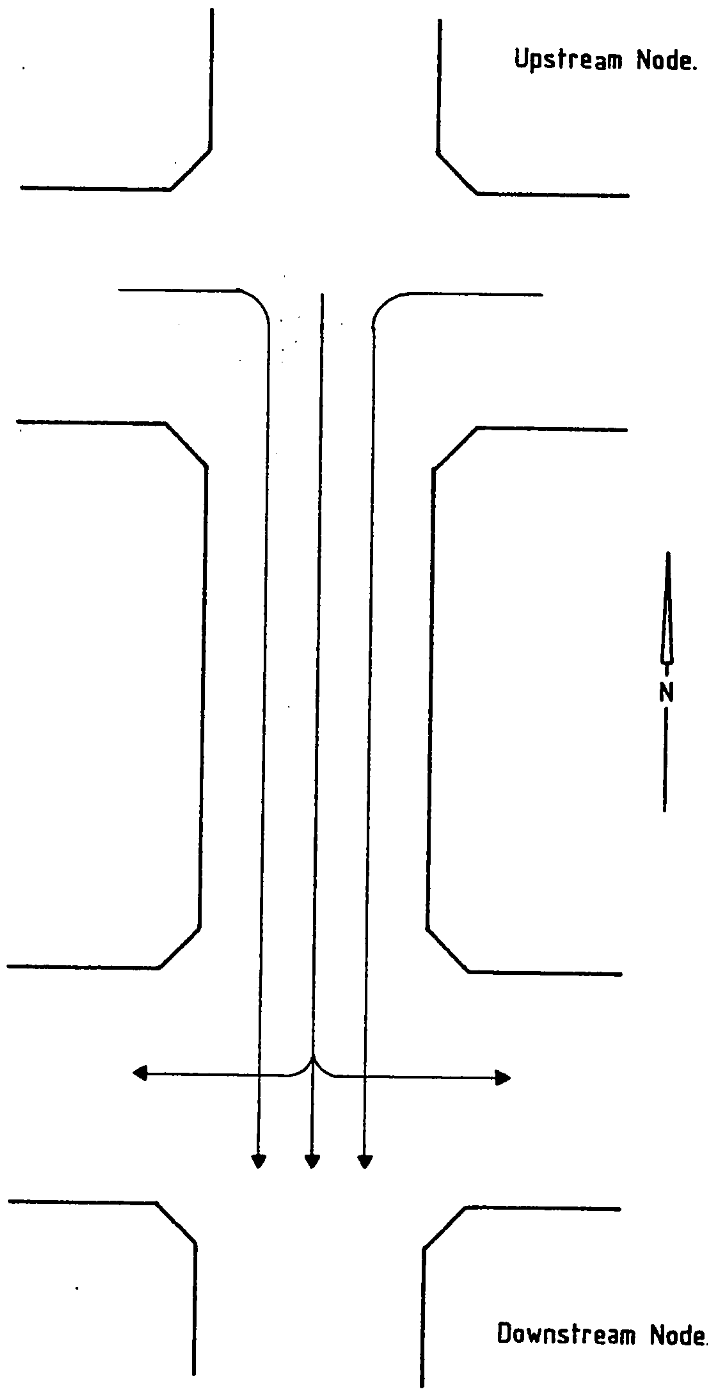


FIGURE: 5.4 GUIDELINES FOR ESTIMATING LINK-TO-LINK FLOWS.

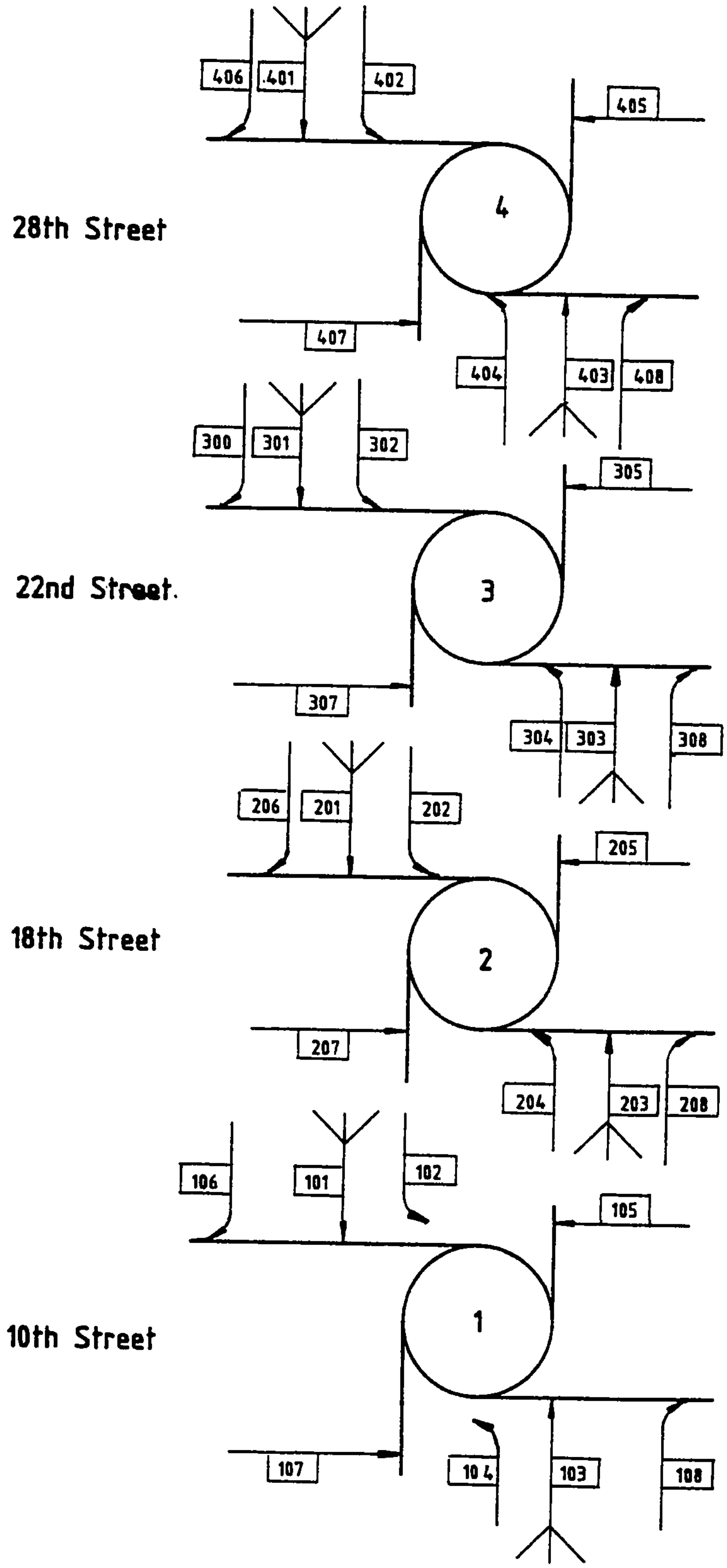


Figure: 5.5 Coding of the Links and Nodes of King Abdulaziz Street.

Table 5.1: Volume Data on King Abdulaziz Street (Between 8:30 AM and 9:30 AM)

Intersection	North Bound				West Bound				East Bound				South Bound			
	Right	Thru	Left	Total	Right	Thru	Left	Total	Right	Thru	Left	Total	Righ	Thru	Left	Total
10th Street	197	1039	173	1409	125	147	153	425	32	205	153	390	49	231	1038	1318
16th Street	87	1163	188	1438	62	105	148	315	124	192	68	384	62	1140	232	1434
22nd Street	92	1187	182	1461	62	63	82	207	48	96	69	213	45	1136	176	1357
28th Street	68	984	343	1395	89	366	242	697	66	345	395	908	*	987	*	*

* Volume leaving the arterial

Table 5.2: Volume Data on King Abdulaziz Street (Between 9:35 AM and 10:35 AM)

Intersection	North Bound				West Bound				East Bound				South Bound			
	Right	Thru	Left	Total	Right	Thru	Left	Total	Right	Thru	Left	Total	Righ	Thru	Left	Total
10th Street	201	1144	214	1559	166	178	207	551	25	226	161	412	61	1062	268	1391
16th Street	95	1272	260	1627	84	146	127	357	122	167	59	348	65	1145	246	1456
22nd Street	76	1218	190	1484	78	76	73	227	57	78	93	208	30	1090	165	1285
28th Street	81	1009	323	1413	133	405	227	765	88	290	393	771	*	1001	*	*

* Volume leaving the arterial

averaged. The car should be in the middle of the platoon and should float with the traffic flow keeping a speed near the platoon average speed. Table 5.3 shows the speed data. The outside links which include every link connecting a node on the arterial to another node outside the arterial listed nodes, were assumed to have a speed of 60 km/hr.

The percentages of stops were collected by five graduate students who were informed in the field about the required data. They were first, asked to collect the percentage of stops on the same approach for 20 minutes. The resulting data shown in Table 5.4 indicates that they all measured stops consistently. The arterial has 16 approaches out of which, five were chosen to collect data at. The number was limited to five because there were only five graduate students to collect percentage of stops data. The five approaches which were chosen along the arterial and external links were avoided, because the vehicle arrivals are assumed to be random along these links, which might not be true, and therefore, the simulation ability of the model could not be assessed. The chosen approaches were as follows:

1) Node number 1 south-bound approach
2) Node number 2 south and north approaches
3) Node number 3 south and north approaches

Table 5.3: Summary of Speed Data

Link	Average Speed
203	57.3
303	47.4
403	54.1
301	59.2
201	56.1
101	57.4

* Number of runs = 10

Table 5.4: Test Data for Stops and Non-Stops

Observer	Stops	Non-Stops
1	281	130
2	288	133
3	284	131
4	278	135
5	282	120

Tables 5.5 and 5.6 show the data of stops and nonstops at these approaches for the two hour periods.

5.2.3 Signal Timing Plan

The data about the signal timing plan were collected immediately after the volume data collection. Each intersection has four unidirectional phases. That is, the green phase is given to one approach at a time. All intersections had a common cycle length of two minutes. After each phase, there is a three second yellow phase and two seconds all red period. The remaining 100 second, outside the yellow and all-red periods, are divided into four green phases; 30 seconds for the approaches on the arterial and 20 seconds for the cross street approaches, except for intersection number 4, where the green time is equal for all approaches; which is 25 seconds. The offset, between the start of the green phases of the north-bound approaches were 20 seconds, 58 seconds and 97 seconds. Figure 5.6 shows the signal timing plan.

5.2.4 Driver Performance Characteristics Data

The driver performance characteristics data include the saturation flow, start-up lost time, green extension time, average vehicle spacing and platoon dispersion factors. These data depend on the behavior of drivers in the study area. Ratrout (25) col-

Table 5.5: Percentage of Stops Between 8:30 AM and 9:30 AM

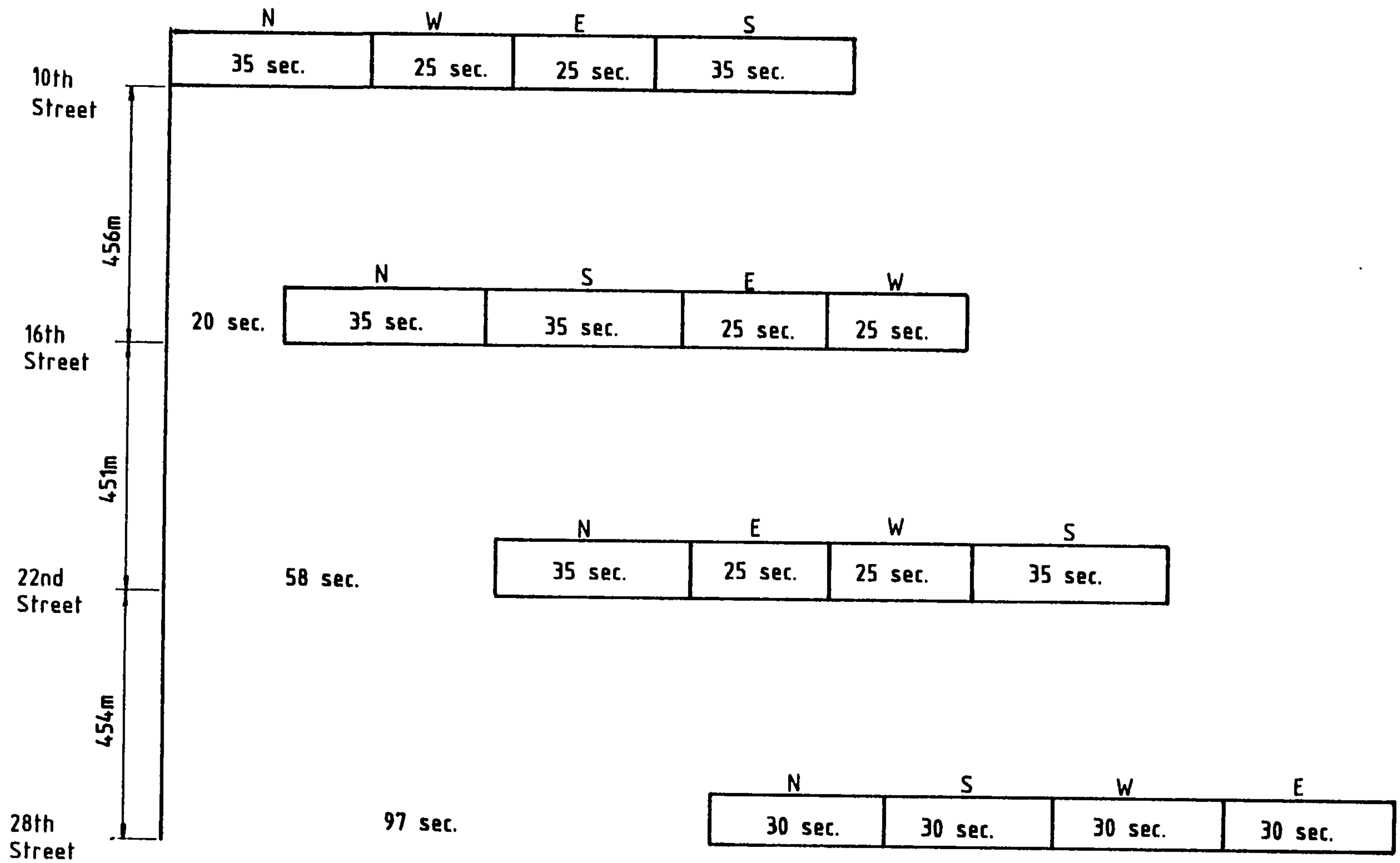
Approach*	Stops	Non-Stops	% Stops
10th Street	530	944	36
16th Street	534	952	36
16th Street	588	800	42
22nd Street	632	713	48
22nd Street	644	688	48

* The approaches are on King Abdulaziz Street and identified by the crossing streets and direction.

