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ASSESSMENT OF THE APPLICABILITY OF "TRANSYT-7F"
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OF AL-KHOBAR AND DAMMAM, SAUDI ARABIA.

By

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ABSTRACT

ASSESSMENT OF THE APPLICABILITY OF "TRANSYT-7F" OPTIMIZATION MODEL TO THE TRAFFIC CONDITIONS IN THE CITIES OF AL-KHOBAR AND DAMMAM, SAUDI ARABIA.

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Several studies showed that traffic optimization produces significant benefits in terms of reduced delay, vehicle stops, and fuel consumption. With the increasing complexity of urban networks, computer-based traffic algorithms are necessary to obtain an optimal timing plan.

The main objective of this study was to select a candidate algorithm for optimizing the traffic in Saudi Arabia and to calibrate the algorithm (model) to fit traffic conditions in the cities of Dammam and Al-Khobar, Saudi Arabia.

An exhaustive research of the literature was conducted to identify all network optimization models. The features of these models were compared, and it was concluded that the TRANSYT-7F model is the best candidate for application in Saudi Arabia.

To use the model accurately, the saturation flow rates, start-up lost time, extension of effective green, and average vehicle spacing were evaluated in the study area. Their

values were found to be similar to those used in the United States.

Calibration of the TRANSYT-7F model consists of determining that value of the platoon dispersion factor (PDF) which reduces the discrepancies between the simulated and observed flow profiles. The average best-fit PDF values were 28 and 40, respectively. The TRANSYT-7F manual suggests a value of 25 for low friction links and 35 for moderate friction links. Both sets of values were used to conduct a sensitivity analysis involving 4 parameters and 25 hypothetical networks.

The optimal timing plan using the calibrated PDF values did not product significantly better results than optimization runs using the values recommended in the manual. This led to the conclusion that there is little value in developing a calibrated set of PDF values for use in the cities of Dammam and Al-Khobar.

Dedicated to my father and my mother whose blessing, love, support, and continuous encouragement have been greatly instrumental in the accomplishment of this feat.

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CHAPTER 1

INTRODUCTION TO THE STUDY

1.1 Introduction.

In contrast to many developing countries, Saudi Arabia is a rich country. It has been changing very rapidly from being a pre-industrial society to a modern industrialized country. This rapid growth exerted pressure on public utilities in general, and on transportation facilities in particular.

To cope with this rapid growth, the government has built a huge (i.e. more than 35,000 KM) and modern network of roads and highways throughout the country. In fact, at the present time, Saudi Arabia possesses one of the best transportation facilities in the Middle East. Following construction of this road network, the attention is now focused on operating and maintaining this network in the most efficient way. A large portion of this modern network is concentrated in the large cities, such as Riyadh, Jeddah, Dammam, and Al-Khobar.

Dammam city lies in the center of the Eastern province of Saudi Arabia by the Arabian Gulf. It is the third largest city in the country, and the largest in the Eastern province. The city of Al-Khobar is less than twenty kilometers from Dammam, and is considered to be the second most important city in the Eastern province. Generally speaking, both cities are considered to constitute a single metropolitan area. Both Dammam and Al-Khobar are close to the city of Dhahran, where the third largest international airport in the country and the headquarters of the Arabian American oil Company (ARAMCO) are located. They are also very close to King Fahed University of Petroleum and Minerals (KFUPM), one of the finest universities in Saudi Arabia. The state of Bahrain, which has one of the important financial and stock markets in the Middle East, is less than fifty kilometers from either city. This unique location of Dammam and Al-Khobar made them the major commercial and economic activity center of the Eastern province.

There are approximately ten major arterial streets and fifty signalized intersections in each city. All signals are fixed timed. Neither of the two cities possesses a comprehensive plan for collecting traffic and operational data. Such data, if it exists, is usually collected as a part of a specific study or project and not as a part of a comprehensive plan.

1.2 The problem.

One of the most important transportation problems that is typically faced by traffic engineers is the optimization of traffic flow in an urbanized area. The process of optimizing traffic flow in an urban network is achieved by interconnecting and operating the signalized intersections to minimize the delay and stops in the system. This minimization of delay and stops in a network will provide a convenient driving environment, improve the network capacity, and reduce excess fuel consumption. As an example, in a comprehensive optimization study conducted in the United States (8), it was concluded that for the average intersection in the study, "each year vehicle delay was reduced by 15,470 vehicle-hours, 455,921 vehicle stops were eliminated, and 10,524 gallons of fuel were saved".

With the increasing complexity and magnitude of urban signal networks, traffic optimization is almost an impossible task to perform manually. Recently, several optimization and simulation computer models have been introduced:

1. TRANSYT .... network optimization
2. SSTOP .... network optimization
3. SIGOP III .... network optimization
4. SIGRID .... network optimization
5. COMBINATION .... network optimization
6. PRIFRE .... freeway optimization

7. PASSER II .... arterial optimization

8. SOAP .... intersection optimization

9. PASSER III ...... diamond interchange optimization

10. SUB .... arterial bus simulation

11. NETSIM ....network simulation.

Computer-based models for network optimization all contain an algorithm for computing signal offsets and splits that minimize some combination of delay and stops in a network. These models have made the procedure for optimizing the signal timing plans in a given urban area relatively easy, regardless of the complexity and the magnitude of the traffic conditions in the given area. Moreover, the introduction of such optimization models in a microcomputer version made these models available and practical to be used in any country or city in the world with very little investment and without the need of highly experienced personnel.

In each of these models, there are a number of constants that represent the driving habits and traffic conditions in the country where the model was originally introduced and calibrated. Typically, these constants include a number of traffic characteristics, such as saturation flow, vehicle spacing, queue dispersion, headway distribution, and driver response to different signal phases.

It is well known that such traffic characteristics (i.e. constants) can vary considerably from one society to another. Because of such a possibility, any traffic signal timing optimization model (and any model that deals with traffic operation) has to be tested for its validity in the place where it is proposed to be used. Consequently, some, or all, of the model constants might have to be modified to match the traffic conditions and driving habits in the country in which it will be used.

In addition to these constants which might need some modification, optimization models require considerable data that describe the physical features of the network and the traffic characteristics. These include intersection and road geometry, traffic flow and volume, signal timing plans, speed, and traffic composition.

In western countries such as the United States, this type of data is easily and economically obtained using sophisticated equipment and techniques. Moreover, most of the time, such data is readily available, and often in a computerized format. In contrast, in Saudi Arabia, the data collection system is undeveloped, and frequently data of this nature does not exist, or it is not updated regularly.

Therefore, to assess the applicability of any network optimization model to the Saudi Arabian traffic conditions, one first has to collect the required input data for that particular model. The model must then be analyzed to determine which constants and internal relationships need to be modified (if any) in order to calibrate the model for the local driving habits and traffic environment of Saudi Arabia.

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This calibration effort will provide a better understanding of the traffic characteristics in Saudi Arabia. This, in turn, will provide some general clues about the applicability of traffic models introduced in western countries (such as the U.S.A.) to the traffic environment of Saudi Arabia. Furthermore, the study will result in a better understanding of the virtues and deficiencies of the selected model. Finally this study will contribute to improving and optimizing the traffic environment in Saudi Arabia.

All network optimization models were reviewed (chapter 2) to select the best candidate for optimizing traffic in Saudi Arabia. It was concluded that the TRANSYT-7F model is the most appropriate model in this regard. The main reason for selecting the TRANSYT-7F model is the fact that it is the only one which was extensively and successfully used in many countries under various traffic conditions and driving habits. In addition to this, the TRANSYT-7F model has the ability to handle many special traffic conditions, such as more than four phases in a cycle and sign controlled intersections. This ability makes the model applicable to almost every network configuration in Saudi Arabia.

1.3 Objectives.

This study is designed to achieve the following main objectives:

1. To identify the similarities and differences in traffic characteristics and driving habits on urban networks between the United States and Saudi Arabia.
2. To adapt TRANSYT-7F for use in optimizing the traffic in the study area.
3. To perform a parametric analysis on the TRANSYT-7F model to determine which constants and internal relationships (if any) need to be modified to calibrate the model for the study area traffic conditions.
4. To determine if the model calibrated to the local traffic conditions provides better results than its original calibration.
5. To assess the applicability of the TRANSYT-7F model to the Saudi Arabian traffic conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Advantages of traffic optimization.

Traffic optimization is, by definition, the act of developing an optimum signal timing plan (optimum signal offsets and splits), by which the signalized intersections in a given network are interconnected and operated to minimize delay and stops. This minimization of delay and stops in the network will provide a more convenient driving environment, improve the network capacity, and reduce excess fuel consumption (1, 2, 3, 4, 5, 6).

One of the most comprehensive and important examples of the potential benefit of traffic optimization is the National Signal Timing Optimization Project (8). In this project, eleven cities in the United States optimized a portion of their street network (ranging from 23 to 81 intersections per city) using the TRANSYT-7F program. It was concluded (based on TRANSYT estimates) that, for the average intersection in the project, "each year 15,470 vehicle-hours of delay were saved, 455,921 vehicle stops were eliminated, and 10,524 gallons of fuel were saved". It was also reported that driving through urban areas became faster and easier as a result of implementing the optimized signal timing plans. It was estimated that two million gallons of gasoline per day could be conserved if the signal timing at most of the 240,000 signalized intersections in the United States were optimized.

Similar conclusions were also reported in a case study of fuel efficient traffic signal operation in the city of Garden Grove, California (9). Using the TRANSYT program (version 8), improved traffic signal timing was developed for a test network (70 intersections) in Garden Grove. The following was concluded from the study:

> The field test indicated that significant improvement in traffic flow and fuel consumption result from the use of timing plans generated by the TRANSYT optimization model. Changing from pre-existing to an optimized timing plan yields a network wide 5 percent reduction in total travel time, more than 10 percent reduction in both the number of stops and stopped delay time, and 6 percent reduction in fuel consumption.

Rach (1) summarized the results of an optimization project carried out by the British Road Research Laboratory using the TRANSYT program. He reported that, as a result of that optimization project, the mean travel time was reduced by 16 percent and the effective capacity was increased by 25 percent.

An improvement in the air quality is another possible advantage of traffic optimization. Schlappi (10) found that there was a relationship between vehicle stops and carbon monoxide concentration. He reported that a ten percent reduction in the number of vehicles stopping would result in a five to seven percent reduction in the concentration of carbon monoxide.

2.2 Network optimization models.

Computers were first introduced as a possible tool for studying and analyzing traffic problems in the 1950s. However, it was not until the late 1960s that computers and computer programs were practical and widely used in analyzing, designing and evaluating traffic facilities (11).