Table 5.6: Percentage of Stops Between 9:35 AM and 10:35 AM

Approach*	Stops	Non-Stops	% Stops
10th Street	531	936	36
16th Street	520	963	35.1
16th Street	731	832	46.8
22nd Street	654	748	46.6
22nd Street	696	740	48.5

* The approaches are on King Abdulaziz Street and identified by the crossing streets and direction.



After each phase there is 3 sec. yellow phase and 2 sec. all red.

Figure: 5.6 Signal timing plan for King Abdulaziz Street lected these data in 1988 in the same study area. In this research it is assumed that the drivers' performance characteristics have not changed significantly during the last few years. Hence, the data from Ratrout's study were used in this study. Tables 5.7 and 5.8 show summaries of these data.

5.3 CALIBRATION RESULTS

The data collected in the first hour were entered into the TRANSYT model and the simulation model was run. The output of the model was checked and the measures of effectiveness were studied. The comparison between the field percentage of stops on the five approaches and the simulated percentage of stops, as presented in the second row of Table 5.9, shows that the model almost always overestimates the percentage of stops with the TRANSYT default stop reduction curve, (4 out of 5 approaches). Inspection of the stop reduction curve suggested and used by the TRANSYT model (Figure 5.2) shows that short delays were considered as partial stops (e.g. 4 seconds delay is considered 78% stops). Inspection of the drivers' behavior in the field showed that drivers often try to avoid stopping by reducing their speed long before they reach the intersection when they see the red light or the queue back. This slowing down over a long distance causes delays

Table 5.7: Average Vehicle Spacing and Extension of Effective Green in the Study Area

The Study Area	
Extension of effective green (sec)[a]	Average Vehicle Spacing (dm)
3	70

Source: Ratrout (25)

Table 5.8: Start-up Lost Time and Saturation Flow Rate in the Study Area

City of Dammam			City of Al-Khobar		
Start-up Lost-Time (sec) [a]	Saturation Flow rate (vphg/lane) [c]		Start-up Lost-time (sec) [a]	Saturation Flow rate (vphg/lane) [c]	
	Thru	Turn [b]		Thru	Turn [b]
2	1720	1690	2	1780	1650

a: Only integer seconds may be used in TRANSYT-7F.
b: Protected, unopposed turning movements.
c: Rounded to the nearest 10 vehicles.

Source: Ratrout (25).

Table 5.9: Percentage of Vehicles Stopped as a Function of Delays (Sec)

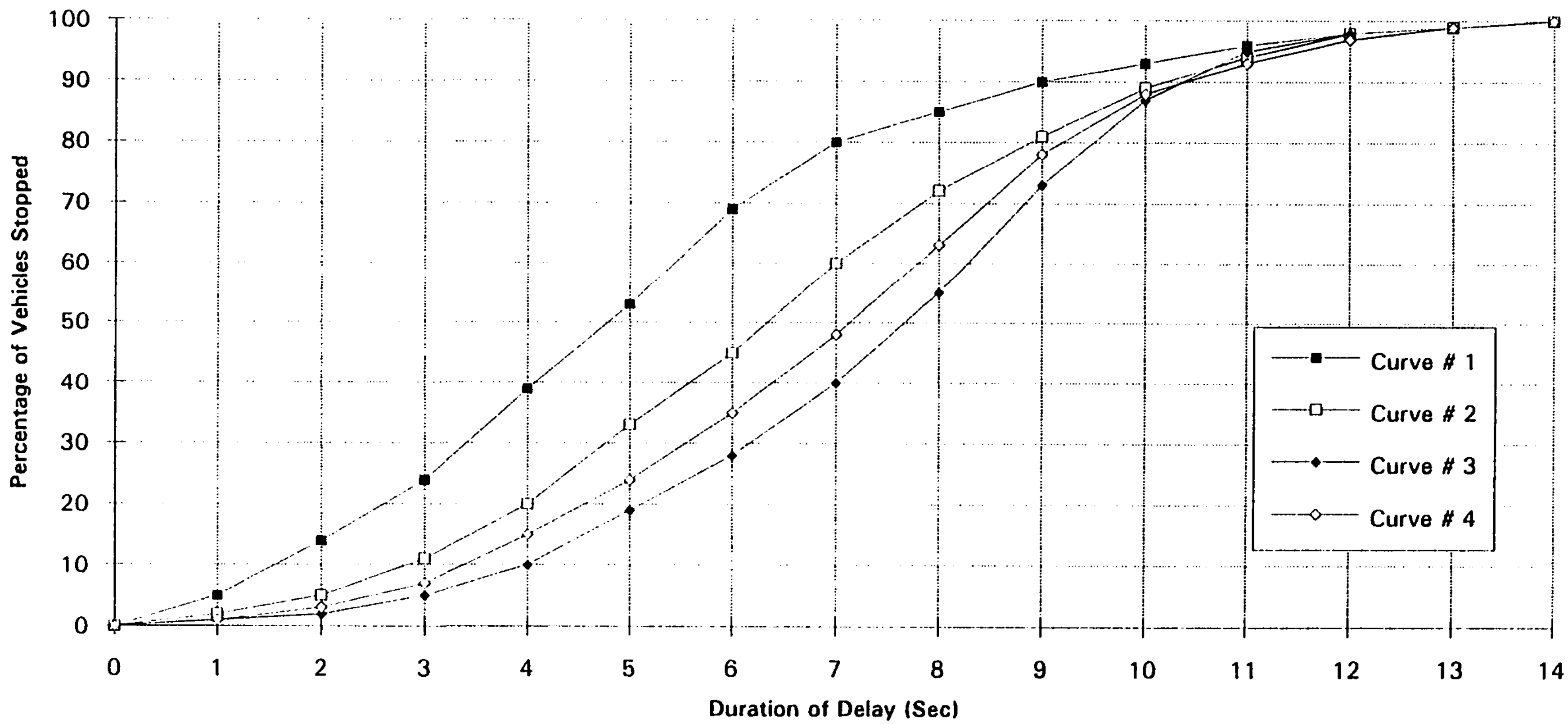
Curve \ Delay	1	2	3	4	5	6	7	8	9	10	11	12	13	14
TRANSYT Default	20	50	65	76	83	88	93	95	97	99	100	100	100	100
Curve 1	5	14	24	39	53	69	80	85	90	93	96	98	99	100
Curve 2	2	5	14	20	33	45	60	72	81	89	94	98	99	100
Curve 3	1	2	5	10	19	28	40	55	73	87	95	98	99	100
Curve 4	1	3	7	15	24	35	58	63	78	88	93	97	99	100

without stopping.

In order to improve the simulation of stops, the stop reduction curve was modified until the model simulated the percentage of the stops seen in the field. This process was done by trial and error; by using curves that are similar to, but flatter than, the original curve in the shape. These curves reduced the percentage of short delayed vehicles that are considered stops on the original curve. The short delays form a large percentage of the total flow when the arterial has some coordination, which is the case in the King Abdulaziz arterial. This is because during good coordination the platoon arrives at the beginning of the green phase and short delays are caused by the platoon discharging at the intersection. The change of the stop reduction curve will not affect uncoordinated links because most of the vehicles will be delayed for longer periods and will be considered complete stops, which is the real case in the field. Therefore, the curve that can simulate the number of stops on a coordinated arterial will be able to simulate the number of stops on an uncoordinated arterial.

Figure 5.7, which is obtained from Table 5.9, shows the series of graphs that were used in comparing the actual field values and the model percentage of stops using these curves. Curve 4 gave the best simulation of the number of stops very close to

Fig.5.7 Stops Reduction Curves



field values.

The second set of data (the second hour of study between 9:35 and 10:35 AM) was also entered into the program and was run using the above mentioned curves. Table 5.11 shows that curve 4 was again the best curve. This result confirms that curve 4 gives the best simulation of stops, as observed in the field.

In order to prove that the difference between the simulated percentages of stops and the field percentages are not statistically different the following t test was conducted:

$$H_o: d_1 = 0$$

$$H_1: d_1 \neq 0$$

where d_1 is the mean of the differences between percent stops of curve (4) and the field percent stops. For the first set of simulated data, the mean of the differences was 0.100% with a standard deviation of 3.928. Now we can calculate t-statistic as follows:

$$t = \frac{d_1 - 0}{\sigma/\sqrt{n}}$$ where n is the number of approaches,

$$t = \frac{0.100 - 0}{3.928/\sqrt{5}} = 0.056$$

Table 5.10: Simulation of % Stops Using Different Stop Reduction Curves For The First Hour

	% Stops for Approach					
Source	10th Street South Bound	16th Street South Bound	16th Street North Bound	22nd Street South Bound	22nd Street North Bound	Absolute Dif.Bet.Field & TRANSYT Estimates
Field Values	36	36	42	48	48	0
Estimations with TRANSYT Default Stop Reduction Curve	54	64	40	56	69	77
Estimation with Modified Curve No.1	42	49	37	53	57	38
Estimation with Modified Curve No.2	32	33	34.6	51	41	24.4
Estimation with Modified Curve No.3	34	36.1	34.8	51.6	43.7	17.2
Modified Curve No.4	35.7	40	35.3	52	47.5	15.5

Table 5.11: Simulation of % Stops Using Different Stop Reduction Curves For The Second Hour

	% Stops for Approach					
Source	10th Street South Bound	16th Street South Bound	16th Street North Bound	22nd Street South Bound	22nd Street North Bound	Absolute Dif.Bet.Field & TRANSYT Estimates
Field Values	35.1	36	46.8	46.5	48	0
Estimations with TRANSYT Default Stop Reduction Curve	56	62	49	50	70	74
Estimation with Modified Curve No.1	44	48	43	48	55	32.6
Estimation with Modified Curve No.2	33	32	39	47.6	38	24.4
Estimation with Modified Curve No.3	35	34.7	39.6	47.7	41.2	17
Modified Curve No.4	37.3	38.6	40.4	47.9	45.2	15.8

$t_{table} = 2.776$

t is less than t_{table}, therefore, the difference is not significantly different than zero. So, simulation using curve 4 gives acceptable results that do not significantly differ from the field values.

Conducting the same t-test on the second set of data is as follows:

$d_2 = -0.72 \qquad \sigma_2 = 3.54$

$$t = \frac{-0.72 - 0}{3.54/\sqrt{5}} = 0.454$$

$t_{table} = 2.776$

t is less than t_{table}, therefore, the differences are not significantly different from zero.

For the remaining part of this research curve 4 which gives the best simulation of the field values of stops will be used. This curve is presented in Figure 5.7 given above.

Chapter 6

INCORPORATION OF SAFETY INTO THE OPTIMIZATION MODEL

6.1 INTRODUCTION

In this chapter, various tasks were performed for the purpose of incorporation of a safety aspect into the optimization model. First, sensitivity analysis of stops and delays to K in the performance index and to cycle length are investigated to show the magnitude of the effect of changing K and cycle length on stops and delays; which are the main contributors to the total costs. Then the TRANSYT cost function was revised to represent Saudi Arabian conditions. Accident costs were investigated using available data so that they could be added to total costs. This investigation included the severity percentages and the estimation of each severity category costs. It also included the costs due to excess delays and stops resulting from blockage of intersections when an accident takes place. Given these costs it was possible to calculate K values that would optimize safety as well as other cost items. The effect of different accident severities on K values was assessed through a sensitivity analysis. Similar analysis was performed to assess the effect of K value on total costs. The effect of signal coordination on safety and costs was investigated by proposing different signal timing plans and comparing their impact on safety and costs. Similar analysis was performed to assess the impact of different phasing on total costs. Finally, the effect of safety inclusion on signal timing plans was investigated by using K value that optimized safety and compared the resulting signal timing plans with plans that were obtained using a K value that doesn't optimize safety.

6.2 SENSITIVITY OF STOPS AND DELAYS TO K IN THE PERFORMANCE INDEX

The aim of this chapter is to investigate the effect of changing K on delays and stops, which are the main items affecting costs. K is the weight of stops compared to delay, as shown in equation 2.1 in Chapter 2. A value of 100 means that one stop is equivalent to 100 seconds of delay. In this analysis, delay and stops will be optimized using a set of K values that range from zero to 250.