Prior to this, the timing (optimization) of a network was done manually by either the volume priority method, or the preferential street method (2). The procedure in these two techniques consists of ranking all links in the network in order of decreasing link volume or in order of decreasing preference (i.e. importance). Link offsets are timed to insure good individual progression, starting with the link of the highest rank and continuing in order of decreasing rank, until reaching those links whose offsets are determined by other previous settings.

However, because such manual techniques are cumbersome and time consuming, it was more common to provide preferential treatment (i.e. good individual progression) for only a small number of arterial streets in the network. Clearly enough, such manual procedures do not provide the optimal timing plan for a network. Nevertheless, it was the only practical and logical procedure for timing a network of signalized intersections without the help of computers.

One of the earliest models for network optimization is the COMBINATION program developed in the U.K. and used by the Greater London Council (1,12). The COMBINATION program is based on the assumption that delay depends solely on the offset difference between the signals at each end of the link and not on any other signal in the network.

Basically, the program calculates the delay/difference-of-offset relationship for each network link, and then combines links in series or in parallel to obtain a set of optimum offsets such that the network delay is minimized. Consequently, the program does not include delay caused by random fluctuation in the traffic. Also, it does not calculate the optimum signal splits at the intersections in the network under consideration. The signal splits at each intersection have to be known (used as input) in order to use the model. The program represents the earliest effort in utilizing computers for network optimization. It was used a number of times in the 1960s, mainly in the U.K. (1). The literature does not show any current utilization or modification in the program.

Robertson (13) used the COMBINATION program for some time, which in turn stimulated him to write the TRANSYT

(TRAffic Network StudY Tool) program in 1967. He wrote in this regard (11):

> TRANSYT grew from my chance to use the COMBINATION method and study its virtues and vices, both of which center on the simplicity of the platoon structure. I wrote TRANSYT program in 1967 using assembler language, and it was first tested later that year on the Cromwell Road in London.

Since that time, Robertson and his colleagues (13) made several major improvements on the original program, and produced nine versions of the TRANSYT program (in addition to the original program), with the latest version being TRANSYT/9, released in 1987. Based on the seventh version of TRANSYT (TRANSYT/7), the Federal Highway Administration produced an Americanized version of TRANSYT, referred to as TRANSYT-7F. The TRANSYT program is a macroscopic, deterministic optimization model. It is comprised of two main sections; a traffic model and an optimization procedure. The traffic model is a macroscopic, deterministic simulation model. The term "macroscopic" refers to the fact that the model considers platoons of vehicles (hereafter called platoons) rather than individual vehicles. The simulation process is based, primarily, on simulating the dispersion of platoons as they progress along network links. This is done by using a platoon dispersion algorithm developed by Robertson (13). The algorithm describes (collectively) the desire of individual drivers to maintain comfortable time headway as they progress along network links. It was found that the algorithm (i.e. the comfortable headway) is a function of roadway characteristics, as will be discussed later. Based primarily on Webster's methodology (14), the traffic model calculates delay and stops for each network link. Following that, the weighted sum of the delay and number of stops suffered by all vehicles in the network is obtained and called the "performance index," or "PI" of the network.

The optimization procedure is an iterative, gradient search (hill-climbing) technique that optimizes signal phase lengths (i.e. splits) and offsets of a signalized network. The first step in the optimization process is to determine the performance index (PI) of the original signal timing plan. This is done by the traffic model, discussed previously. For offset optimization, the offset of the first signal in the network (as input by the user) is increased by a pre-specified amount. The traffic model is then called to recalculate the new PI. If the new PI is less than the previous value, the TRANSYT program continues to increase the offset by the same amount as long as the PI continues to decrease. On the other hand, if the new PI is greater than the previous value, the program will decrease the offset by the same amount and continue to decrease the offset (by the same amount) as long as the PI continues to decrease. The optimum offset of this signal is achieved when no further improvement can be made (i.e. PI can not be decreased) by varying its offset. The same procedure is repeated for every signal in the network under consideration. The phase length optimization process is similar to the offset optimization process discussed above. Finally, the optimum signal timing plan (i.e. optimum splits and offsets for all signals) is reported.

The TRANSYT model can be used as a simulation and as an optimization tool for arterial roads as well as urban networks. A more detailed discussion of the TRANSYT-7F program is presented in chapter three of this study.

Practically speaking, all researchers involved in traffic operation agree that TRANSYT has been widely and successfully applied throughout Europe, the United States, and other countries (8, 13, 15, 17, 18, 19, 20, 24, 25, 26, 27, 28, 30, 38, 39, 40, 41, 43, 44, 45, 46, 47, 48, 49). For example, Rouphail (15) reported that TRANSYT "has been successfully applied at many intersections in Europe and the United States." Cohen and Liu (16) also wrote in this regard:

> The TRANSYT model is the most widely used computer program for developing signal-timing plans for urban signal systems. An Americanized version of the program, TRANSYT-7F was developed for use in the United States and has been successful.

Rach (1) described and evaluated the TRANSYT program, together with other network optimization models. He also summarized the results of one of the earliest applications of TRANSYT. Rach wrote:

> Overall,TRANSYT has been demonstrated to be reliable and effective both as a design and as an evaluation tool. In a study carried out by the Road Research Laboratory, it was found that TRANSYT accurately predicted network delay. Also, the hill-climbing process in TRANSYT was found to be very effective in obtaining optimum offsets. When compared to existing signal timing settings, the

> TRANSYT settings reduced mean travel time by 16% and increased effective network capacity by 25%.

As a part of the National Signal Timing Project (8), TRANSYT was used by eleven cities in the United States representing a wide range of geographical locations and traffic characteristics. The cities optimized the signal timing in a portion of their street network (on average 46 intersections per city) and evaluated the effectiveness of the optimized signal timing plans. It was found that these plans provided significant reductions in vehicle delay, vehicle stops, and fuel consumption. Therefore, it was concluded that, "TRANSYT-7F is a very valuable tool for signal timing optimization projects."

Wallace (17) critically reviewed the TRANSYT program. He concluded that:

> TRANSYT-7F is a major new tool available to traffic engineers for analysis of traffic signal system, evaluation of alternative control strategies and design of optimal signal setting.

Currently, TRANSYT-7F is in use by over 400 cities, states and consultants throughout the United States (18). For example, TRANSYT-7F was recently used in North Carolina as a part of its management program for energy conservation (19). TRANSYT-7F is the only network optimization model that is reported in both the Software and Source Book (18) and the Handbook of Computer Models for Traffic Operation Analysis (3). In fact, the handbook (3) described TRANSYT-7F as being "one of the most widely used design models."

Although TRANSYT was originally developed as an optimization program, its "realistic" traffic simulation model (20) makes it a valuable candidate for traffic evaluation. In fact, Yagar and Case (21) recommended that "TRANSYT be seriously considered for any evaluation purpose to which it is applicable." McCoy et al (20) described the traffic simulation sub-model in the TRANSYT program as one of the "most realistic in the family of macroscopic computerized traffic simulation models." Dudeck et al (22) reported that NETSIM (state-of-the-art microscopic model for traffic simulation) and the TRANSYT-7F model produce "compatible estimates of travel although the differences are at times appreciable."

The TRANSYT model was also used effectively as an arterial optimization model (3, 16, 18, 23, 26, 29, 31). For example, Skabardonis and May (23) used MAXBAND, PASSER-II (state-of-the-art models for arterial optimization), and TRANSYT-7F in optimizing an 11-signal arterial. It was found that, in terms of traffic performance, no model was capable of producing signal timing plans that are superior to those generated by the TRANSYT-7F model.

Another early model for network optimization is SIGRID (SIgnal GRID design) developed by Traffic Research Corporation for the Toronto traffic computer control system in 1964 (1). The program is a time-volume geometry method of optimizing offsets in a network. The program does not optimize the individual signal splits and link offsets. The program user has to predetermine the optimum signal splits and link offsets (i.e. optimum offset difference for each successive pair of intersections) by another program, or simply from experience. Having these values for each network link, the program minimizes the discrepancy between the optimum offsets and the actual ones. Therefore, the program does not necessarily minimize the system delay. It should be noticed that the program uses oversimplified assumptions in calculating average waiting times, and hence, these times do not necessarily reflect the actual delay characteristics. The literature does not show any modification or current application of the programs. Generally speaking, the SIGRID program is unsophisticated and obsolete.

Another major breakthrough in the field of signal network optimization was the development of the SIGOP (SIGnal Optimization Program) model. Originally, SIGOP was developed by Peat, Marwick, Livingston and Company, for the U.S. Bureau of Public Roads (1). Basically, the original SIGOP model was nothing more than an extended version of the above SIGRID program. However, later versions of SIGOP were modified and improved substantially. The latest version of the model (SIGOP-III) was developed by KLD Associates, Inc. for the office of Research, Federal Highway Administration (32).

Generally speaking, both SIGOP-III and the previously mentioned TRANSYT-7F are similar optimization programs that can be used for optimizing arterial roads and grid networks of urban streets. Both programs are macroscopic models that can be used for design and evaluation purposes. Each model consists of two main parts; a traffic flow algorithm and an optimization sub-model. The major difference between SIGOP-III and TRANSYT-7F is in the structure of the objective function which is used as an optimization criterion. The objective functions of both models are expressed directly in terms of vehicle delay and vehicle stops. However, the objective function of SIGOP-III has a third term reflecting excess queue length relative to available storage capacity. Furthermore, unlike TRANSYT, which allows all splits to vary (subject to a minimum green constraint) in order to achieve the lowest value of the objective function, SIGOP-III calculates minimum green requirements using Webster's method (3).

The TRANSYT traffic sub-model provided the basis for much of the SIGOP-III traffic sub-model. The platoon dispersion technique used in TRANSYT (Robertson platoon dispersion algorithm) is used indirectly in SIGOP-III. Delay and queuing calculations in both models are based on Webster's methodology. Unlike TRANSYT, the SIGOP-III program suffers from two major limitations. First, the program does not explicitly deal with minor intersections (i.e. controlled by stop or yield signs) and, secondly, it can not be used for intersections having more than four phases in a cycle. Furthermore, links longer than one mile are not accepted by the program.

Generally speaking, the SIGOP-III model seems to receive little attention from researchers and traffic engineers. The literature does not indicate any significant application or validation of SIGOP-III.