The K values start from zero and then are increased by 5 to 100, and then by 20 to 200 and by 50 to 250. The increment of 5 was chosen in the first range to see the exact behavior of stops and delay, and fuel consumption in this range which is suggested by the TRANSYT Manual. Then the increment is increased to 20 and 50 to cover the ranges from 100 to 200 and 200 to 250, respectively to give us an approximate idea about the behavior in this range that might occur after the inclusion of safety cost.

The results of simulation run in terms of three measures of effectiveness values (MOE's) of stops, delay and fuel consumption with different values of K which are presented in Figures 6.1, 6.2 and 6.3 respectively.

Figure 6.1 shows that stops decrease significantly up to a K value of 55-60 but after that they don't change much. An inspection of Figure 6.2 reveals that a significant increase in delays occurs at this value but delays are constant before this value. Figure 6.3 shows that fuel consumption reduces significantly from K values of 5 to 20 but then it remains more or less the same up to very large values of 180-200. Therefore, fuel consumption is not very sensitive to K values between 15 to 200. Hence the minimum stops, delays and fuel consumption can be obtained by using K values around 55-60.

6.3 SENSITIVITY OF STOPS AND DELAY TO CYCLE LENGTH

The aim of this analysis is to study the effect of cycle length on stops, delay and eventually fuel consumption. The model will be optimizing splits and offsets for different cycle lengths ranging from 80 seconds to 160 seconds. The results can

Figure.6.1 : Stops vs K

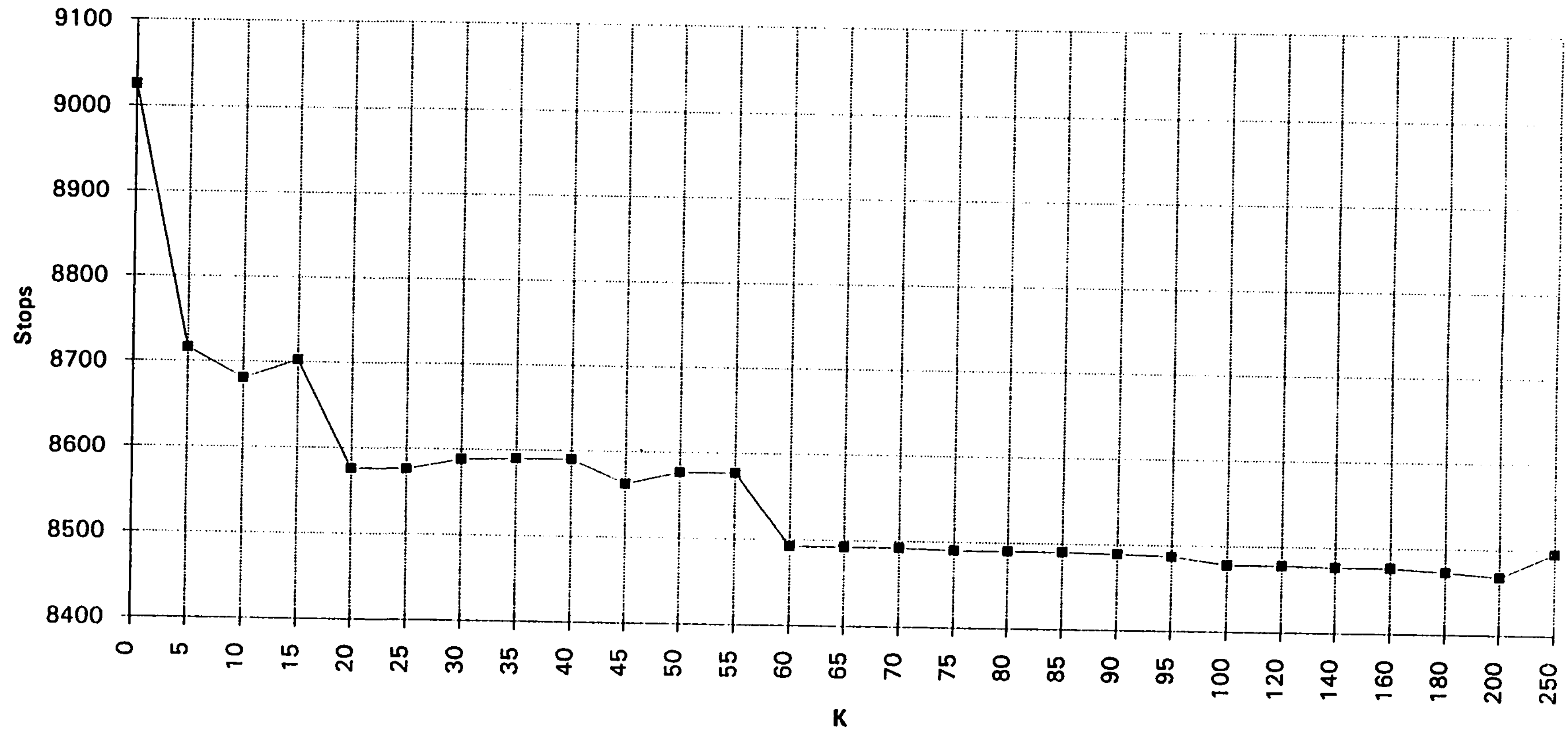


Figure.6.2 : Delay vs K

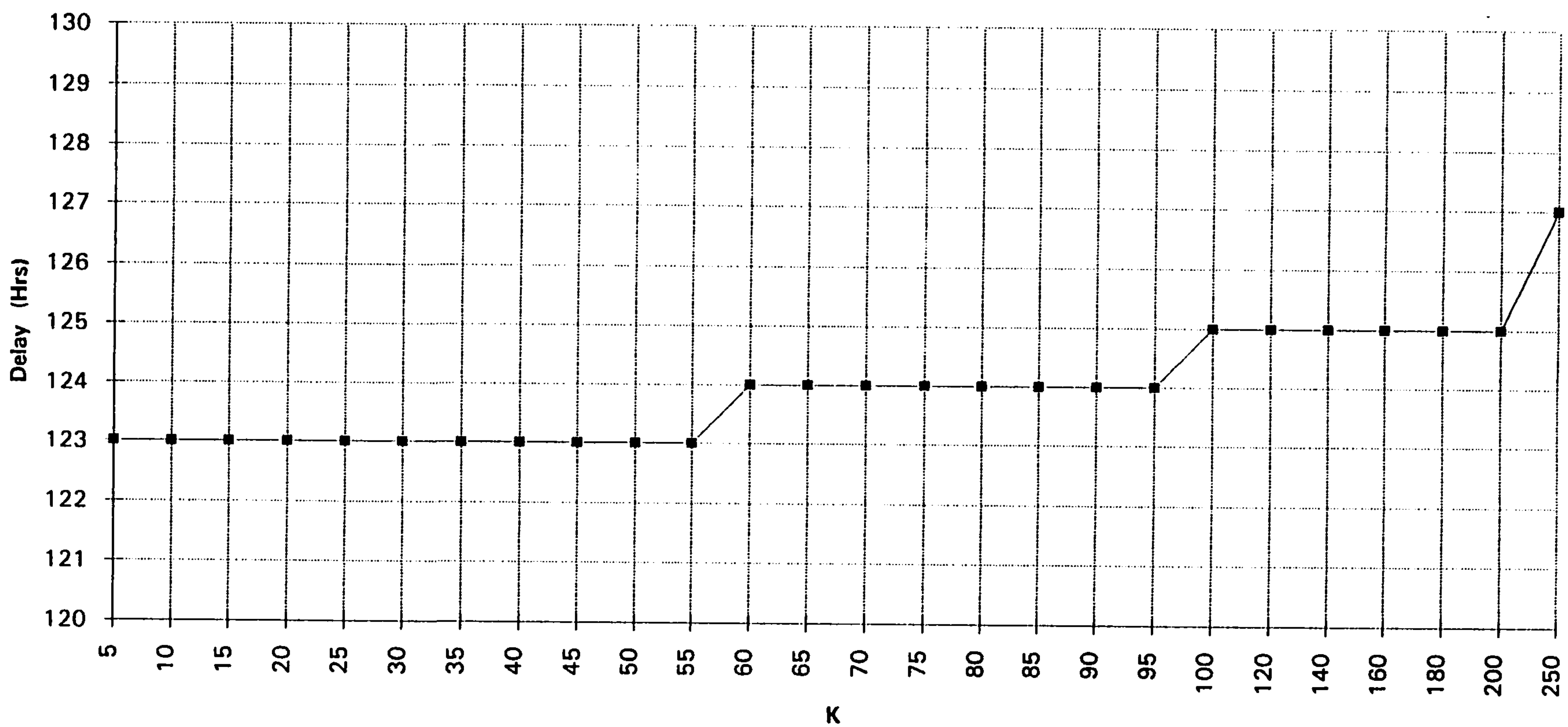
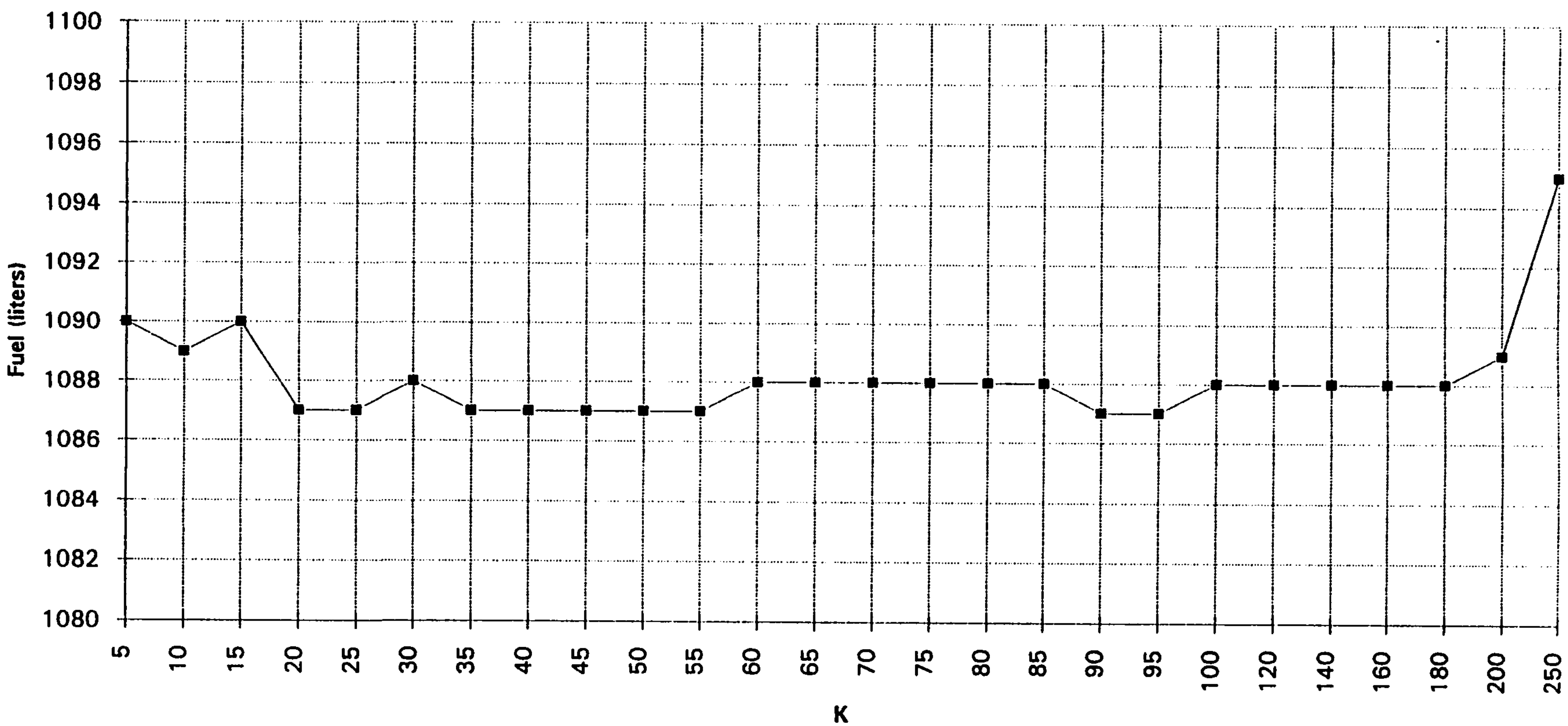


Figure 6.3 :Fuel Consumption vs K



not be generalized because they depend on the network and volumes, but they give a good idea about the importance of choosing the proper cycle length. The K value and speed were kept constant throughout the analysis (K = 35, speed = 60 kph).

Figures 6.4, 6.5 and 6.6 show the effect of cycle length on stops, delays and fuel consumption, respectively. It seems that the cycle lengths of 100-110 seconds give the lowest delays, stops and fuel consumption. There is a very sharp increase in all the three MOE's for cycle lengths shorter than the optimum values of 100-110 seconds. Obviously short cycle lengths, especially with four phase signalling, are not good for coordinated arterials.