In the early 1970s, Datta et al (34, 35) developed TRASOM (TRAffic Signal Optimization Model) as a part of a "Traffic Signal Optimization Project" for the Oakland County Road Commission, Pontiac, Michigan. The model is basically a linear (road) optimization program that utilizes a sequential optimization process similar to the preferential street method, discussed previously. In a given network, TRASOM determines an optimal linear solution (the best progressive system) for every roadway in the network separately. Unlike the preferential street method, TRASOM utilizes the speed-volume relationship of the road under consideration as a constraint in determining the optimal progressive speed on that particular road. After determining the optimal linear solution for all the roadways constituting the network, the model fits in the intersecting nodal offsets according to a pre-specified sequential strategy, in a manner similar to the one used in the preferential street method. This sequential strategy is established by rank ordering each road in the network on some priority system, such as importance of direction of travel, maximum critical demand volume, and so on. The assigned priorities do not change the cycle splits on any road in the network. However, since the optimal offsets on all roads might not be attainable, these assigned priorities establish the sequence used in determining a feasible network solution. Road offsets are timed to provide the optimal individual progression, starting with the road of the highest rank, and continuing in order of decreasing rank, until the model reaches some road whose offsets (one or more) are already determined by previous setting. Consequently, this model does not provide a mathematically guaranteed optimum network solution. However, Datta et al reported that the model optimization process provided network solutions which were feasible, practical, and near optimal. The model was also efficient in terms of its computer-time requirement. The model has been used by the authors in designing timing patterns for 200 traffic signals covering an area of 36 square miles in southeast Oakland County, Michigan. The TRASOM program was fully developed using private funds and has been used only by the authors in designing signals. The model is obsolete when compared to present programs such as TRANSYT-7F and SIGOP-III.

A relatively new traffic signal optimization program is the SSTOP (Signal SysTem Optimization Program) developed in the late 1970s (34, 35). The program was originally developed as an on-line traffic signal optimization program for Metropolitan Toronto. The program was then converted to an off-line version (optimization program for fixed-time signal systems) by the Traffic Research Group at McMaster University under contract to Transport Canada. The program is a macroscopic, deterministic network optimization model.

The first operation of SSTOP is to read in, check and sort the input data for obvious errors. Once this step is completed, the program starts the optimization process by determining the practical minimum and optimum cycle lengths for each individual intersection based on Webster's cycle length procedure. The practical minimum cycle length is the best cycle length as determined by Webster's procedure taking into consideration the minimum green time necessary to provide adequate capacity for each phase, and satisfying pedestrian walk time requirements. The practical optimum cycle length, on the other hand, is the minimum cycle length which allows for an additional 10 percent capacity to cope more efficiently with random traffic fluctuations.

The next step in the optimization process is to select the best cycle length for the system (single cycle length for all intersections) from pre-specified cycle lengths. For overall network control, the program accepts up to ten specified candidate system (network-wide) cycle lengths. For each candidate cycle length, intersections which can not be placed under coordinate control in the network are identified. This is done by comparing the candidate cycle length with the practical minimum cycle length of each intersection in the network. Whenever the candidate system cycle length is less than the required individual minimum cycle length (i.e.

practical minimum) at an intersection, that intersection is placed under isolated control. The signals at the isolated intersections are allowed to operate at their optimal cycle length (practical optimum cycle length), thereby avoiding the possibility of over saturated signals in the network. Once these intersections are identified and isolated from the system, the rest of the intersections are placed under coordinated control.

Following this step, signal splits for both coordinated and isolated signals are calculated, based on Webster's method by setting the green times proportional to their respective volume/saturation ratios. For every link in the coordinated network, link entry flow patterns are generated using signal and volume data from the upstream signal. Using Robertson's platoon dispersion model (used also in TRANSYT), link exit flow patterns are then formed at the downstream signal. For every offset difference between the upstream and downstream signals, a delay (i.e. uniform delay) and stop value is calculated from the arrival and departure patterns at the link exit signal. This computed value is based on the logic adapted from the COMBINATION program (previously mentioned), and hence, it does not include delay caused by random fluctuation in the traffic. Therefore, a random delay component is added to the above delay value. This delay component, on a given link, is based on its degree of saturation.

A performance index is then calculated for each given offset difference between the upstream and downstream signal. This performance index is obtained by the addition of the uniform delay, random delay, and number of stops resulting from any particular offset difference. The optimum offset difference for the pair of signals under consideration is the one which produces the minimum performance index.

Delay-offset and stop-offset relationships (curves) are established for every link in the coordinated network. The optimum offset for some links might not be achievable when the links are considered, collectively, as a whole network. This is because at least one of the two intersections, at both ends of a link, might be a part of one or more links whose offset have to also be taken into consideration. Therefore, a technique adapted from the SIGRID program (previously discussed) is used to calculate the optimum offsets for the coordinated network. The SIGRID program will determine network offsets that are as close as possible to the optimal offsets of individual links determined previously (those resulting in the minimum performance index of each individual link).

Delay and stops for these coordinated links whose offsets are varied from the optimal ones are reobtained from the delay-offset and stop-offset curves previously calculated. The performance indices of isolated signals are also determined (in terms of delay and stops) using the technique developed by Webster. Finally, the overall system performance index is obtained by adding the performance indices of the isolated and coordinated signals. The overall performance index of each candidate system cycle length is obtained in the manner described above. The system cycle length which produces the minimum overall system performance index is considered the optimum cycle length.

The program was first tested for effectiveness and validity in 1979. Three field demonstration projects were conducted in three Canadian cities (34). The program was tested again and compared to the TRANSYT/7 program in 1980. This study was conducted in the downtown area of Galt in the city of Cambridge, Ontario (34). The signal timings generated by SSTOP were similar to those obtained from TRANSYT/7. Lam, et al (34), commented on the results of these tests as follows:

> Generally, the results of SSTOP vs. TRANSYT comparison indicate that the signal timings generated by SSTOP compare favorably with those generated by TRANSYT. Input preparation for SSTOP is easier and faster than for TRANSYT. Computer requirements and running costs are much lower for SSTOP.

However, they also commented on the features which the model lacks. Lam, et al, wrote in this regard the following:

> Various theoretical refinements are possible to increase the flexibility of SSTOP. A brief list of possible additional features is:
> - To provide for a network-wide lost time parameter
> - To provide the ability to input link specific stop penalty factor
> - To be able to include a double cycle length in the coordinated network

- To provide special treatment of over and under saturated intersections
- To be able to force congested intersections to remain in a coordinated network
- To be able to coordinate networks based on user input signal splits.

The literature does not show any other (i.e. other than what was mentioned previously) reported study on the application or validation of the SSTOP program. It seems that Canada is the only place where the program was ever tried. Based on a private communication with the developers, it is understood that SSTOP has an "error" in the way it handles left-turns, and that this error will not be corrected because it will be "expensive" to do so (50).

It is clear from the discussion in this section that TRANSYT, SIGOP-III, and SSTOP are the state-of-the-art computer models for network optimization. It is also clear that TRANSYT is superior and more appropriate in fulfilling the objectives of this study.

2.3 Reasons for selecting TRANSYT.

One of main reasons for selecting the TRANSYT model for this particular study is the fact that it has been widely and successfully used in many countries. In the previous section, a number of examples were cited. Furthermore, TRANSYT is the only optimization program which has been tested and calibrated in several countries. Several validation and calibration studies of TRANSYT were conducted in the U.K. (where the model was originally developed), Canada, Australia, Germany, Sweden, and other countries. This is in addition to the major effort performed by the Federal Highway Administration in developing the Americanized version of the TRANSYT/7 program (TRANSYT-7F), and then in testing it in eleven cities as a part of the previously discussed National Signal Timing Optimization Project (8). The experiences of all these countries in the calibration and application of TRANSYT proved that the model is transferable under various traffic conditions and driving habits. These experiences will aid in achieving the objectives of this study.

In addition to this, TRANSYT (in contrast to SIGOPIII) has the ability to handle special traffic conditions, such as up to seven phases in a cycle and sign-controlled intersections. This ability makes the TRANSYT program suitable in Saudi Arabia, where such traffic conditions are not uncommon. Furthermore, the fact that TRANSYT (in contrast to SSTOP) can be used as a design and evaluation tool for arterial roads makes it a practical model to be transferred to Saudi Arabia.

In summary, the reasons for selecting TRANSYT are as follows:

1. TRANSYT is the only network optimization model which has been subjected to validation and calibration studies in several countries under various traffic conditions and driving habits.

2. TRANSYT is the only model which was extensively and successfully used in practice.
3. TRANSYT is an optimization as well as a simulation model. This feature makes TRANSYT easy to validate and calibrate in any country.
4. TRANSYT can be used as a design and evaluation tool for arterial roads as well as urban networks.
5. TRANSYT is available in a microcomputer version which makes it available and practical to be used in any city or country in the world with very little investment.
6. The objective function (i.e. the function that will be minimized) in TRANSYT is very flexible. This function is a linear combination of delay and stops, in which the user can express the importance of stops relative to delay for each link in the network according to his objectives and convenience.
7. TRANSYT has the ability to handle the following special situations
    a. Sign-controlled intersections.
    b. Up to seven phases in a cycle.
    c. The use of double cycles for major intersections.
    d. The use of half cycles for minor intersections.
    e. Grouped nodes.

f. Mid-block sources.

g. Multiple links at common stop line.

h. Bus operations.

i. Multiple greens for a movement.

j. 100% green operation.

k. Bottlenecks.

Other network optimization models (i.e. SIGOP-III and SSTOP) can not be used in most of the above situations.

The Americanized version of TRANSYT (i.e. TRANSYT-7F) is used in this study because it is available free of charge and without a licence. Therefore, transferring the model to Saudi Arabia will not introduce any legal problems. The modifications introduced in later versions (British versions 8 and 9) do not affect the objectives of this study. This is because the traffic model (platoon dispersion algorithm) which was used in the TRANSYT-7F program is also used in versions 8 and 9. Consequently, the results that will be obtained from calibrating TRANSYT-7F (proper value of the parameters that describe drivers performance characteristics and habits) can be applied to any later version of the TRANSYT program.

2.4 Calibration of the TRANSYT program.

The reliability and effectiveness of the TRANSYT model in simulating and optimizing the traffic flow in a given network depends, primarily, on the ability of its platoon dispersion algorithm to accurately predict the flow pattern from one signal to another. The platoon dispersion algorithm used in TRANSYT is considered to be one of the most realistic algorithms used in macroscopic traffic simulation models (20). It is based on the theory that a platoon of vehicles starting from an upstream intersection will continuously disperse as it travels downstream along the link. Robertson (13) developed the following recurrence relationship to simulate this phenomenon:

$$Q^1(i+\beta t) = F*Q(i) + \{(1-F)*Q^1(i+\beta t-1)\} \qquad (1)$$

where,

$Q^1(i+\beta t)$ = number of predicted arrivals in interval $i+\beta t$ at a point downstream of a signalized intersection,

$Q(i)$ = number of departures in interval i from the signalized intersection,

β = empirical travel time factor expressed as ratio between average travel time of leading vehicle in platoon and average travel time of entire platoon,

t = average travel time from the signalized intersection to the point at which the platoon is being calculated,

F = empirical smoothing factor, which controls rate at which platoon disperses, expressed as $F = 1/(1 + \alpha\beta t)$,

α = empirical dispersion factor.

It is clear that the amount of dispersion in the traffic flow pattern, as predicted by the above recurrence equation, depends on the values of α and β. Generally speaking, a large dispersion (which is usually caused by a high level of friction to traffic flow) is represented by high value of α.

A value of 1.0 for β represents a situation in which platoons do not disperse (average travel time of leading vehicle in platoon and average travel time of entire platoon are equal). On the other hand, a value approaching zero for β represents a large dispersion. Theoretically, the parameters α and β can take any value between zero and one. Consequently, the successful utilization of the TRANSYT model depends, to a large extent, on the selection of values for α and β that best represent and replicate the traffic flow pattern in a given network.

2.4.1 British Experience.

Robertson (13) studied 700 platoons at four sites in west London, England, and concluded that values of 0.5 and 0.8 for α and β, respectively, produce the best agreement between actual and computed platoon dispersion. Although the sites selected by Robertson covered a wide range of traffic and roadway conditions, he indicated that the appropriate values of α and β might be a function of roadway characteristics such as roadway width, slope, traffic composition, crossing pedestrians and parking activities. The fact that such a relationship exists between the parameters (i.e. α and β) and the roadway characteristics was reported by several researchers in the United States, Europe, Canada, Australia, and other places. McCoy et al (20) summarized results of three major studies on platoon dispersion conducted in England.

These studies are discussed (based on McCoy documentation) in the following three paragraphs.

Collins and Gower (38) studied the dispersion of platoons of passenger cars in the suburbs of London, England. Data were collected along three-lane dual carriage-ways (high-type arterial road). The values of α and β that produced the best agreement between the predicted (by Robertson platoon dispersion model) and the observed flow patterns were then found to be 0.20 and 0.80, respectively.

In Sheffield, England, El-Reedy and Ashworth (39) examined dispersion of platoons of vehicles along a 33ft wide single carriage-way. The road was subjected to a 30 mph speed limit, and had a bus volume of 12 per hour. Data were collected at three different stations on three different days. The stations were on a 5 percent downgrade at distances of 1082, 1378, and 1837ft downstream from a signal. At the second station (i.e. at 1378ft from the signal), the best agreement between the observed flow patterns and those predicted by the platoon dispersion model was achieved when α and β were set to be 0.6 and 0.63, respectively. At the third station (i.e. at 1837ft from the signal), the best agreement was observed when values of 0.70 and 0.59 were selected for the parameters α and β, respectively.

Similar studies were conducted by Sneddon (40) in Manchester, England. The data were collected on two different sites. The first site was a three lane dual carriage-way with

10 to 15 percent commercial vehicles in the peak hours, and reasonable freedom for over taking. The other site was a two-way road 35ft wide with 2 to 3 percent commercial vehicles, two narrow lanes in the direction studied, and severely restricted over taking. With the parameter β being fixed at 0.8, it was found that the values of α that provided the best fit between the observed and predicted platoon dispersion were 0.4 and 0.63 for the first and second site, respectively.

2.4.2 Experience in Canada and the U.S.A.

In Toronto, Canada, Lam (41) conducted platoon dispersion studies on Leslie street (a high type four-lane two-way suburban arterial with no driveways and with left turn bays) in order to evaluate the applicability of the parameter values suggested by Robertson (i.e. $\alpha = 0.5$ and $\beta = 0.8$). Using these suggested values for the parameters, Lam applied the Robertson platoon dispersion model to six roadway segments on Leslie street for three times a day. He found that the average error in the computation of delay was 13.8 percent. Lam then calibrated the platoon dispersion model using his observed traffic flow date, and found that an α of 0.24 and β of 0.8 provided the best fit between observed and predicted platoon dispersion for the conditions existing on Leslie street. The calibrated model (i.e. $\alpha = 0.24$ and $\beta = 0.8$) was capable of reducing the error of the delay estimate to 8.2 percent.

To validate the accuracy of the platoon dispersion model for traffic conditions found in the U.S.A., Tarnoff and Parsonson (24) collected traffic flow data on Route 7 east of its intersections with Towlston Road in Fairfax County, Virginia. Data (i.e. time of arrival of every vehicle) were collected at 100, 400, and 800ft from the intersection. Since the data collected closely matched the free flow suburban arterial case evaluated by Lam, Tarnoff and Parsonson decided to use the parameter values determined by Lam in their study. Consequently with α and β being equal to 0.24 and 0.8, respectively, the Robertson dispersion model was applied to the data collected at the 100ft station to predict the platoon flow patterns at the 400 and 800ft stations. At both the 400 and 800ft stations, close agreement was obtained between the observed and predicted flow patterns. Furthermore, better agreement was obtained during peak periods, where heavier traffic volumes are experienced. This was explained by the fact that the heavier traffic volumes in peak periods reduced the variability of the data, and thus the accuracy and reliability of the predictions were increased. Although it was acknowledged that additional research should be conducted to refine the relationship between the parameters α and β and the roadway conditions, some general recommendation regarding the relationship between these two parameters and the roadway environment were developed. These recommendations are shown in the first two columns of Table 2.1.

TABLE 2.1 Parameter values recommended in NCHRP* report # 233 and in TRANSYT-7F manual.

NCHRP* 233		TRANSYT-7F Manual		
α	β	α	β	Roadway Characteristics
0.50	0.8	0.50	0.8	Heavy friction[1]
0.37	0.8	0.35	0.8	Moderate friction[2]
0.24	0.8	0.25	0.8	Low friction[3]

(Source:References 7, and 24)

* Tarnoff and Parsonson (Reference 25)

1 Combination of parking, moderate to heavy turns,moderate to heavy pedestrian traffic, narrow lane width; traffic flow typical of urban CBD.

2 Light turning traffic, light pedestrian traffic, 11- to 12-ft lanes, possibly divided; typical of well designed CBD arterial.

3 No parking, divided, turning provisions, 12-ft lane width; suburban high-type arterial.

Based on the study of Tarnoff and Parsonson (24) and preliminary work performed by the University of Florida, parameter values that are almost identical to those recommended by Tarnoff and Parsonson were suggested in the user's manual for TRANSYT-7F (7). These values are shown in columns 3 and 4 of Table 2.1. However, the manual indicates that these parameter values are only a general guidance for TRANSYT-7F users that are based primarily on the Tarnoff and Parsonson work. Consequently, one should not consider such agreement between the parameter values of the TRANSYT-7F manual and those suggested by Tarnoff and Parsonson (see Table

2.1) as a validation of the relationship shown between the roadway conditions and the parameter values.

It should be noted that the recommended values for the parameters α and β in the TRANSYT documentation for the original program (13) and in versions through, to, and including TRANSYT/7 is 0.5 and 0.8, respectively. However, the Transport and Road Research Laboratory (TRRL) has changed these values in TRANSYT/8 (42) to 0.35 and 0.8 for α and β, respectively. It is interesting to note that these values (i.e. α = 0.35 and β = 0.8) are also used as a default values in TRANSYT-7F which is an Americanized version of the British TRANSYT/7.

It is essential to understand that, in all TRANSYT versions, the user is only allowed to select the value of α in accordance with the roadway characteristics. All TRANSYT versions do not allow the user to change the default value of the parameter β which is kept as a constant value of 0.8.

As a part of the National Signal Timing Project (8), TRANSYT-7F was calibrated and used by eleven cities in the United States. The evaluation report of the project (8) indicated that TRANSYT-7F was calibrated by adjusting some of its input parameters, such as the platoon dispersion factors. However, more explicit information about this calibration process was not provided.

McCoy et al (20) studied the dispersion of 1700 platoons of passenger cars under low friction traffic conditions in

Lincoln, Nebraska. The study was conducted on six arterial street segments downstream of signalized intersections. All of the selected sites were level, tangent sections without parking. Other attributes of the studied sites are shown in Table 2.2.

TABLE 2.2 Characteristics of sites studied by McCoy et al.

Site	Lanes No.	Observed Width (ft)	Driveway Access	Speed Limit (mph)	Peak Period Studied
1*	1	13	None	35	p.m.
2*	1	13	Limited	35	p.m.
3**	2	12	None	45	a.m.
4**	2	12	None	45	a.m.
5**	2	13	None	45	a.m.
6**	2	12	Limited	45	a.m.

(Source:Reference 20)

* Two-way two-lane arterial street.
** Four-lane divided arterial street.

At each study site, data were collected (time of arrival for every vehicle) at four stations downstream from the signalized intersection. The first station was located immediately downstream from the intersection. The other three stations were located at 300, 600, and 1000ft downstream from the first station. The Robertson dispersion model was then applied to the data (i.e. platoon flow patterns) collected at the first station to predict the platoon flow patterns at the other three stations. Flow patterns were predicted for several combinations of α and β. The values of α and β were varied in increments of 0.01 over the range of 0.00-1.00 and 0.5-1.00, respectively. The pair (combination) of α and β values that produced the best agreement between the observed (actual) and predicted platoon flow patterns at the three downstream stations (i.e. at 300, 600, and 1000ft) was selected as the best value of α and β for the study site. In a similar manner, the best-fit value of α with β being equal to 0.8 was determined for each study site. This was done to provide a basis of comparison with other platoon dispersion studies and because the default value of β (β = 0.8) in the TRANSYT program is not under control of the user. The results of the study are summarized in Table 2.3.

TABLE 2.3 Best-fit parameter values along sites studied by McCoy et al.

Site	Best-Fit Parameter Value α	β	Value of α for β = 0.8	Range of Platoon Size	No. of Platoons
1*	0.22	0.99	0.51	5-15	294
2*	0.20	0.96	0.35	5-20	319
3**	0.16	0.95	0.38	5-38	309
4**	0.13	0.97	0.35	5-23	303
5**	0.14	0.99	0.36	5-23	286
6**	0.16	0.96	0.38	5-15	180

(Source:Reference 20)

* Two-way two-lane arterial street.
** Four-lane divided arterial street.

The Kolmogorov-Smirnov (K-S) test was used to evaluate the goodness of fit of the actual (observed) flow patterns with those predicted by the calibrated platoon dispersion model (i.e. using best-fit values of α and β in the model).

Similarly, the test was also applied to flow patterns predicted by the platoon dispersion model with the best-fit values of α for β equal to 0.8 (column 4 in Table 2.3). In both cases, the K-S test showed that the observed flow patterns fit those predicted by the calibrated platoon dispersion model at the 10 percent significance level. It was also found that larger platoons dispersed slightly more than smaller ones. It was concluded that the appropriate values (average results of the study) of the parameters α and β for passenger-car platoons under low friction traffic flow conditions on urban arterial streets are α equal to 0.21 and β equal to 0.97 on two-way two-lane streets, and α equal to 0.15 and β equal to 0.97 on four-lane divided streets. Consequently, it was stated that the user of the TRANSYT program should be able to specify the proper values of β as well as α.