6.4 REVISION OF TRANSYT COST FUNCTION

The TRANSYT model has a cost function as presented in Appendix (A). In this section the cost items of road users included in this cost function will be revised to represent Saudi Arabian conditions. Furthermore, the accident costs will be estimated for Saudi Arabia and included in the analysis of the effects of signal coordination on safety. The detailed calculations are presented in Appendix B, while the main assumptions are listed below:

In order to estimate the cost of passenger and vehicle

Figure 6.4 : Stops vs Cycle Length

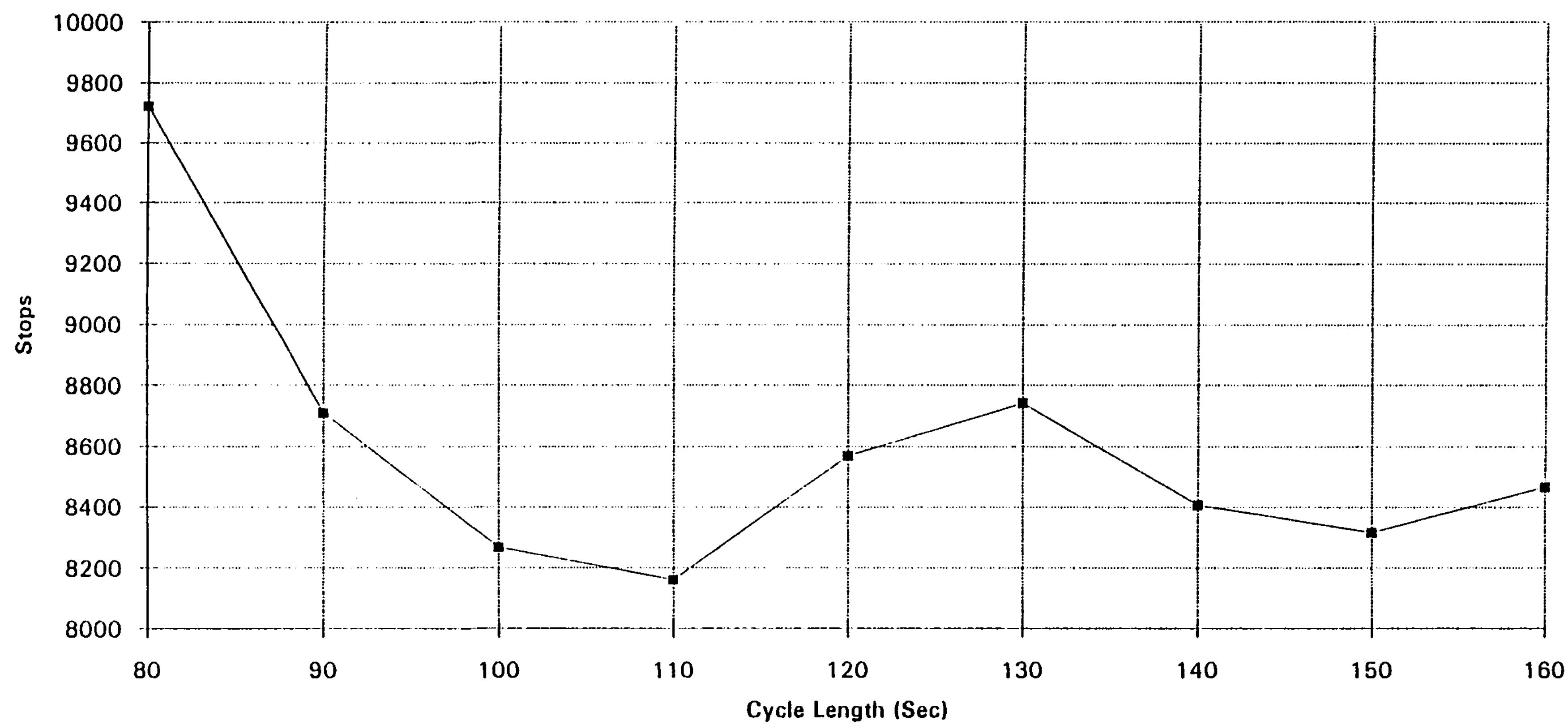


Figure 6.5 : Delay vs Cycle Length

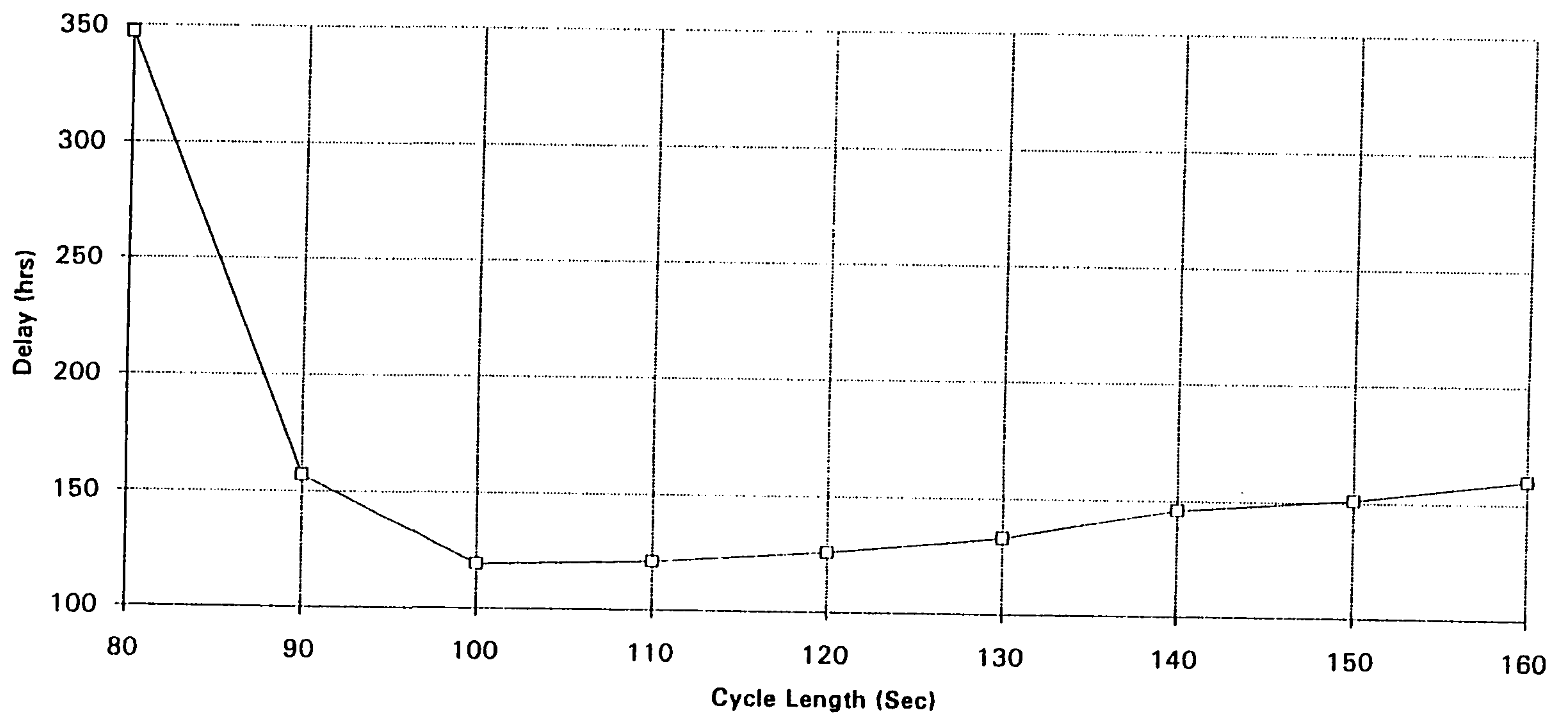
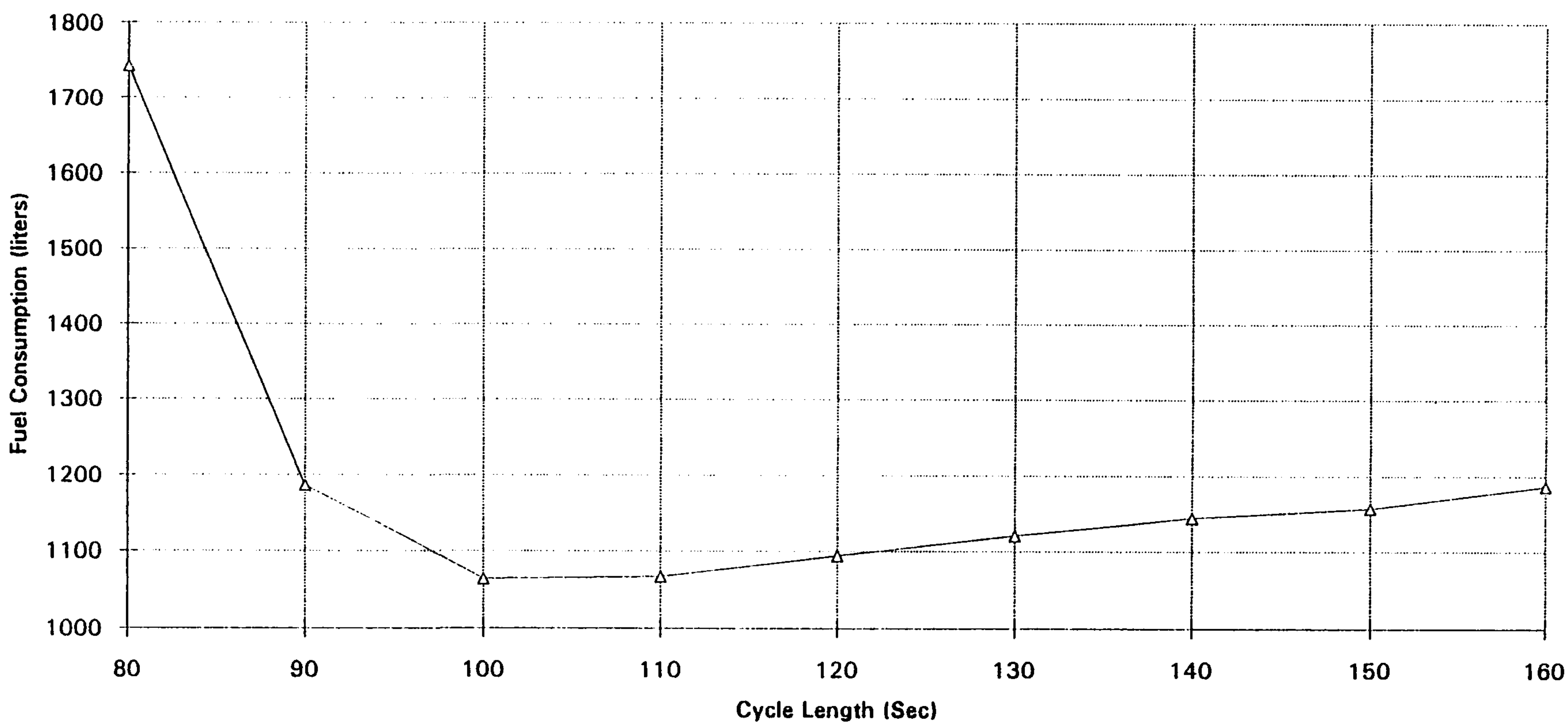


Figure 6.6 : Fuel Consumption vs Cycle Length



delay, the following assumptions are:

a. Fifty percent of the population are in the work force, while most drivers and passengers are in the work force.

b. The income per capital is 7060 US dollars for Saudi Arabia in 1990 (37).

c. The vehicle delay cost in Saudi Arabia is the same as the cost suggested by the TRANSYT Manual inflated to 1990 in Riyals.

d. The inflation factor is the ratio between the consumer index in 1990 and 1987 (103.1 and 99.1 respectively).

e. The vehicle occupancy is 1.2 passengers/vehicle (29).

The vehicle occupancy takes place on one of the arterial approaches, excess delay, stops and fuel consumption are expected due to the interruption of traffic flow. This was not considered in previous research but was estimated for this work.

For this, the simulation model (TRANSYT-7F) was used to simulate the increases in delay, stops and fuel consumption due to accidents. The following assumptions are made for this:

1. One lane is closed due to the accident.

2. The average time to remove the vehicles involved in

accidents is one hour.

3. The effect of accidents is measured at all major approaches.

4. The average excess cost is the average of the excess costs of all rear-end accidents on the major approaches. The expected number of accidents on each approach is assumed to be proportional to the number of stops on each approach.

The cost of accidents as a function of stops using the Human Capital Cost (HK) approach and willingness to pay adjusted Human Capital (WTP/HK) approach explained in Apendix B were calculated and found as follows:

Cost of Accident, (using Human Capital Cost) = 0.0467 SR per stop.

Cost of Accident, (using Adjusted WTP/HK) = 0.0467 SR per stop.

6.5 CALCULATION OF K VALUE

The original intention was to add the accident cost to the operation cost model and, then use the operation cost function as an objective function to optimize. This would result in a signal timing plan that minimizes operation cost. Unfortunately, this could not be done because the built-in coefficients of the operation cost model can be overriden within a specific format that cannot be changed (e.g. one coefficient must be negative and cannot be written positive). Due to this difficulty, it was decided to use K in the original performance index (PI) as a parameter to reflect the changes due to accident cost and other revised cost items. K is defined as the stop penalty, which is the amount of delay in seconds equivalent to one stop. It is possible to calculate this amount given the cost of one stop and the cost of one second of delay. If the costs of stops include the cost due to accidents, then the model will optimize safety as well as other costs based on economical measure. It will give the best signal timing plan that minimizes the overall cost including accident cost.

In order to calculate the optimum K that minimizes the cost with and without accident cost, the cost of one stop has to be divided by the cost of one second of delay. This ratio by definition is the K value used in the objective function of the TRANSYT optimization model.

The cost of one stop (w/o accident cost) = vehicle cost + Excess fuel cost (See Appendix B)

= 0.0986 + 0.01035 = 0.10895 SR/Stop

The cost of one second of delay = (vehicle and passenger delay cost + E xcess fuel cost) ÷3600 sec/hr

$$= (7.41 + 0.88716) \div 3600$$

$$= 0.002305 \text{ SR/Second of delay}$$

$$K = \frac{0.10895}{0.002305} = 47.2$$

$$= 47$$

This value falls within the range of K suggested by the TRANSYT Manual (20-50) not considering the cost of accident. It is also very near to the optimum value (50-55) found in Section 6.2 above.