2.4.3 Experience in other countries

In the State of Kuwait (on the northern border of Saudi Arabia), Castle and Bonniville (43) conducted platoon dispersion studies along a number of high standard arterial roads in the fringe area of the city of Kuwait and on one street in its central business district (CBD). The distances between signalized intersections along most of the arterial roads were in the range of 1000 to 2000m (i.e. 3300 - 6600ft). Data were collected at three stations on each study segment. The first station was located just beyond the upstream intersection. The other two stations were located downstream from the intersection at varying distances from the first station. The maximum distance between any two stations on any link was 2.2 km. The Robertson dispersion model was then applied to the data collected at the first station to predict the flow pattern at the two downstream stations. This was done using a value of 0.8 for the parameter β and five different values for the dispersion factor α. The values of the parameter α investigated were 0.5, 0.4, 0.35, 0.30, and 0.20. The value of α that produced the best agreement between the predicted and the actual flow patterns at the two downstream stations was then determined.

It was found that a value of 0.5 for the parameter α, provided the best fit between the observed and predicted flow patterns in the central business district. On the other hand, a value ranging between 0.3 and 0.4 for α was found to be appropriate in predicting platoon dispersion on most of the high standard arterial roads. On only one of the arterial roads, it was found that an α value of 0.5 (i.e. as in the CBD area) was appropriate in predicting platoon dispersion. It was thought that the extremely high speeds along that particular arterial road (averaging 56 mph) might contribute in suppressing the free flowing conditions, which are usually conducive to a high degree of platoon cohesion (i.e. low value of α). It should be mentioned that the discussion of Castle and Bonniville implied that, for the same traffic conditions, the value of α for a particular link is more affected by the average speed than by the distance between successive intersections (i.e. link length). In fact, it was indicated that platoons were observed to remain grouped and did not reach random flow over distances of up to 2000m.

To examine the sensitivity of timing plans to different values of α, data were prepared by Castle and Bonniville for a small network in the study area (five intersections in the fringe area of Kuwait) and three optimized timing plans were calculated (by TRANSYT) using three values for the parameter α (0.5, 0.4, and 0.3). The performance indices (total delay in vehicle hours per hour plus weighted number of vehicle stops) for these three timing plans (PI_{50}, PI_{40} , and PI_{30}) were then determined.

A series of six TRANSYT simulation runs were then performed in which the program merely simulated the effect in terms of delay and number of stops which would result from a specific set of signal splits and offsets. In any single run, signal timing (splits and offsets) were fixed at the optimized values found earlier with a specific α value (0.5, 0.4, or 0.3). However, a different value of α was used in the platoon dispersion model. For example, in the first simulation run, signal timing was fixed at the optimal values found with α = 0.5 but an α of 0.4 was used in the platoon dispersion model. The value of the performance index calculated in this simulation run was denoted as $PI_{50/40}$. The value of the performance index determined by optimizing the network with α being equal to 0.4, was denoted as PI_{40}. A comparison between the two indices $PI_{50/40}$ and PI_{40} will indicate the extra delay and stops that would result from implementing a signal timing plan calculated with an α of 0.5 if, in fact, an α of 0.4 describes more accurately the platoon dispersion on that particular network.

Similarly, five additional simulation runs were conducted to determine the values of $PI_{50/30}$, $PI_{40/40}$, $PI_{40/30}$, $PI_{30/40}$, $PI_{30/50}$, and their values were compared to the performance indices of the optimized plans, PI_{30}, PI_{40}, and PI_{50}. The experiment was conducted for two sets of traffic flow along the tested network, which represented the a.m. and p.m. peaks. It was found that the maximum difference in the PI resulting from assuming an inappropriate α for the network never exceeded 1.56 percent of the optimum value. This difference (1.56 percent) represents the extra delay and stops that would result from implementing a signal timing plan calculated with an α of 0.3 if, in fact, an α of 0.5 describes more accurately the platoon dispersion on that particular network. The value of the error was determined by subtracting PI_{50} from $PI_{30/50}$ and dividing the result by PI_{50} (i.e. (378.4 - 372.6) / 372.6).

Although it was acknowledged that different values of α produced noticeably different patterns of arrival on any single link, it was concluded that the TRANSYT optimized signal timing plans (for a network) were not very sensitive to the value used for the parameter α, in the 0.3 to 0.5 range. Castle and Bonniville wrote in this regard the following:

> In effect, the requirement to minimize delay throughout the whole network, and not merely on an individual link, acts as a constraint on the potential sensitivity of TRANSYT plans to platoon dispersion rates. The results obtained suggest that for a wide variety of network configurations and characteristics, the use of the default platoon dispersion factor of 35 is quite adequate. The optimized timings found by TRANSYT appear to be sufficiently insensitive to the precise value of this factor that most users can expect satisfactory results by utilizing the program's default value.

Smelt (44) studied the dispersion of 47 platoons of traffic along the "Princes Highway East" which is a major suburban divided arterial road in Melbourne, Australia. Data were collected (time of arrival for every vehicle) during the p.m. peak period at five stations along the major road. These stations were located at 200m, 400m, 600m, 800m, and 1200m downstream from a signalized intersection on that road. The observed platoons at each station were grouped into four categories according to their sizes. The Robertson dispersion model was then applied to the data (i.e. platoon flow patterns) collected at the first station (at 200m from the intersection) to predict the platoon flow patterns at the other four stations.

To calibrate the platoon dispersion model to reproduce the actual traffic pattern as close as possible, pairs of α and β were tested together. The values of α and β that produced the best agreement between the observed and predicted (by platoon dispersion model) flow patterns were then determined for each category of platoon size at every station. Consequently, 16 calibrated pairs of α and β were obtained (at each station, a pair of α and β was found for each size category).

It was found that all pairs of α and β were similar and that that platoons remained together and did not disperse greatly (i.e. did not reach random flow) over the 1000m between the initial station and the final station. Therefore it was concluded that "α and β do not vary greatly either with increasing platoon size or increasing length of section." Finally, Smelt reported that the results of his study show that the average values of α and β are 0.19 and 0.89, respectively.

In Malmo, Sweden, Leden (45) did a validation study of TRANSYT and Rosim (a simulation program of a road network controlled by traffic responsive signals) in which he mentioned that the value of the parameter α depends on the road characteristics and on the average speed along the link under consideration. In one of the studied links, it was shown that the platoon dispersion model was much more sensitive to changes in β than in α. On this particular link, Leden found that the values of α and β that provided the best fit between the observed and predicted traffic flow patterns were 0.3 and 0.8, respectively. However, more explicit information regarding the relationship between the road characteristics and speed, and the values of α and β, was not given in the study.

Axhausen and Körling (46) examined the effect of variations in the parameter α and link speeds along a real network of eleven intersections in the cities of Pforzheim and Karlsruhe, Federal Republic of Germany. Link speeds varied between 30 and 60 km/h (18 - 38 mph). The default value for the parameter α was chosen to be 0.4, however on some of the links it was lowered according to the recommendation given in the TRANSYT-7F users manual. The network was then optimized and the resulting performance index (PI) was determined. This optimization run was referred to as the base case.

A number of additional optimization runs were conducted by varying (increasing or decreasing) the speed and the values of α along all the links by a specific amount. For example, in one of the runs, the values of α were increased by 25 percent along all links, and at the same time link speeds were decreased by 25 percent. The optimal signal timing plan (offsets and splits) and the performance index (PI) for these runs were then determined. Each of these optimal signal timing plans was simulated using the original values of α and link speeds (i.e. the same values of α and link speeds used in the base case) and the resulting performance indices were compared with the performance index (PI) of the base case. It was found that the maximum difference is about 5 percent of the value of the performance index of the base case. On one of the studied links, it was found that inappropriate values of the parameter α resulted in a large number of additional stops. It was also mentioned that incorrect values of α and speed could lead to "grave errors" in the choice of the appropriate offset.

Axhausen and Körling wrote the following in this regard:

> It is also obvious that errors in the specification of α and speed might lead to grave errors in the choice of the offsets. These grave errors do not create problems for the theoretical validity of the TRANSYT results, but for the application of TRANSYT results to real networks, as a consulting engineer will be hard pressed to defend such errors as the result of an optimization of the signal setting.

A second study was conducted for the calibration of the parameters α and β. Axhausen and Körling reported that out of the large number of possible factors that might affect the proper values of α and β, only five seemed to be the most important in the "European context," namely, number of lanes available to traffic, slope, crossing pedestrians downstream, flow conditions at the stop line (disturbance by narrow lanes, crossing pedestrians, turning vehicles blocking the lane), and parking activities.

To study the effect of these factors on the parameters α and β, data were collected from eight sites in the cities of Karlsruhe and Pforzheim during the p.m. peak. The "least-squares" criterion was used to calibrate the platoon dispersion model. It was found that there were a large number of

α and β pairs that produced almost the same results in terms of the "least-squares" criterion. Therefore, it was concluded that the model should be calibrated for α, while fixing β at a given value. Axhausen and Körling wrote in this regard:

> A closer look at the squared deviation surface showed that there is a wide region of pairs of α and β for which the height of the surface is nearly equal.

They continued:

> The value of β has to be fixed externally, i.e. as the ratio of the travel-time of the first to the mean or median vehicle of the platoon, to find an unambiguous solution for α.

Because of this, and since the default value of β (i.e. β = 0.8) in the TRANSYT program can not be changed, it was decided to calibrate the model for the default value of β. However, it was acknowledged that the model with β being equal to 0.8 did not generally produce the absolute minimum of the calibration criterion. The study revealed that the mean value for α is 0.37, which is close to the default value of 0.35 used in TRANSYT-7F and TRANSYT/8. Analysis of variance was also introduced to test the relationship between the values of α and the five factors (mentioned previously) that describe the roadway conditions. The results of the analysis are summarized in Tables 2.4 and 2.5.

The results showed clearly that the number of lanes, slope, and crossing pedestrians were the proper factors in explaining the variance. Hence, one can conclude that these three factors are very important (at least, in this study) in

TABLE 2.4 Results of analysis of variance in Axhausen and Körling study. Effect of "source" on α.

Source	SS	df	F	Significant at
Number of lanes	0.15	1	7.36	0.01
Slope	0.09	2	2.43	0.12
Parking activity	0.00	1	0.00	0.95
Crossing pedestrians	0.49	1	25.56	0.00
Flow at stop line	0.00	1	0.03	0.87
Subtotal : Model	0.74	6	6.37	0.02
Error	0.27	14		
Total	1.01	20		

(Source:Reference 46)

TABLE 2.5 Mean of α for the level of the design factor in Axhausen and Körling study.

Source	Level	Mean
Number of lanes	One	0.46
	Two	0.29
Slope	Slightly upwards	0.48
	Level	0.33
	Slightly downwards	0.34
Parking activity	Parking activity	0.37
	No parking activity	0.37
Crossing pedestrians	Crossing pedestrians	0.53
	No crossing pedestrians	0.23
Flow at stop line	Disturbed	0.37
	Smooth	0.38

(Source:Reference 46)

selecting the proper value for α. Axhausen and Körling recommend that in any further study of the problem the number of measurements taken be increased and to include other factors in the analysis. These factors might include the available width of the road, the percentage of trucks, and mean speed on the link. It was also suggested to describe the study sites, as much as possible, with quantitative variables. For example, it was suggested to use number of parking and un-parking vehicles instead of "parking activity," saturation flow instead of "flow at stop line," and so on.

Axhausen and Körling (46) summarized the results of four platoon dispersion studies conducted in the Federal Republic of Germany, Poland, Florida and Texas. These studies are discussed (based on Axhausen and Körling documentation) in the following four paragraphs.

Dhardi (from ref. 46) examined the dispersion of platoons along three sites in West Germany. Each site had two lanes. The traffic flow was disturbed by parking activities at the first site, and by pedestrian activities at the second site. The traffic flow at the third site was not disturbed. With the parameter β being fixed at 0.8, it was found that the values of α that provided the best fit between observed and predicted traffic flow patterns were 0.26, 0.32, 0.24 for the first, second and third site, respectively.

Tracz (47) studied the dispersion of platoons along two sites in Poland. Each site had two lanes with an average width of 4m per lane. With β being fixed at 0.8, the platoon dispersion model was calibrated. It was found that the α values that provided the best fit between the observed and predicted platoon dispersion were 0.3 for one site and 0.23 for the other site.

Lorick (48) calibrated the platoon dispersion model along three sites in Gainesville, Florida. Each site had two lanes, an average lane width of 3.7m, no pedestrian activities, and all sites were on a level slope. The best fit values of α and β for the three sites were different. These values ranged between 0.3 and 0.5 for α and between 0.65 and 0.8 for β.

Denney (49) studied the dispersion of platoons along one site in Austin, Texas. The site had three lanes, drive ways that disturbed traffic flow, an average lane width of 4m, and no parking activities. With β being fixed at 0.8, the platoon dispersion model was calibrated. He found that the value of α which provided the best fit between the observed and calculated traffic flow patterns was 0.25.

Among all the studies mentioned in this section, the user's manual for TRANSYT-7F is the only source which provides general guidelines for selecting the values of α. Nevertheless, five important conclusions can be drawn from these studies:

1. The reliability and effectiveness of the TRANSYT model depends on selecting the proper values of α and β.

2. The proper values of α and β are a function of the traffic conditions and geometric features of the network under consideration.
3. For similar traffic conditions and geometric features, different values of α and β are reported in different countries. This might be explained by the fact that driver performance characteristics and habits differ from one society to another. Consequently, one can hypothesize that the values of α and β are affected by the driver performance characteristics and habits.
4. Calibrating the TRANSYT model by determining the most appropriate (best-fit) value of the parameter α while keeping the parameter β constant at its default value of 0.8 produces satisfactory, but not necessarily the best results.
5. Length of links and size of platoons seem to have little influence, on α and β.
6. The performance index (PI) of an entire network is not very sensitive to values of α between 0.3 and 0.5.

2.5 Conclusions.

The basic conclusions from the above literature review are the following:

1. Traffic signal optimization is an essential step for achieving smooth and efficient flow on a street system.
2. From all network optimization models, TRANSYT is the only model which has been extensively and successfully used in practice. Furthermore, the model can be constructed to handle the Saudi Arabian traffic conditions.
3. The TRANSYT-7F model is appropriate in fulfilling the objectives of this study.
4. The TRANSYT-7F model has to be tested and calibrated for the traffic conditions in Saudi Arabia.
5. Even though the parameter β is not under the control of the TRANSYT user, calibration of the model can be accomplished by determining the appropriate value of the parameters α.
6. The appropriate values of α and β are a function of the traffic conditions, geometric features of links, and driver performance characteristics.

CHAPTER 3

THE TRANSYT-7F MODEL

3.1 Model structure.

As discussed previously, the TRANSYT-7F program consists of two principal parts; a traffic model and an optimization procedure. A pictorial representation of the interaction between these two parts is shown in Figure 3.1. The optimization procedure utilizes the traffic model to evaluate the effect of changes in the signal phase durations and offsets. Optimization of the signal settings (signal phase durations and offsets) is achieved by minimizing an objective function called the Performance Index (PI). This Performance Index is a linear combination of delay and stops, in which the user can express the importance of stops relative to delay for each link in the network according to his objective and convenience. A more detailed discussion about the traffic model and the optimization procedure was given in chapter 2 of this study.

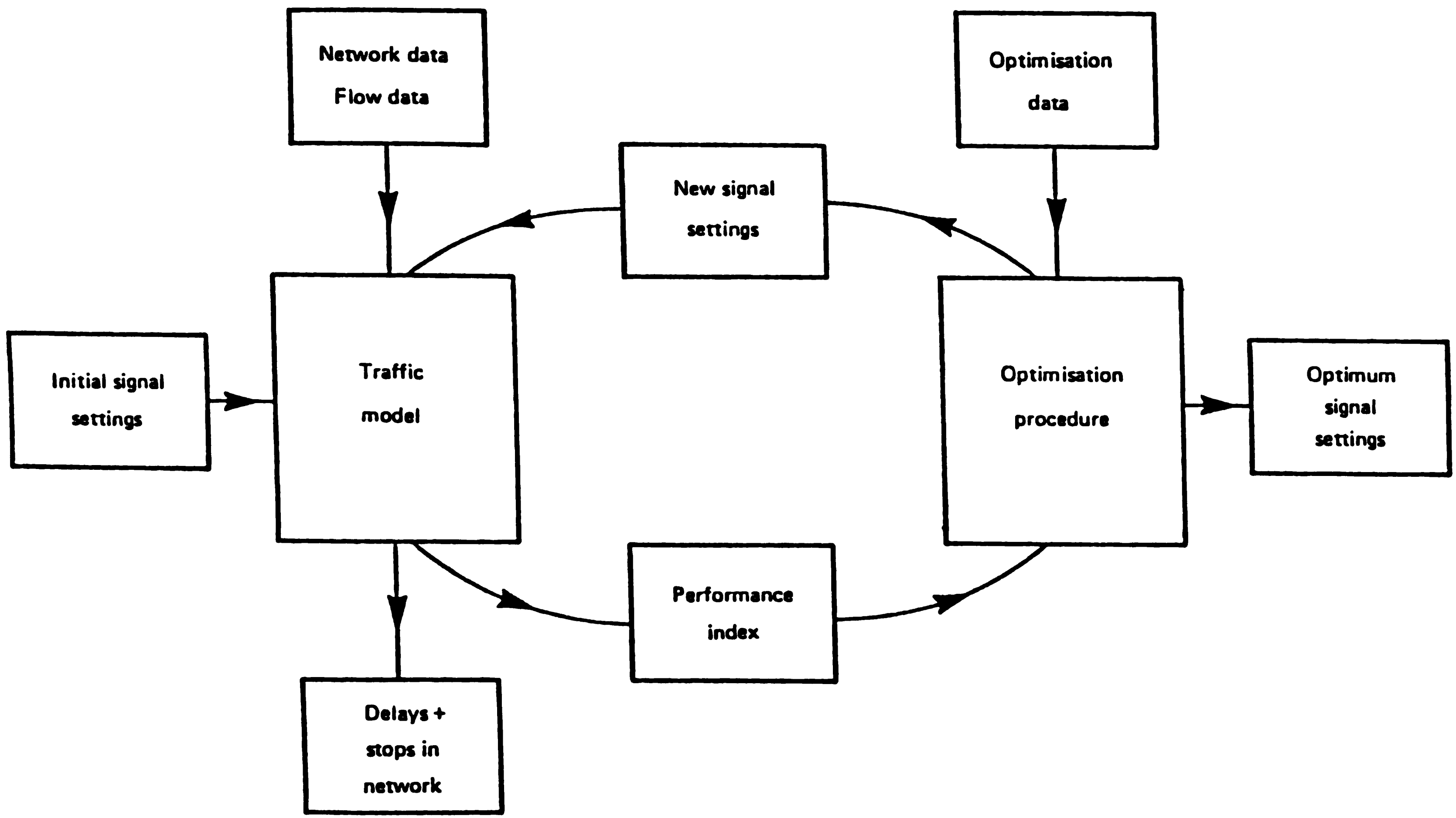


Figure 3.1 The structure of the TRANSYT program.

3.2 Input requirements.

The input data required to operate the TRANSYT-7F program can be grouped into six major categories as follows;

1. Network representation. The entire network must be represented in terms of nodes (intersections) and links (streets).
2. Network data. These data describe the geometric features of the network. Basically, this category includes link lengths and number of lanes per link.
3. Timing data. The entire signal timing plan has to be input in the program. The plan includes cycle length, signal splits, an initial set of offsets, phase duration, and sequences.
4. Traffic data. This category of data includes average cruise speed, traffic classification, flow from mid-block sources, and volume data (total flow by link and by movement).
5. Driver characteristics data. These data describe the driver performance characteristics and include saturation flow rates, start-up lost time, green extension time, average vehicle spacing, and the platoon dispersion factor α. It should be mentioned that TRANSYT-7F has default values for these parameters that can be used if more precise information does not exist.

6. Control data. These data include all the parameters by which the user may instruct the program to perform different tasks. For example, the user can instruct the program to perform a simulation or an optimization run.

3.3 Output characteristics.

The TRANSYT-7F program produces five major categories of outputs, namely, input data report, traffic performance table, signal timing tables, time-space diagrams, and flow profile plots.

The input data report is a listing of the input data reported in the same order and format the data were input to the program. Warning and error messages are also included in this report. This diagnostic report is used to detect missing or questionable data resulting in warning and error messages. Although this report is optional and can be suppressed, the warning and error messages will always be reported.

The traffic performance table reports several measures of effectiveness (MOE's) of traffic performance for each link in the network separately, and for the entire network, collectively. The most important measures of effectiveness are the following:

1. Total delay (veh-h/h)
2. Average delay (sec/veh)

3. Uniform stops (veh/h, & %)
4. Performance index
5. Total travel time (veh-h/h)
6. Fuel consumption (ga/h).

The signal timing tables provide a complete signal timing plan. This plan includes interval lengths and offsets for all the nodes in the network under consideration.

The flow profile plots are used, primarily, to calibrate the platoon dispersion algorithm used in the TRANSYT-7F program. These plots are optional and can be requested for some or all the links in the network under consideration. Basically, the flow profile plot is a histogram that shows the average flow rate at the stop line during the cycle length.