In order to incorporate safety into the optimization process of the TRANSYT model, the cost of rear-end accidents should be introduced to the objective function. The way to do that is by recalculating the K value and including the cost of rear-end accidents. The cost of a stop due to accidents should be added to the numerator of the K formula mentioned above. Two K values are calculated below, one for the Human Capital Cost and one for the Adjusted WTP/HK Cost.

The Human Capital Technique is a method of estimating cost of death in which lost income and benefits due to a lost life are estimated, while the Willingness to Pay Human Capital Technique is a method that includes an estimate of value of lives on top of lost income and benefits.

$$K\ (\text{Human Capital}) = \frac{0.10895 + 0.0467}{0.002305}$$

$$= 67.52 = 68$$

$$K\ (\text{Adjusted WTP/HK}) = \frac{0.10895 + 0.0809}{0.002305}$$

$$= 82.34 = 82$$

Using the new K values should theoretically optimize safety as well as other cost items. Higher values of K would reduce the number of stops at the expense of more delay.

6.6 SUGGESTED K VALUES FOR DIFFERENT SPEEDS

Notice that all the above mentioned calculations were done on the assumption that the speed is 60 k/hr (37.29 mph). A small basic program was written to repeat all the calculations for a range of common speeds on urban arterials (40 kph - 85 kph). This program was used to do the sensitivity analysis of accident cost. The output of the program was the K values for each speed. The outcome of the above mentioned basic program that calculates K for different speeds is listed in Table 6.1 . Notice that for low speeds, K is small because the cost of vehicle and fuel suggested by the TRANSYT cost function, which are directly proportional to

Table 6.1 : K Values for Different Speeds for HK and Adjusted HK/WTP Cost Approaches

Speed (kph)	K(w/o Accident Costs)	K(HK costs)	K(HK/WTP Costs)
40	21	42	56
45	26	47	62
50	33	53	68
55	40	60	75
60	47	68	82
65	56	76	91
70	65	86	100
75	75	96	111
80	87	107	122
85	99	119	134

speed, are lower than the costs at higher speeds.

6.7 SENSITIVITY ANALYSIS OF K TO ACCIDENT COST AND SPEEDS

As mentioned in the previous chapter, the percentage of fatal accidents wasn't very reliable. It was decided to conduct a sensitivity analysis to see the effect of different percentages of fatal accidents on the value of K. The effect of changing the percentage of fatal and serious accidents on the average accident cost due to one stop is shown in Tables 6.2 and 6.3. Table 6.4 shows the sensitivity of K to accident cost for Human Capital approach (HK) and Willingness-to-Pay Adjusted Human Capital (WTP) as well as to changes in speed. Inspection of Table 6.4 shows that K is more sensitive to speeds than for severity percentages. K increases by 10 when the fatal accidents increase from 1% to 3% of Human Capital cost, while K increases by 18 when fatal accidents increase from 1% to 3% of Willingness-to-Pay cost. On the other hand, K increases by more than 60 when the speed increases from 40 km/hr to 80 km/hr for both estimation approaches. It is therefore more important to estimate the cruising speed on the arterial links than to estimate the percentages of severities.

Table 6.2: Accident Costs for Different Accident Severities (HK)

% Fatal	% Injury	% POD	Average Accident Cost	Cost per 1000 Stops
0.0	8.5	91.5	4325	10.15
0.5	8.0	91.5	8755	10.55
1.0	7.5	91.5	13186	30.95
1.5	7.0	91.5	17617	41.35
2.0	6.5	91.5	22047	51.74
2.5	6.0	91.5	26478	62.14
3.0	5.5	91.5	30908	72.54
3.4	5.1	91.5	34453	80.86

Table 6.3: Accident Costs for Different Accident Severities (WTP/HK)

% Fatal	% Injury	% POD	Average Accident Cost	Cost per 1000 Stops
0.0	8.5	91.5	4325	10.15
0.5	8.0	91.5	6642	15.59
1.0	7.5	91.5	8960	21.03
1.5	7.0	91.5	11278	26.47
2.0	6.5	91.5	13595	31.91
2.5	6.0	91.5	15913	37.35
3.0	5.5	91.5	18231	42.79
3.4	5.1	91.5	20085	47.14

Table 6.4: Sensitivity of K to Changes in the Percentage of the Severity

Method of Cost Estimation	Speed km/hr	Severity Percentage Fatal %/Injury %		
		3.0/5.5	2.0/6.5	1.0/7.5
With Human	40	40	35	30
Capital Cost	60	66	61	56
HK	80	105	100	96
With Willingness to pay Adjusted	40	53	44	34
Human Capital	60	79	70	62
WTP/HK	80	118	109	100

6.8 SENSITIVITY OF TOTAL COST TO K

Cost items can be calculated as functions of stops and delay. Knowing the behavior of stops and delay as a function of K, the behavior of cost functions vs K can be calculated. From the previous chapter, we know that as K increases, delay increases and stops decrease (Figs. 6.1 and 6.2). The total costs associated with delay are increasing gradually as K increases, while costs associated with stops decrease as K increases. The total cost for the cases of no accident cost, Human Capital accident cost and Willingness-to-Pay accident costs were calculated for different values of K by optimizing signal timing plans using different values of K and, then, using stops and delays to calculate total cost in the same way presented in Section 6.4. Figure 6.7 shows a presentation of the output of these calculations of costs vs K. Comparing the total costs, with and without accident costs for both HK and WTP/HK, it can be noticed that, in general, the cost of accidents constitutes a large portion of total cost. For example, when the speed on the arterial is 60 kph, the road user costs, without accident costs are SR 1956, while they increase to SR 2369 and SR 2658 including HK and WTP/HK accident cost respectively. This is an increase of 11.2% and 35.8% for HK and WTP/HK accident cost respectively. This is a large increase in operation cost and it would affect the feasibility study of any traffic management plans.

Figure 6.7 shows that the costs are minimal in a wide range of K (20-95). However, a close inspection reveals that the minimum costs are found at different values of K. If the accident costs were not considered, the lowest total cost would be at K = 45. If the accident costs were considered, the lowest total would be at K = 95 for both HK and WTP/HK adjusted accident cost. Therefore, if accident costs were ignored, the user would choose a K value that does not give the best signal timing plan in terms of total cost. The difference between the plan with and without accident cost consideration would be as follows:

Difference in total cost = 2653 - 2647 = 6 SR per hour

If the user used the default value suggested by the TRANSYT Manual (20-50) and he chose 35 as a median value the difference would be as follows:

Difference = 3658 - 2647 = 11 SR per hour

Calculating the saving for one year and for 25 arterial the saving would be as follows:

Total saving in one year = 11 * 16 * 365 * 25

= SR 1,606,000 per year.

The savings due to choosing the right K value constitute a small portion of the total cost for the case of one arterial with four

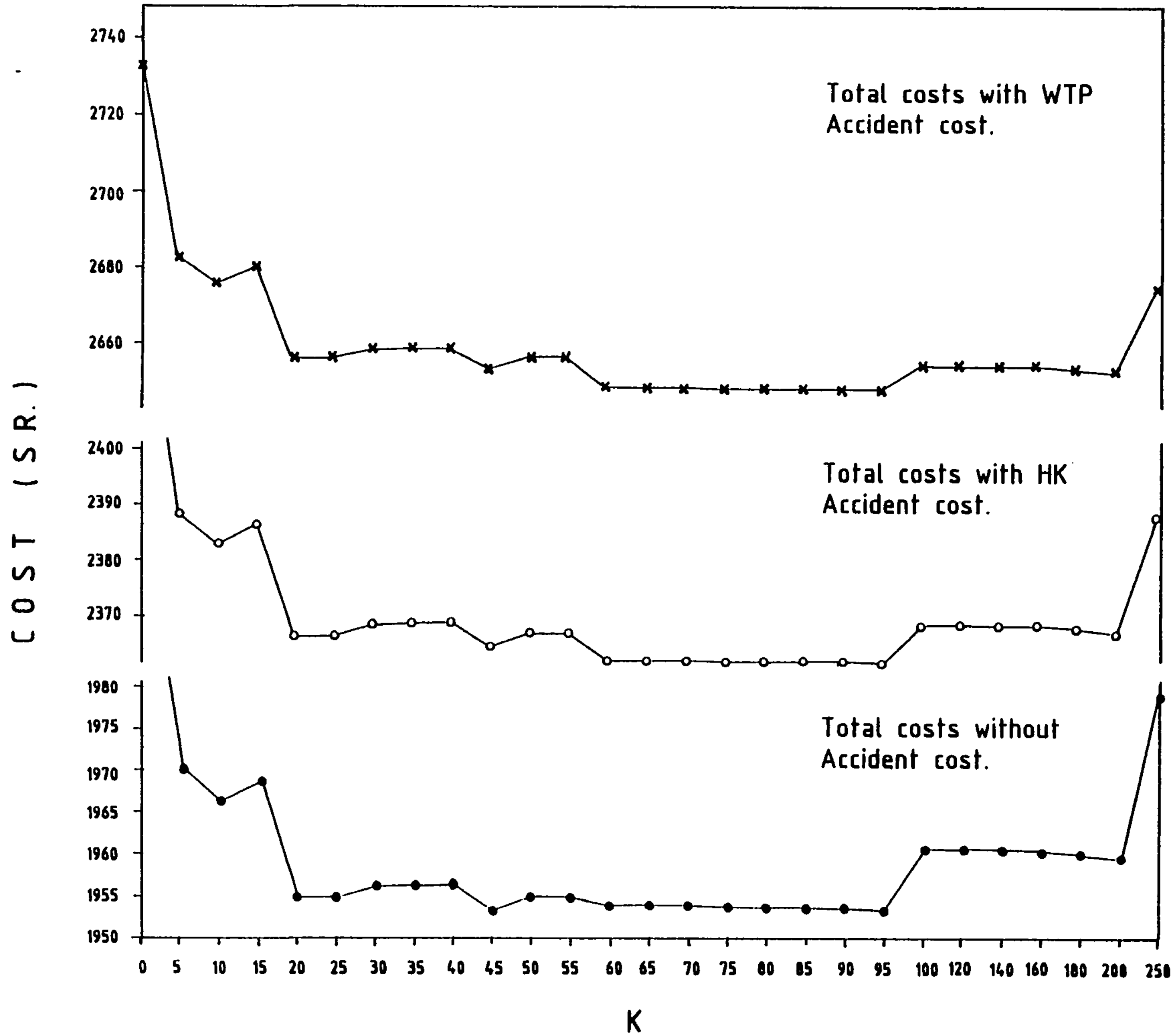


Figure: 6.7 Total Costs vs K.

signalized intersections. However, the saving might be larger for large networks, and for different speeds. Furthermore, the use of the right K is a very simple procedure for TRANSYT users and the saving in total costs justifies the process of choosing the right K.

The total costs for the existing signal phasing sequence happened to be less sensitive to K value. However, other types of signal phase sequence (e.g. TLEW presented in Section 6.11) are more sensitive to K values and the potential for saving is expected to be more.

6.9 THE EFFECT OF SIGNAL COORDINATION ON SAFETY AND COST

In this section, the potential improvements in safety and saving in operation cost due to signal coordination were investigated. This was done by simulating the traffic conditions on the study arterial for different signal timing plans. The first signal timing plan was the existing signal timing plan, but the offsets will be random. The second signal timing plan was chosen as it had the best splits generated by the TRANSYT optimization model but with random offsets. Random offsets were chosen from random numbers tables. Four sets of random offsets were simulated for each case and, then, the MOE's were averaged. The third signal timing plan was the optimum signal timing plan found by the TRANSYT model in terms of splits and offsets.

The differences in MOE's between the first plan and the second plan are due to the split optimization, while the differences in OME's between the second plan and the third plan are due to signal coordination. The stops, delays, expected yearly accidents and yearly costs of the three signal timing plans are presented in Table 6.5. Investigation of the table reveals that there are few improvements in accidents and costs as a result of split optimization only. The improvements as a result of signal coordination are very significant, with a reduction of accidents and costs of 29% and 29.5% respectively; compared to the first plan which had a reduction of 26.8% and 26.2% respectively compared to the second plan. Therefore, signal coordination is expected to reduce delay, stops, accidents and costs considerably and should be introduced wherever possible since it is easy to design, implement and maintain. It can be concluded that signal coordination is one of the most efficient and cost-effective alternatives available for traffic engineers to improve safety at signalized intersections.

Table 6.5: The Effect of Signal Coordination on Safety

Signal Timing Plan and Costs	Delays (hr/hr	Stops (Per Hour)	Accident (Per Year)	Total Cost (SR) Per Year (mil)
Existing Plan + Random Offsets	180.17	11,834	158	21.29
Best Splits + Random Offsets	167.19	11,516	153	20.34
Best Splits + Best Offsets	121.61	8,403	112	15.01

1) NSEW for 4-intersections arterial

2) All MOE's are obtained by averaging the results of four simulation runs with four different random offsets.

6.10 THE EFFECT OF SIGNAL PHASING ON OPERATIONAL COST

In this section, four different types of phasing were chosen among many signal phasing alternatives suggested in the TRANSYT manual. These four schemes are most common and suitable for the study area because they are all protected. In Saudi Arabia permitted phasing is not used and therefore they were excluded from this analysis.