The time-space diagrams are optional and can be requested for any contiguous series of links. These diagrams are valuable tools in evaluating the through progression of traffic along network streets.

3.4 Tasks performed by the model.

The TRANSYT-7F model can perform any of the following tasks:

1. Simulation run. Traffic simulation is performed to evaluate the effectiveness of an existing signal timing plan. Simulation runs are also used in calibrating the model (see section 4.4).

2. Optimization run. If the network under consideration has a single cycle length (or a multiple of this common cycle length), the model will optimize signal splits and offsets to determine the optimal signal timing plan. On the other hand, if the network has different cycle lengths, the model will first select the optimal cycle length (by executing a cycle length evaluation run), and then optimize the signal splits and offsets.
3. Cycle length evaluation run. The cycle length evaluation run is performed to select the optimal (best) cycle length, for a given network, from a number of specified cycle lengths. To accomplish this, the model will optimize the entire network using each specified cycle length. The cycle length that produces the lowest value of the performance index (PI) is the optimal cycle length.
4. Input data scan run. None of the above tasks is performed in this run. The input data are just checked for any errors or missing information.

3.5 Limitation of the model.

The TRANSYT-7F has three limitations. These limitations are summarized as follows:

1. As an evaluation (simulation) tool, the model is only applicable to systems (networks or roads) possessing a single cycle length or a multiple of this common cycle length.
2. The model does not explicitly optimize phase sequences. Consequently, to obtain the best (optimal) phase sequences at a given node, a number of possible or desirable phase sequences have to be identified. Following that, an optimization run has to be performed for each set of phase sequences. The set of phase sequences that produces the lowest value of the performance index is the optimal phase sequences.
3. The model does not consider volume to capacity ratio (V/C) and queue capacity as constraints in the optimization process. It is not uncommon for the model to provide an optimal signal plan that produces queues longer than links (spill over) or a V/C ratio in excess of 95% along some links. In most of these situations, the problem can be alleviated with simple adjustments of the signal splits and/or by increasing the cycle length by a small percentage.
4. The TRANSYT-7F program does not optimize signal offsets and splits simultaneously. The program will optimize either one in each optimization step. A

default list of optimization steps is available in the program. However, the user can change the size, sequence, and/or the number of steps in this list. Although the default list provides an acceptable signal timing plan, it is not necessarily the optimal (best) one.

5. The TRANSYT-7F program assumes that vehicles enter the network (i.e. from the external links) at a constant uniform rate. Although this assumption is not theoretically appealing, it is not unrealistic over long period of analysis such as one hour.

6. The only platoon dispersion factor under the control of the TRANSYT user is "α" (i.e. PDF). The parameter "β", on the other hand, can not be altered from the default value of 0.8.

3.6 Computer requirements.

The microcomputer version of the TRANSYT-7F program will run on any IBM PC (or PC compatible) microcomputer that has at least 256K of memory and two double disk drives. The DOS 2.0 operating system (or any later DOS version) is also required to execute the program.

The execution time in optimization runs is a function of the number of nodes and computer architecture. For an IBM microcomputer possessing a math co-processor, the execution time is 5 minutes per node. However, without the math co-processor, the execution time may be as high as 30 minutes per node. On the other hand, the execution time in simulation runs is only a few seconds per node.

The TRANSYT-7F program can handle up to 50 nodes and 250 links. Larger networks can be analyzed using the overlaying technique, or by reducing the size of the link and node-related arrays as discussed in the TRANSYT-7F manual (7).

CHAPTER 4

DATA COLLECTION METHODOLOGY

The methodology followed in this study consisted of collecting the required input data for a selected network in the study area, comparing the traffic flow patterns computed by the model with those observed in the field (along the test network), calibrating the model to decrease the discrepancy between calculated and observed flow patterns, validating the modified model in another test network, and comparing the results of the calibrated model with that of the same model using default values for the model parameters.

4.1 Adaptation of the model.

As discussed in chapter one, the successful utilization of the TRANSYT-7F model (as well as any optimization or simulation model) depends on selecting the proper values of the factors that describe the driver performance characteristics. In the TRANSYT-7F model, there are four such factors that have to be determined (i.e. measured from the field) for the study area traffic conditions. These are the start-up lost time, extension of the green phase into the clearance interval, average vehicle spacing, and saturation flow rate.

In addition to these factors, the platoon dispersion algorithm used in TRANSYT-7F has to be calibrated for the traffic conditions existing in the study area. As discussed previously, this algorithm describes the desire of individual drivers to maintain a comfortable time headway as they progress along network links. The platoon dispersion algorithm is affected by the drivers performance characteristics. The algorithm used in TRANSYT-7F was calibrated for conditions existing in the United States, and is not necessarily valid for the traffic conditions in the study area.

As discussed in previous chapters, the calibration procedure consists of determining that value of "α" which, when used in the platoon dispersion algorithm, produces best agreement between the simulated and observed flow profiles. A more detailed discussion on this procedure is given in the next chapter.

4.2 Site selection.

The TRANSYT-7F model can not be used to simulate traffic in a network possessing different cycle lengths. Thus to be capable of simulating the traffic in a network (and consequently to calibrate the model), the entire network must have only one cycle length or a multiple of this common cycle length. To select a study section, the cycle length of every signalized intersection in the cities of Dammam and Al-Khobar was determined from the field. Unfortunately, only two arterials in Dammam and one in Al-Khobar satisfied the criterion of a common cycle length. Furthermore, one of the two arterials in the city of Dammam was undergoing a substantial pavement rehabilitation, which made it unavailable for this study. Consequently, only two arterials (one in each city) were used in this research.

Each arterial consisted of four signalized intersections, three lanes in each direction, and they were both located in areas of mixed residential and commercial activities. Sketches of the two arterials studied and a typical phase sequence are provided in Appendix A. Further description of these two arterials is given in the next chapter.

4.3 Data collection.

The data collection phase was a major step in this study. The TRANSYT-7F requires a considerable amount of data that describe the geometric features of the network and the traffic characteristics within it. These include road geometry (length and width), signal timing plans, control volume counts, traffic flow by link and by movement, and the average speed on each link. This is in addition to the previously mentioned data needed to describe the drivers performance characteristics. A summary of TRANSYT-7F data requirements is shown in Table 4.1.

Because traffic and operational data does not exist for the study area, the data needed for this study was collected from the field. With the exception of the average vehicle spacing and the platoon dispersion data, the procedure recommended by the TRANSYT-7F manual was followed in collecting and presenting the required data (7).

The average vehicle spacing is used by the TRANSYT-7F program in the calculation of queue capacity along each link in the network under consideration. The program uses only one value for the average vehicle spacing in this calculation. This is logical, given the fact that this value is a characteristic of the driver and is not a function of road features. The average vehicle spacing in the study area was determined by randomly choosing a link from the study area and studying the queue characteristics along this link. A total of 105 queues were observed along the selected link. Vehicle spacing was calculated for each queue by dividing the length of the queue by the number of vehicles. The average vehicle spacing was then determined by averaging the values of the vehicle spacing obtained from all the studied queues. The average vehicle spacing was 7 meters, and the variance was 0.27 meters, providing a 95% confidence interval of ± 0.1 meter.

TABLE 4.1. Summary of TRANSYT-7F data requirements.

MAJOR CATEGORY	DATA TYPE
Network Data	1. Nodes (i.e. intersections). 2. Links (i.e. streets). 3. Link distances. 4. Parking and turn restrictions. 5. Bus routes.
Timing Data	1. Existing cycle length. 2. Existing offsets. 3. Existing interval duration. 4. Existing phase lengths.
Driver Performance Characteristics Data	1. Saturation flow. 2. Start-up lost time. 3. Green extension time. 4. Average vehicle spacing. 5. Platoon dispersion data.*
Speed Data	1. Cruise speed on the links.** 2. Bus dwell time.
Volume Data	1. Control volume counts. 2. Total flow by link and by movement. 3. Flow from mid-block sources. 4. Classification of traffic. 5. Input flows from upstream links

(Source:Reference 7)

* For model calibration.
** See Appendix B for speed data.

A total of 369 observations were made at the eight intersections studied for determining the start-up lost time. The mean value was 2.49 seconds, and the variance was 1.42. For determining the extension of the effective green, a total of 304 observations were made at the same locations. The mean value and the variance were 3.44 and 1.70 seconds, respectively. Because TRANSYT-7F requires single digit values for the start-up lost time and the extension of the effective green, the values of 2 and 3 were used, respectively.

The platoon dispersion data, or equivalently, the arrival flow patterns, were needed to calibrate the platoon dispersion algorithm used in TRANSYT-7F program for the traffic conditions existing in the study area. The arrival flow pattern (profile) was obtained for every link in the study area. This was done by counting the vehicles arriving at a point upstream of the investigated intersection at a distance large enough to insure that the arriving flow pattern was not disturbed or influenced by the vehicles queued at the downstream intersection. This distance ranged from 80 to 200 meters depending on the traffic characteristics of each investigated link.

Given that the cycle length in the study area was 120 seconds, the cycle was divided into 24 intervals (steps) each of which was five seconds long. The number of vehicles arriving in each step was counted separately. This was done over 30 consecutive cycles (TRANSYT recommends at least 10 cycles), which represented a one hour study period.

4.4 Schedule of activities.

The data used in this study was collected during the summer of 1988 in the cities of Dammam (First Street), and Al-Khobar (King Abdul Aziz Street). During this period there were no abnormal conditions that might have affected the traffic characteristics in the study area.

The help of fifteen civil engineering students (studying at KFUPM) were required to undertake the data collection task. All of the students had previous experience in collecting traffic data. In addition, they were all extensively trained to collect the data needed in this study.

Volume, speed, signal timing, and driver performance characteristics data were collected near, but not during the morning peak hour. In the city of Al-Khobar the data was collected between 9:00 and 10:00 a.m., and in Dammam from 9:30 to 10:30 a.m. The morning peak hour, which is around noon in both cities, was found to impose a large burden on the student collecting volume data, and consequently increases the chance of human error. In addition, it was uncomfortably hot for the students to conduct their tasks reliably during the noon hour. Other physical and geometric data, such as number of lanes, locations of non-signalized intersections, length of links and turning bays were collected either in the early morning, or late in the afternoon.

The first ten days were devoted to locating and determining the cycle length of every signalized intersection in the cities of Dammam and Al-Khobar. The next two weeks were spent in selecting and training the participating students. Another three weeks were spent in collecting the required data.