The four phasing plans which are given in Table 6.6 , are as follows:

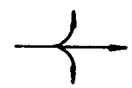
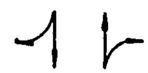
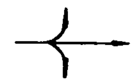
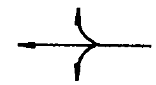
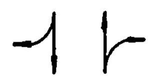
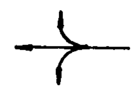
1. NSEW: For this scheme a separate protected phase is given to each approach.

2. STNEW: This is similar to the first plan with an extra phase for through movements in the south and north direction.

3. SLNEW: This is also similar to the first plan with an extra phase for left turn movements coming from the north and south.

4. TLEW: This phasing plan has a separate phase for through movements from the south and north and a separate phase for left turn movements coming from the north and south, while the east and west phasings are

Table 6.6 Signal Phasing Terminology

Phasing Design		Phases				
No.	Code	A	B	C	D	E.
1	NSEW					
2	STNEW					
3	SLNEW					
4	LTEW					

protected unidirectional phases.

These four different phasing plans were investigated to find the best plan in terms of operation cost (including accident cost (WTP/HK)) for different intersection spacing and different volume levels. The intersection spacing was varied between 250 and 1000 meters and the volume levels were varied between 165 and 400 vplph.

Sixty four optimization runs were performed by the TRANSYT model for various combinations of intersection spacing and volume levels to find the best signal timing plan. The delays, stops and fuel consumption of each run were used to calculate the total operation costs (including accident costs). Table 6.7 shows the final result of the cost analysis. The signal timing plans with the minimum cost in each volume-distance category are highlighted by a star. If the difference between the minimum and second minimum cost is less than SR 50, both plans are considered to have the minimum cost and both are highlighted.

Inspection of the costs in Table 6.7 revealed the following conclusions:

1. Signal timing plan number 3 is not good as it resulted in the highest costs in all cases with the traffic conditions similar to those in King Abdul-Aziz Street. Plan 3

Table 6.7: Cost Per Hour Including Accident Cost (WTP/HK)

		Traffic Volumes per Lane Vphpl			
Distance (m)	**Phase**	**165**	**250**	**330[3]**	**400**
250	1	1004[2]	1616[2]	2396[2]	3545[2]
	2	1067	1678	2508	4348
	3	1227	2011	3084	5549
	4	1065	1699	2501	3499[2]
Actual 450-500	1	1027[2]	1653[2]	2485[2]	3584[2]
	2	1154	1843	2801	4669
	3	1278	2117	3318	5838
	4	1151	1922	2784	3760
750	1	1185	1899	2857	3974
	2	1028[2]	1648[2]	2803	4741
	3	1171	1933	3160	5592
	4	1063[2]	1677[2]	2463[2]	3714[2]
1000	1	1166	1876	2787	4046
	2	1028[2]	1719[2]	2618	4501
	3	1181	1935	2978	5446
	4	1072[2]	1730[2]	2566[2]	3543[2]

1) The phases are:

1 = NSEW
2 = STNEW
3 = SLNEW
4 = TLEW

2) Minimum Cost

3) This volume represents the morning off-peak volumes for the arterial.

includes an extra left turn phase which might be suitable for a case where large left turn volumes justify the inclusion of such a phase.

2. When the intersection spacings are < 500 meters, signal timing plan 1 is best for all volume levels. This is due to the flexibility of signal timing plan 1 compared to the other plans, where the sequence of phases can be changed to favor good progression in the main street.

3. When the intersection spacings are < 750m and traffic volumes are < 250 vplph, signal timing plans 2 and 4 have the lowest cost. Large spacing between intersections provide good progression for both direction on the main street and plans 2 and 4 have simultaneous phases for through movements in the main street which are the heaviest movements. When intersection spacing is < 750 and traffic volumes are > 330 vphpl (existing morning off-peak volumes on the study arterial), signal plan 4 has the lowest cost. Plan 4 has only four phases compared to plans 2 and 3 which reduce the delay caused by start up lost time. Through movements on the main street have a simultaneous phase which allows a long split for these heavy movements.

The existing signal phasing plan is plan 1 and it happened to be the best plan for the existing combination of volumes and intersection spacing. The above analysis, emphasizes the importance of carefully selecting the right signal phasing plan because it can affect costs significantly. The analysis shows also that, in general, four phase plans (plan 1 to 4) give lower operation cost than five phase plans.

6.11 THE EFFECT OF SAFETY INCLUSION ON SIGNAL TIMING PLANS

The inclusion of safety is achieved by using a higher K value that reflects the importance of reducing stops and hence, reducing accidents. Using higher values of K is expected to result in longer cycle lengths because the green given to any approach is expected to be longer so that vehicles approaching the intersection are not forced to stop. Stops are avoided because they are given more importance in the performance index. Major streets are expected to be given a higher percentage of green time because there will be more vehicles approaching the intersection when green a phase is given to that approach than in the case of minor streets. Using different signal phasing plans explained in Section 6.10 with two different K values: 35 (TRANSYT recommended value) for signal timing plans that do not include safety and, 82 (recommended in Section 6.5) for signal timing plans that include safety, would enable us to compare signal timing plans and comment on the effect of safety inclusion. Table 6.8 shows the split percentages between main street and cross street for each intersection for four different signal phasing plans. Intersections No. 1 and No. 4 are neglected because the inflow into those intersections was assumed to be random and because intersection No. 4 is an intersection between two main streets. Comparing the splits of intersections No. 2 and No. 3 shows that, in general, there is less time given to the cross streets for signal timing plan with safety compared to plans without safety inclusion. This conclusion confirms the TRANSYT manual statement, that the neglecting stops in the PI function would result in signal timing plans with more time assigned to minor streets (29). Table 6.16 also shows that the cycle lengths were increased slightly for some phasing schemes if safety is included. Signal phasing scheme S_4 has a higher increase in cycle length from 85 sec to 105 sec and a higher increase in main street split percentage from 58% to 70% because the main street approaches were given the green simultaneously for through movements and for left turn movements; therefore, the effects on cycle length and splits were more pronounced.

In summary, the inclusion of safety inclusion on signal timing plans is expected to result in longer cycle lengths and more

Table 6.8: The Effect of Safety Inclusion on Split and Cycle Length

Signal Phasing	Intersection	Without Safety Inclusion			With Safety Inclusion		
		Main %	Cross %	Cycle (Sec)	Main %	Cross %	Cycle (Sec)
S_1 NSEW	2	61	39	100	63	37	100
	3	68	32	100	68	32	100
S_2 STNEW	2	67	33	115	67	33	120
	3	71	29	115	72	28	120
S_3 SLNEW	2	68	32	110	68	32	110
	3	72	28	110	72	28	110
S_4 TLEW	2	58	42	80	67	33	105
	3	58	42	80	70	30	105

green given to the main street. These effects vary in magnitude from signal phasing scheme to another.

Chapter 7

SUMMARY AND CONCLUSIONS

Traffic signal optimization is one of the most efficient tools available for traffic engineers to improve traffic conditions, lessen delay, stops and to reduce fuel consumption. Little has been done to investigate the effect of signal coordination on intersection safety. Some earlier studies have shown that signal coordination reduces intersection accidents (3,4). This study was conducted on urban intersections in Dammam and Al-Khobar cities; to investigate the effect of signal coordination on intersection safety and a methodology was suggested to incorporate safety into the optimization algorithm of a selected optimization model (TRANSYT 7F).

This research hypothesized that traffic signal coordination mainly affects rear-end accidents and that rear-end accidents are mainly related to stops. To obtain the relationship between the rear-end accidents and stops first, the relationship between conflicts and stops was established using data from 38 intersections in the Dammam and Al-Khobar areas. This relationship, which is given below, was obtained using regression analysis:

$$\text{Conflicts} = 0.01154 \text{ stops} \quad , \quad R^2 = 0.869$$

In the second step a relationship was obtained between rear-end conflicts and rear-end accidents using the data collected by Al-Isa et al (2) in 1988. The resulting equation, which was developed using regression, is as follows:

Accidents (in two years) = 2.309 (conflicts/hour) , $R^2 = 0.869$

These two equations were then combined to obtain a direct relationship between the (rear-end accidents per hour) to (stops per hour) after making adjustments for time. The resulting equation is as follows:

$$(\text{Rear-end Accidents/hr}) = 2.347 * 10^{-6} * (\text{stops/hr})$$

It was concluded that rear-end accidents are mainly affected by number of stops at signalized intersections rather than volumes entering the intersection and, hence, stops could be used as an exposure measure for rear-end accidents at similar intersections.

The next stage of the research was to calibrate the optimization model TRANSYT 7F so that it simulates the stops observed on the field. Ratrout (25) calibrated the model for the study area in 1988. He collected the driver performance characteristics and calibrated the platoon dispersion factor for the study area. Starting with his results, the volumes, stops and geometric data were collected and the simulation model was used to get the percentage of stops. Comparing the percentages of stops simulated by the model with the observed percentages of stops showed that the model overestimates the percentages of stops. The default stop reduction curve suggested by the TRANSYT manual was revised until the observed percentages of stops matched the simulated percentages of stops. Statistical tests showed that there remained no significant differences between the two sets of percentages.

The next stage was to incorporate safety into the optimization model by revising the operation costs due to stops and delay so that it included accident cost. This was done by revising stop and delay costs suggested by the TRANSYT manual so that it reflected costs in Saudi Arabia. The accident costs were revised using reported costs collected by the Al-Khobar police department for PDO and injury costs. Fatal accident costs were obtained by modifying the estimates of USA fatal accidents costs for the conditions in Saudi Arabia. The average cost of accidents was estimated to be SR 20,085 using Human Capital Cost Estimate and SR 34,559 using Adjusted Willingness to Pay Human Capital Cost Estimate. These cost estimates include costs due to excess delay and stops caused by accidents in urban intersections. This cost was estimated using the simulation model TRANSYT 7F.

The ratio between stops costs and delay cost is the K value in the performance index (PI). PI is the value optimized by the model when finding the optimum signal timing plans. K can take a value between zero to 1000 and a value between 20 and 50 is suggested by TRANSYT manual. The sensitivity of stops and delays was first investigated for values of K between zero - 250 and the result showed that delay increases as K increases and stops decreases as K increases and it was shown that K value of 55-60 was appearing to give minimum combination of stops and delay (Figures 6.1, 6.2 and 6.3). Another sensitivity analysis of stops, delay and fuel consumption to cycle length was performed. The results showed that cycle length is a very important factor and can change delay, stops and fuel consumption significantly (Figures 6.4, 6.5 and 6.6). It was concluded that a cycle length shorter than optimum may increase these MOE's significantly and, hence, shorter than optimum cycle lengths should be avoided.

Given the cost of one stop and the cost of one second of delay, the following K values were calculated:

K (without accident cost) = 47

K (Human Capital cost) = 68

K (Adjusted WTP/HK) = 82

The above-mentioned K values are for the cruising speed of 60 kph, however, K values for a range of speeds between 40 and 85 kph were given in the main text (see Table 6.10). The Human Capital Technique is a method of estimating cost of death in which lost income and benefits due to a lost life are estimated, while the Willingness to Pay Human Capital Technique is a method that includes an estimate of lives on top of lost income and benefits. The latter is suggested for use because it reflects the willingness of the community to reduce fatalities.

Sensitivity of K values to varying percentages of fatal and serious accidents was conducted to assess the impact of the accuracy of these percentages on K values and to facilitate revisions of K values if the percentages of fatal and serious accidents are proved to be different than the percentages mentioned in this research. It was concluded that the accuracy of severity percentages is important and could affect K values significantly. Cruising speed estimation was found to be very important and could affect K values significantly.

The effect of signal coordination on safety and operation cost was investigated and it was shown that rear-end accidents could be reduced by 29 percent and the cost could be reduced by 29.5 percent by the introduction of signal coordination into a signal timing plan that lacks the right offsets or the right phase splits.

The effect of four different signal phasing schemes, NSEW, STNEW, SLNEW and TLEW on operation costs, including accident costs, was investigated for different intersection spacings and different levels of volumes. It was shown that the NSEW scheme seems to give the minimum cost for intersection spacings of less than 500 meters for all ranges of volumes (165 - 400 vphpl). While the second scheme (STNEW) and the fourth scheme (TLEW) seem to give minimum costs for intersection spacing > 750 meters and volumes < 250 vphpl. The fourth scheme seems to give minimum cost for volumes > 330 vphpl and intersection spacing > 750 meters. The third scheme SLNEW seems to yield the worst results for the traffic conditions of the study area. The existing signal phasing scheme is NSEW and it happened to be the best scheme for the existing intersection spacings and traffic volumes. This analysis indicated that four phases scheme are generally better than five phases scheme for arterials similar to King Abdulaziz Street.

The investigation of the effect of safety inclusion on signal timing plan revealed that, in general, less time is given to the cross street and a longer cycle length is selected by the TRANSYT model when safety is included in the performance index. Including safety by using higher K values would cause the green phase to be longer for approaches with higher volumes; to allow vehicles to avoid stopping at the expense of more delay for the already stopped vehicle on minor streets. Therefore, a longer green phase is given to major streets and a longer cycle length is selected. This effect varies in magnitude from one signal phasing scheme to another, especially when major street approaches are given the green simultaneously (e.g. TLEW scheme).

The practical uses of this research's findings can be summarized in the following points:

1. Rear-end accidents at signalized intersections can be estimated by simulating the number of stops for any given signal timing plan and then using equation 4.5 to calculate the expected annual rear-end accidents.

2. The costs of PDO, injury and fatal accidents presented in Table 6.9 can be used in similar research in the study area; and for economical analysis and feasibility studies of traffic management schemes.

3. K values for different speeds presented in Table 6.10 can be used to optimize signal timing plans for different arterials and networks. The TRANSYT model enables the user to use different K values for different links on the same arterial or network.

4. Signal phasing schemes presented in Section 6.10 could have a major impact on operation costs. The guidelines presented in Section 6.10 could be helpful for traffic engineers when choosing signal phasing schemes.

5. Monitoring of traffic conditions is important after the implementation of any signal timing plan with special emphasis on cycle length evaluation. If the traffic volumes change so that it needs a longer cycle length, then, the implemented plan will be shorter than the optimum cycle length, a case that should be avoided because it will result in sharp increase in delay, stops and fuel consumption. Longer than optimum cycle length could be recommended to allow for normal variation in volumes and to reduce the frequency of revising the signal timing plans.

Areas for Further Research:

The following areas need further research:

1. The direct relationship between stops and accidents could be established through a good and fully documented accident recording and filing system; and maintaining a record of signal timing plans through selected arterials.

2. Accident costs could be further investigated through a good accident recording and filing system and more accurate documentation of injury classification. The cost of fatality can be further studied when the necessary information is released.

3. TRANSYT cost function can be used to optimize safety if the coefficients can be easily changed because the current format makes it impossible to change some coefficients freely.

4. The cost of air pollution due to stops and delays can be included in the cost function of K value if there are estimates of these costs.

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APPENDICES

APPENDIX - A

TRANSYT COST FUNCTION

Fuel Consumption Model:

$$F = K_1TT = K_2D + K_3S$$

where

$$K_1 = A_{11} + A_{12} + V + A_{13} V^2$$

$$K_2 = A_{21} + A_{22} + V + A_{23} V^2$$

$$K_3 = A_{31} + A_{32} + V + A_{33} V^2$$

and

F = **Fuel Consumption, gal.**

TT = **Total travel, veh-min.**

D = **Total delay, veh-hr, and**

S = **Total stop, veh-hr**

A_{11} = **0.075283**

A_{12} = **0.0015892**

$A_{13} = 1.5066 * 10^{-5}$

A_{21} = **0.73239**

$A_{22} = A_{23} = A_{31} = A_{32} = 0$

$A_{33} = 6.1411 * 10^{-6}$

Operating Cost Model:

$$C(\text{Cost}) = [(K_1 T + K_2 S + DC * D)/100 + FC * F + OTC(T/V + D)]\ I$$

$$K_1 = A_{11} + A_{12} V + A_{13} V^2 + A_{14} V^3$$

$$K_2 = A_{21} + A_{22} V + A_{23} V^2 + A_{24} V^3$$

A_{11} = 45.395

A_{12} = 0.1017

A_{13} = 0.0044

A_{14} = 0.0006

A_{21} = -0.2145

A_{22} = 0.1084

A_{23} = 0.0117

A_{24} = 0.0001

D = 0.05264

FC = 1.25

TC = 0.50

I = 1.20

where

C = Cost (Dollars)

I = Inflation Rate

DC = Unit cost of vehicle delay, ($1,000/veh-hr)

D = Total delay, (veh-hr)

S = Stops (1,000 veh-hr)

FC = Unit cost of fuel ($/gal.)

O = Average occupancy (person/veh)

TC = Cost of passenger time

V = Vehicle cruising speed

Source: TRANSYT MANUAL (29)

APPENDIX - B

REVISION OF TRANSYT COST FUNCTION

In reference to Section 6.4, the detailed calculations of different cost items are presented in the following sections.

B.1 Fuel, Delay and Stops Costs

The fuel cost in Saudi Arabia is 0.32 Riyals per liter. To calculate the cost of excess fuel as a function of stops and delay, TRANSYT formulas can be used to convert the fuel consumption into fuel cost as a function of stops and delay. The TRANSYT formula relating delays to excess fuel consumption is as follows

$$\text{Excess fuel consumption due to delay} = 0.73239 * D$$

where D is excess delay in hours and excess fuel consumption is expressed in gallons. Using this, the excess fuel cost can be calculated as follows:

$$\begin{aligned} \text{Excess fuel cost} &= 0.73239 * 3.7854 * 0.32 \\ &= 0.88716 \text{ SR per hour of delay} \end{aligned}$$

The TRANSYT formula relating excess fuel consumption to stops is as follows:

$$\text{Excess fuel consumption due to stops} = 6.1411 * 10^{6} * V^2$$

where V is speed in mph and fuel consumption is expressed in gallons per one stop. Assuming a speed of 60 kph (37.29 mph), which is similar to the speed studied.

$$\text{Excess fuel cost} = 6.1411 * 10^{-6} * 37.29^2 * 3.7854 * 0.32$$
$$= 0.01035 \text{ SR per stop.}$$

The next step is to estimate the cost of passenger and vehicle delays. In order to estimate the cost of passenger and vehicle delay, the following assumptions are made:

a. Fifty percent of the population are in the work force, while most of drivers and passengers are in the work force.

b. The income per capita is 7060 US dollars for Saudi Arabia in 1990 (37).

c. The vehicle delay cost in Saudi Arabia is the same as the cost suggested by the TRANSYT Manual inflated to 1990 Riyals.

d. The inflation factor is the ratio between the consumer index in 1990 and 1987 (103.1 and 99.1 respectively).

e. The vehicle occupancy is 1.2 passengers/vehicle (29).

With these assumptions, the cost of one hour of passenger delay can be calculated as follows:

$$= \frac{7060 * 3.75 \ 1.2}{(365 * 24 * 0.5)} = 7.205 \text{ SR/hou}$$

Cost of vehicle delay will be calculated using the vehicle delay cost suggested by the TRANSYT manual in 1987 which was 0.526 USD per hour, inflated to 1990 SR as follows:

$$= 0.0526 * 3.75 * \frac{103.1}{99.1} = 0.205$$

Cost of vehicle and passenger delay:

$$= 7.205 + 0.205 = 7.41 \text{ SR/hr}$$

The cost of stops, excluding accident cost, is calculated using TRANSYT formula and inflating it to 1990 Riyals.

$$\text{Cost of Stops} = (-0.2145 + 0.1084*V + 0.0117*V^2 + 0.0001*V^3) * \frac{103.1}{99.1}$$

Assuming V = 60 km/hr (37.29 mph)

Cost of Stops = 0.0986 Riyals per one stop.

B.2 Accident Costs

Accident costs are not included in the TRANSYT 7F cost function. One of the main objectives of this research is to include accident cost into the optimization process of the TRANSYT model.

Accident costs can be divided into two categories: Cost incurred by the drivers involved in the accident including the cost of related agencies and future income losses. The other category is the cost incurred by other road users due to excess delay, stops and fuel consumption caused by the blockage of the intersection until the vehicles are removed. This category will be referred to as accident congestion cost.

Accidents are classified into three types based on the severity of each accident. These three types are: property damage only (PDO), injury (INJ) accidents, and fatal accidents. In order to estimate the average accident cost, the percentage of each type of accidents should be estimated. Given the percentages and the cost estimates of each type, the average accident cost (AAC) could be calculated easily by the following formula:

$$AAC = \frac{a(\text{PDO cost}) + b(\text{INJ Cost}) + (\text{Fatal Cost})}{100}$$

where a, b and c are the percentages of each type of accident and PDO Cost, INJ Cost and fatal cost are the average cost of each accident type. In the following section the percentage and the average cost of each accident type will be investigated.

The data that were used to classify accident by severity are the same data used to establish the relationship between accident and conflict in Chapter (4). These data were collected by Al-Khobar Police Department in 1405 and 1406 Hijri. They were used because they were complete and coded in the University mainframe computer and are relevant to and consistent with the previous part of this research. The same type of intersections and traffic conditions are used throughout the research. The analysis of data showed that 177 rear-end accidents took place on major intersection approaches. Ninety one point five percent of these rear end accidents were PDO, 5.1 percent were injury accidents and 3.4 percent were fatal as shown in Table B.1. A study conducted by TRRL in 1986 showed that rear-end accidents

Table B.1: Accident Severity in the Study Area

Security	No.	Percentage
Fatal	6	3.4
Serious	9	5.1
POD	162	91.5

at cross urban signalized intersections have different distribution (38). The study considered only injury accidents and the fatal accidents were 0% of injury accidents for rear-end accidents. For all types of accidents, fatal accidents were 0.6 percent while the fatal and serious accidents were 20 percent of all types of accidents. Table B.2 shows the severity by accident types of that study.

The TRRL rates and severity of rear-end accidents are slightly different that the data of this research. The percentage of fatal accidents for the local conditions is more than the TRRL study percentage. This could be due to the difference in driving habits between Saudi Arabia and England; where the TRRL study was conducted (e.g. the safety belt is mandatory in England and optional in Saudi Arabia). Roadway and motor vehicle conditions could be another cause of the high level of fatalities on Saudi Arabian roads. The reporting method of accidents may be different (e.g. which accident is considered a serious accident. Insurance in England probably covers a higher percentage of vehicles and drivers than in Saudi Arabia. This might be another cause of higher percentages of reported serious accidents in England than in Saudi Arabia.

Another probable cause of more fatal accidents in Saudi Arabia may be reporting mistakes; where serious injuries might be reported as fatal by the policeman. However, the data will be assumed correct and a sensitivity analysis done later to investigate

Table B.2: Accidents by Severity and Accident Type*

Accident Type	Number of Accidents				Accident Severity % Fatal & Serious	Average Casualties Per Accident
	Fatal	Serious	Slight	Total		
Single Vehicle	1	25	129	155	16.8 (3.3)	1.10
Approaching	0	12	142	154	7.8 (2.9)	1.12
Right Angle	3	66	165	234	29.5 (3.6)	1.61
Principle Right Turn	0	87	383	470	18.5 (2.0)	1.40
Other Right Turn	0	21	94	115	18.3 (4.0)	1.41
Left Turn	1	4	52	57	8.8 (3.9)	1.12
Pedestrian	6	118	386	510	24.3 (2.2)	1.06
Other	0	11	.66	77	14.2 (4.3)	1.20
All Types	11	344	1417	1772	20.0 (1.1)	1.26

* Figures in brackets are standard errors of the mean values.

Source: TRRL (38)

the lower percentage of fatal accidents and its effect on overall average accident cost.

The cost of PDO accident was calculated in two steps. The first step was to calculate the average cost of PDO accidents collected by the Al-Khobar Police Department in 1405-1406 H at major intersections. The second step was to multiply the average cost by the inflation ratio obtained from the annual report of the Saudi Arabian Monetary Agency issued in 1990 (39). The base year for the total accident cost will be the year 1990.

The average cost of PDO accidents was obtained from the computer files of accidents, held in KFUPM and was SR 1360 per accident. The Cost of Living Index for a middle income household in the category of transport and communication was 74.6 for the year 1985 and 121.1 for the year 1990. The year 1985-G is matching about 1/2 of 1405 and 1/2 of 1406 H. So, the index for 1985 can be considered an average of 1405 and 1406 H. The year 1988 is considered the base year with an index equal to 100. In order to convert the cost of PDO accidents into 1990 Riyals the following calculations were performed:

$$\text{PDO accident cost in 1990} = 1360 * \frac{121.1}{74.6} = 2208 \text{SR/accident}$$

The direct cost of PDO accidents in the United States in 1980 was $350 (SR 1312) per vehicle. Assuming 2.2 vehicles per rear-end accident makes the cost equal to (SR 2888) per accident.

This figure is comparable to the cost of POD accidents in Saudi Arabia bearing in mind that the base year is different and the cost of living in the United States is more than in Saudi Arabia.

The same method used to calculate the PDO accident cost will be used to calculate the cost of serious accidents. The average serious accidents for the years 1405-1406 Hijri is (SR 16416). The medical care index has changed from 98.3 to 100.7 for the years 1985 and 1990 respectively. So, the cost of a serious accident is calculated as follows:

$$\text{Cost of Injury Accidents} = 16416*\frac{100.7}{98.3} = 16817 \text{SR/accident}$$

The cost of a fatal accident is the most controversial among the three types of accidents because loss of life affects the family and society in many different ways. The costs of fatal accidents are classified in two broad categories: Direct Costs and Indirect Cost (40). The direct costs include the following:

- cost of damage to property
- emergency medical and transportation services cost
- medical cost
- legal, court and funeral cost

The indirect costs are less well defined in the literature than direct costs, but they constitute a larger portion of total accident costs than direct costs. Indirect costs include the following:

- social mechanism costs
- human capital (HK) costs
- the cost or value of psychological deteriorations
- the value of life and safety as estimated by willingness-to-pay and related approaches

The social mechanism costs are costs of managing the activities subsequent to an accident or preventing accidents from occurring (e.g. police, fire department, highway department and insurance administration costs).

Human capital cost is the present value of goods and services not produced as a result of fatal accidents. Some analysts treat human capital costs as an estimate of the value of life and safety. Some others treat human capital costs exclusively as an economic cost (40). Willingness to pay estimates are comprehensive assessments of the value of life and safety including the value of all activities that provide benefits of living and a premium for psychosocial deterioration. The empirical studies offer widely divergent value of life estimates and most of them are based on either questionable data assumptions or estimating procedures (40). Currently, there is a political resistance to valuing life, therefore, the willingness to pay approach cannot provide satisfactory estimates of the value of life, even though, it is theoretically superior to human capital costs estimates.

The Federal Highway Administration (40) suggested that a compromise procedure between human capital cost and willingness to pay procedure, developed by Landefeld and Seskin (41), can be used because it has been identified to be theoretically sound and easily implemented. The procedure is called the adjusted willingness to pay/human-capital approach (Adjusted WTP/HK approach).

There are such estimates for Saudi Arabia; neither for human capital costs, nor for willingness to pay approach. The data needed to compute these estimates are not available yet for Saudi Arabia. So, the United States estimates will be used after applying a factor that makes them suitable for Saudi Arabia. The factor will be the ratio between the GNP per capita for Saudi Arabia for the year 1990 and the GNP per capita for the United States for the same year. This factor will be applied to some components of the total cost which is believed to have the same proportion while keeping other components unchanged.

NHTSA (42) estimates of direct cost of fatality included: property damage, emergency medical services, hospitalization cost and legal and court estimates are given in Table B.3. The largest component of the direct cost is the legal and court costs. In Saudi Arabia, the legal system is not as expensive as in the United States and most of the fatality cases due to traffic accidents are settled without long and expensive legal procedure. The researcher cannot obtain any data about legal and court cost estimates for traffic accidents, but thinks that the court and legal cost are a small fraction of the NHTSA estimates. Twenty percent

Table B.3: Recommended Direct Cost Estimates of NHTSA (Ref.42) in 1980 Dollars

	Per Vehicle	Per Victim					
		Maximum Abbreviated Injury Scale (MAIS) Category					
Category	PDO[a]	1	2	3	4	5	Fatality
Property Damage	$705	$ 811	$1354	$ 2120	$ 2865	$ 28454	$ 3406
Emergency Medical Services[b]	--	92	128	126	126	126	124
Emergency Room Care	--	42	110	153	253	363	
Initial Hospital	--	70	888	2054	5148	20162	1370
Physician and Surgeon Services	--	19	319	771	2059	2981[c]	
Follow-on Care, First Year	--	35	60	96	139	2782	
Home Modification	--	--	--	--	--	3739	
Second-Year Unique Services[d]	--	--	--	--	455	1584	
Follow-on Care, Annual	--	35	60	81	2277	96238	
Legal and Court	11	532	583	2688	5147	7864	13394
Total	$716	$1601	$3442	$ 8089	$18467	$138684	$18294

a Reported accidents only.

b Based on NHTSA's urban-rural distribution assumptions.

c Physician and surgeon services included in initial hospitalization cost estimate for spinal cord injuries

d Based on a 4-percent discount rate.

of the legal and court NHTSA estimates were used for Saudi Arabia. In light of these assumptions, the direct cost estimation of fatal accidents for Saudi Arabia will be as follows:

Direct Cost = Property Damage + Emergency
+ Hospitalization + 0.2 (legal court)
= 3406 + 124 + 1370 + 0.2 (13,394)
= 7579 US Dollars

= (7579$) * (3.75SR/$) * (103.1/104.8) = 27,960 in 1990 SR.

The cost for property damage, emergency medical services and hospitalization were assumed to be the same for Saudi Arabia and the United States, so it wasn't factored. The general index of cost of living was 104.8 and 103.1 in 1980 and 1990 respectively for Saudi Arabia (39). This ratio appearing in the calculation above is used to convert the 1980 Saudi Riyals into 1990 Saudi Riyals.

The indirect costs include police costs, fire department costs, coroner medical examiner costs, insurance administration costs, welfare and public assistance costs and human capital costs. Table B.4 shows the NHTSA estimates of these costs for the United States (40). Human capital costs constitute about 96.3 percent of the total indirect cost while insurance administration costs constitute about 3.3 percent. Insurance is not mandatory for all vehicles and a large portion of the vehicle drivers in Saudi Arabia are not covered by insurance. A study in Saudi Arabia by Al-Saif

Table B.4: Recommended Indirect Capital Cost Estimates of NHTSA (Ref.42) in 1980 Dollars

	Per Vehicle	Per Victim					
		Maximum Abbreviated Injury SCale (MAIS Category					
Category	PDO	1	2	3	4	5	Fatality
Police Costs	$ 8[a]	$ 38	$ 54	$ 77	$ 107	$ 129	$ 129
Fire Department Costs	--	--	--	--	$ 44	$ 44	$ 44
Coroner/Medical Examiner Cost	--	--	--	--	--	--	$ 168
Insurance Adm. Costs	$120[a]	$ 550	$ 550	$ 550	$12540	$ 12540	$ 12540
Welfare & Public Assistance Costs	$ 4[a,b]	$ 4[b]	$ 4[b]	$ 16[b]	$ 398[b]	$ 398[b]	$ 576[b]
State Motor Veh Agency Costs	c	c	c	c	c	c	c
State and Local Hwy Dept. Costs	c	c	c	c	c	c	c
Human Capital Costs	$ --	$ 98[d]	$ 557[d]	$1574[d]	$19475[d]	$109786[d]	$358884[d]
Psychosocial Costs	c	c	c	c	c	c	c
Total	$134	$ 690	$1165	$2217	$32564	$122897	$370341

[a] Reported accidents only.

[b] Tentative estimates.

[c] No estimates available

[d] Based on a 4-percent discount rate.

et al. (43) showed that only 24.27 percent of drivers had insurance among a sample of drivers involved in accidents in the Eastern Province of Saudi Arabia. The researcher will use factor 24.27 percent to reduce these costs for the study area. Since there are no available data about insurance administration cost for Saudi Arabia, and since it constitutes a smaller portion of the total indirect cost, the precision of cost estimate of this item will not affect the total indirect cost estimates significantly. The US cost estimates will be used to approximate the insurance administration costs for Saudi Arabia.

Insurance Administration Cost (Saudi Arabia)

$$= 12540 * 3.75 * \frac{24.27}{100} * \frac{103.1}{104.8}$$

$$= 11270 \text{ SR in 1990 Riyals.}$$

The largest portion of indirect cost is human capital cost, which is the lost wages and benefits due to death discounted to present value. Due to the lack of information about the average wages and benefits for each age category of Saudi citizen in recent years, the United States human capital cost estimates will be used after factoring it by the ratio of GNP per capita of Saudi Arabia ($7560) to GNP per capita of USA ($21082) for the year 1990.

Human Capital Cost (Saudi Arabia)

$$= (356{,}884\$) * (3.75 \text{ SR}/\$) * \left(\frac{7060\$}{21082\$}\right) * \frac{103.1}{104.8}$$

= 440,909 SR in 1990 Riyals.

The police, fire department, medical examiner and welfare and public assistance costs were $917 for the United States in 1980. For Saudi Arabia the costs are estimated to be:

$$917 * 3.75 * \frac{103.1}{104.8} = 3,383 \text{ SR in 1990 Riyals}$$

Total Indirect Costs = 440,909 + 3,382 + 1,127

= 455518 Riyals

Total Cost = Indirect Cost + Direct Cost

= 455,518 + 27,960

= 483,478 Riyals per fatality

The indirect cost could be calculated using adjusted willingness to pay/human capital costs. The same method of approximation of Saudi Arabian costs that was used to approximate the human capital costs will be used here. The United States adjusted willingness-to-pay/human capital costs was 710,770 dollars as presented in Table B.5.

Adjusted WTP/HK costs for Saudi Arabia

$$= 710,770 * 3.75 * \frac{7060}{21,082} * \frac{103.1}{104.8}$$

= 878,113 Riyals

Total cost based on adjusted WTP/HK

= 878,113 + 27,960 = 906,073 Riyals

Table B.5: Recommended Total Cost Estimates of NHTSA (42) in 1980 Dollars

	Per Vehicle	Per Victim					
		Maximum Abbreviated Injury Scale (MAIS) Category					
Category	PDO	1	2	3	4	5	Fatality
Total Direct Costs	$716	$1601	$3442	$ 8089	$18467	$138684	$ 18294
Total Indirect Capital Costs [a]	$132	$ 690[b]	$1165	$ 2217[b]	$32564[b]	$122897[b]	$370341[b]
Adjusted WTP/HK Value	--	--	--	--	--	--	$710770[c]
Total Capital Costs[a]	$848	$2291	$4607	$10306	$51031	$261581	$388635
Total Costs Based on Adjusted WTP/HK[a]	$848	$2291	$4607	$10306	$51031	$261581	$742621

a Does not include estimates of State motor vehicle agency costs, State and local highway department costs, and psychosocial costs.

b Based on a 4-percent discount rate and a 1.5 percent productivity growth rate.

c Based on a 4-percent discount rate and a 1.0 percent productivity growth

The two different figures for the total cost of accident fatalities will be used separately in the following sections and the different effects of using each one will be noted.

Another component of accident cost which is the excess delay, stops and fuel consumption caused when an accident takes place at the intersection and the capacity of the approach is reduced until the vehicles are removed from the lane at which the accident took place. This was not considered in previous research but was estimated for this work.

For this, the simulation model (TRANSYT-7F) was used to simulate the increase in delay, stops and fuel consumption due to accidents. The following assumptions were made for this:

1. One lane will be closed due to the accident.

2. The average time to remove the vehicles involved in accidents will be one hour.

3. The effect of accidents will be measured at all major approaches.

4. The average excess cost will be the average of the excess costs of all rear-end accidents on the major approaches. The expected number of accidents on each approach is assumed to be proportional to the number of stops on each approach.

Table B.6 shows the stops on each approach for the no

Table B.6: Percentage of Stops on Each Approach

Approach	Stops	Percentage
101 + 102	459	6.887
103 + 104	907	13.578
201 + 202	725	10.878
203 + 204	392	5.881
301 + 302	704	10.563
303 + 304	1153	17.300
401 + 402	1420	21.305
403 + 404	869	13.039

accident case. The percentages of stops are used as a weighing factor to reflect the percentages of accidents on each approach. The probability of a rear-end accident taking place on the arterial approach (i) will be the same as the percentage of the stops on that approach compared to the total stops on the arterial. These percentages will be multiplied by the excess fuel, stops and fuel consumption for the corresponding approaches, and then, averaged to get the average excess cost of an accident.

Table B.7 shows the excess delay, stops and fuel consumption simulated by the TRANSYT model on different approaches of the King Abdulaziz arterial due to one accident on each approach. The table also shows the expected excess delay, stops and fuel consumption due to one rear-end accident taking place in the arterial.

The simulations of accidents show that there is always an increase in delay and fuel consumption. The stops show different behavior, where in four cases there was an increase and in the other four there was a decrease in stops; with the overall average of a decrease of 92 stops. This result may contradict the expectation but it is not incorrect because the reduction of the volume of one approach might reduce the excess queues at the downstream intersection and vehicles avoid stopping at each intersection. So, even though the stops at a blocked approach might increase, they may be reduced by a larger amount at other intersections, with the net result being a decrease in the overall

Table B.7: Expected Excess Delay, Stops and Fuel Due to One Accident on the Arterial

Approach	Probability of Accident (%)	Excess Delay (hr)	Excess Stops	Excess Fuel (L)
101	6.887	24	418	80
103	13.578	28	142	81
201	10.878	129	125	361
203	5.881	135	-174	368
301	10.563	121	-139	330
303	17.300	153	-562	406
401	21.305	113	-219	316
403	13.039	122	-118	341
Total* Excess MOE's		106.58	- 92	294.3

* Σ(Probability * Excess MOE).

number of stops.

The excess fuel consumption due to one accident is equal to 77.75 gal. and the excess delay caused by one accident is equal to 106.58 hours of delay. The cost of fuel is 1.211 SR per gal. in Saudi Arabia and the cost of 77.75 gal. is 97.18 SR. The cost of one hour's delay is $(0.05264) (TRANSYT Manual) in 1987 dollars. The cost of 106.58 hours of delay is (0.05264 * 106.58) = 5.6 dollars. To get the cost in 1990 dollars we shall multiply by the ratio 103.1/99.1 which is the ratio between the 1990 and 1987 general price index (39). The cost of passenger delay is equal to SR 6.0 per hour per passenger. Assuming 1.2 passengers per car makes it SR 7.2 per hour, which is 767 SR for 106.58 hours of delay. The total excess delay cost per accident is equal to (767 + $5.6 * 3.75 * \frac{103.1}{99.1)}$ = 789 SR.

Excess cost due to one accident

= 97.18 + 789 - 10.96

= SR 875 per accident.

Now all the components of rear-end accident costs are known for each accident category (PDO, Injury and fatal); as well as the excess cost of accidents due to excessive delay, stops and fuel consumption. The next step is to calculate the average cost of an accident for all categories by multiplying each category cost by the percentage of that category of total accidents.

The excess costs due to excess delay, stops and fuel consumption will be added to the average since it is the average of all categories. Two tables are presented below. Table B.8 is for the human capital costs estimates and Table B.9 is for the adjusted WTP/HK costs estimates.

Cost of accident, (using Human Capital Cost)

$$= (20085\ \text{SR/accident}) * (2.347\ 10^{-6}\ \text{accident/stop})$$

$$= 0.0467\ \text{SR per stop.}$$

Cost of accident, (using Adjusted WTP/HK)

$$= (34559\ \text{SR/accident}) * (2.347\ 10^{-6}\ \text{accident/stop})$$

$$= 0.0809\ \text{SR per stop.}$$

Table B.8: Human Capital Costs Estimtes

Accident Severity	Av. Cost	Percentage	Av. Cost %
Fatal	480345	3.4	16332
Injury	16817	5.1	858
PDO	2208	91.5	2020
Excess Delay, Stops	875	100.0	875
Total Average Cost			20085

Table B.9: Human Capital Costs Estimtes

Accident Severity	Av. Cost	Percentage	Av. Cost %
Fatal	906073	3.4	30806
Injury	16817	5.1	858
PDO	2208	91.5	2020
Excess Delay, Stops	875	100.0	875
Total Average Cost			34559