CHAPTER 5

DATA ANALYSIS

5.1 Driver performance characteristics.

As mentioned in previous chapters, the first step in conducting this study was to collect the required data for the model. One type of required data is the driver performance characteristics, which include the extension of effective green time, average vehicle spacing, start up lost time, and saturation flow rates. These driver characteristics, as observed and evaluated in the study area, are summarized in Tables 5.1 and 5.2, in which one can easily see that they are not very different from what is usually encountered in the United States. More specifically, comparing the value of these characteristics with those given in the TRANSYT-7F manual for different categories of drivers seems to indicate that drivers in the study area can be classified some where between normal and aggressive.

Table 5.1 Average vehicle spacing and extension of effective green in the study area.

The study area		TRANSYT-7F recommendations	
[a]Extension of effective green (sec)	Average vehicle spacing (dm)	[b]Extension of effective green (sec)	[c]Average vehicle spacing (dm)
3	70	[d]Change period minus 0-2 seconds	78

a: Only integer seconds may be used in TRANSYT-7F.
b: Recommended values for normal and aggressive drivers.
c: Default value.
d: Change period in the study area ranged between 3 to 5 seconds.

Table 5.2 Start-up lost time and saturation flow rate in the study area.

City of Dammam			City of Al-Khobar			TRANSYT-7F Recommendations			
[a]Start-up lost time (sec)	[c]Saturation flow rate (vphg/lane)		[a]Start-up lost time (sec)	[c]Saturation flow rate (vphg/lane)		Condition	[a]Start-up lost time (sec)	[c]Saturation flow rate (vphg/lane)	
	Thru	Turn[b]		Thru	Turn[b]			Thru	Turn[b]
2	1720	1690	2	1780	1650	Aggressive drivers	2	1800	1700
						Normal drivers	3	1700	1600

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

5.2 Estimating PDF values in the study area.

The two arterials (one in Al-Khobar and one in Dammam) used in this study were, generally speaking, very similar. They were both high type arterials located near the central business district. Each arterial consisted of four major signalized intersections with four approaches in each. Consequently, the flow profiles could be observed for six links (three for northbound traffic and three for southbound traffic) connecting the four intersections in each arterial. The physical, traffic, and geometric features of these two arterials are described in detail in Table 5.3. By comparing these features for each link with the characteristics of different levels of roadway friction as given in the TRANSYT-7F manual, the roadway friction on each link was classified as being either low or moderate. Since the manual recommends a PDF value in correspondence to the roadway friction level, the recommended PDF value for each link was found from the manual as shown in Table 5.4.

The twelve links (six in each city) were classified into eight and four links having low and moderate roadway friction characteristics, respectively. To divide these two categories of links (i.e. links with moderate friction and links with low friction) evenly between the calibration and validation studies, the links serving northbound traffic in Al-Khobar and Dammam were used in the calibration study, and the southbound

Table 5.3 Geometric features and traffic data of the studied links.

CITY OF DAMMAM

Remarks	Lane width (m)	# Lanes	Link[2] Length (m)	# of minor intersections modeled	Ave. speed (speed limit)	Traffic volume[1] (vph)	Pedestrian traffic	Type and density of activity along the side of the link	Parking friction	Link # (node - node)	Direction
Curved and -ve gradient. Probable sight distance problem downstream.	3.8	3	757	none	83 km/hr (70)	857	none	none	none	9101 (12 - 6)	North to Dammam
	3.6	3	327	one (+39, -10 vph)	66 km/hr (50)	651	very low	commercial and residential low density	low	9201 (6 - 7)	
	3.6	3	349	one (+78 vph)	60 km/hr (50)	811	low	commercial and some residential moderate density	moderate	9301 (7 - 1)	
	3.6	3	369	none	65 km/hr (50)	621	low	commercial and some residential moderate density	moderate	9403 (1 - 7)	South to Dhahran
	3.6	3	327	one (+18, -25 vph)	64 km/hr (50)	524	low	commercial and some residential moderate density	moderate	9503 (7 - 6)	
Curved and some +ve gradient. Parking lane used as an acceleration lane.	3.8	3	757	one (+299 vph)	82 km/hr (70)	734	none	none	none	9603 (6 - 12)	

1: Volume at the point where flow profile was obtained.
2: From the upstream intersection to the point where flow profile was obtained.

Table 5.3 (cont'd.).

CITY OF AL-KHOBAR

Remarks	Lane width (m)	# Lanes	Link[2] Length (m)	# of minor intersections modeled	Ave. speed (speed limit)	Traffic volume[1] (vph)	Pedestrian traffic	Type and density of activity along the side of the link	Parking friction	Link # (node - node)	Direction
	3.7	3	376	one (+130 vph)	64 km/hr (60)	1061	very low	commercial and residential low density	low	9401 (24 - 23)	North to Dammam
	3.7	3	371	none	63 km/hr (60)	1036	very low	commercial and residential low density	low	9201 (23 - 22)	
	3.7	3	414	two (+71, -10 vph) (+44 vph)	66 km/hr (60)	1090	low	commercial and residential moderate density	moderate	9001 (22 - 21)	
	3.7	3	414	one (+55, -45 vph)	66 km/hr (60)	1007	very low	commercial and residential low density	low	9103 (21 - 22)	South to Al-Khobar
	3.7	3	371	one (+45, -14 vph)	64 km/hr (60)	1028	very low	commercial and residential low density	low	9303 (22 - 23)	
Some bumps of considerable size	3.7	3	376	one (+73, -90 vph)	64 km/hr (60)	1065	very low	commercial and residential low density	low	9503 (23 - 24)	

1: Volume at the point where flow profile was observed.
2: From the upstream intersection to the point where flow profile was obtained.

Table 5.4 Suggested roadway friction and PDF values.

Used in	PDF* value	Roadway characteristics	City and direction	Link # (Node-Node)
calibration	25	low friction	Al-Khobar N.B.	9401 (24-23)
calibration	25	low friction	Al-Khobar N.B.	9201 (23-22)
calibration	35	moderate friction	Al-Khobar N.B.	9001 (22-21)
validation	25	low friction	Al-Khobar S.B.	9103 (21-22)
validation	25	low friction	Al-Khobar S.B.	9303 (22-23)
validation	25	low friction	Al-Khobar S.B.	9503 (23-24)
calibration	25	low friction	Dammam N.B.	9101 (12-6)
calibration	25	low friction	Dammam N.B.	9201 (6-7)
calibration	35	moderate friction	Dammam N.B.	9301 (7-1)
validation	35	moderate friction	Dammam N.B.	9403 (1-7)
validation	35	moderate friction	Dammam N.B.	9503 (7-6)
validation	25	low friction	Dammam N.B.	9603 (6-12)

*: Recommended by the manual of TRANSYT-7F in accordance to level of roadway friction (third column).

links were used in the validation study. This distribution of links between the two studies is shown in Table 5.4.

5.3 Calibration of the model.

5.3.1 Procedure.

As discussed previously, model calibration consists of determining the value of the platoon dispersion factor (referred to as "α" in the Robertson dispersion algorithm, and as "PDF" in TRANSYT-7F) that when used in the TRANSYT-7F model, achieves the best agreement between the observed traffic flow patterns and those predicted by the model.

Starting with the first link serving northbound traffic in Al-Khobar (between intersections 24 and 23 as shown in Table 5.4), the PDF value which produces the best agreement between the observed and simulated flow patterns was determined by conducting several simulation runs for the entire arterial. In each simulation run, a different value of PDF was used for the first link. The PDF values investigated were in the range of 0.15 to 0.60. For all other links in the arterial, the recommended PDF values were used. In each simulation run, a flow profile plot was requested for the first link. By comparing the flow profile plots obtained with the observed flow pattern and using the sum of absolute difference criterion (which will be discussed shortly) the best fit PDF value was determined for the first link. Using the best fit value of PDF for the first link and the recommended PDF values for all other links, the same procedure was repeated for the second and third links serving northbound traffic in the city of Al-Khobar. This methodology was then repeated for the links serving northbound traffic in Dammam.

The determination of the best fit value of PDF for each link was not a straightforward issue, as one might imagine, because of two basic difficulties. The first difficulty is the fact that the flow profiles obtained from TRANSYT-7F represent the shape of the flow pattern, but do not indicate the number of vehicles arriving in each five seconds of the cycle. These profiles are presented as vertical lines drawn over a horizontal axis that represents the 120 second cycle length. The length of these vertical lines represents the relative number of vehicles arriving in each interval of the cycle. To convert these vertical lengths into the number of vehicles arriving in each interval over the study period, the procedure recommended in the TRANSYT-7F manual was followed. This procedure determines the scale of these vertical lines by dividing the maximum flow along each link (reported with each plot) by the maximum number of vertical symbols in any plot. By calculating the number of vertical symbols (i.e. length of vertical lines) in each interval and using the previous vertical scale together with the proper conversion factors, the total number of vehicles arriving in each interval was determined.

The second difficulty faced in the comparison effort was how to select easily and efficiently from the large number of the simulated flow profiles the one which is in best agreement (best-fit) with the observed flow pattern. The criterion used for this purpose was the minimization of the absolute value of the total differences between the number of vehicles simulated and observed in each increment over the study period. Although this sometimes can be done visually by comparing the simulated and observed flow histograms, quantitative methods are more reliable, especially when the differences between the two flow patterns is relatively small.

The normalization and matching procedure require a considerable amount of time and effort if done manually. Therefore, a FORTRAN program was developed to conduct these tasks. This program converts the vertical lines reported for each interval in the simulated flow profile into number of vehicles, compares this number to the actual flow, finds the absolute difference, and sums these differences for the 24 intervals of the cycle. The program is given in Appendix C under the name "CALIB". A sample output is given in Figure 5.1 for the first link serving northbound traffic in Al-Khobar.

DATA SET KASK1
LINK # 9401
PDF 31
MAX FLOW 4605
SCALE USED : 1/8 inch represents 4.166666667 vehicles

INTR	NPVS	NPCR	NACR	ABDF	SQDF	ACT SCALE	PRE SCALE	DIF SCALE
20	1	7.99	9	1.01	1.01	2.	2.	0.
21	1	7.99	13	5.01	25.05	3.	2.	1.
22	1	7.99	6	1.99	3.98	1.	2.	0.
23	6	47.97	54	6.03	36.38	13.	12.	1.
24	15	119.92	123	3.08	9.47	30.	29.	1.
1	21	167.89	157	10.89	118.61	38.	40.	-3.
2	24	191.88	206	14.13	199.52	49.	46.	3.
3	16	127.92	132	4.08	16.67	32.	31.	1.
4	10	79.95	61	18.95	359.02	15.	19.	-5.
5	7	55.96	43	12.96	168.05	10.	13.	-3.
6	4	31.98	25	6.98	48.71	6.	8.	-2.
7	2	15.99	22	6.01	36.13	5.	4.	1.
8	2	15.99	15	.99	.98	4.	4.	0.
9	1	7.99	11	3.01	9.03	3.	2.	1.
10	1	7.99	7	.99	.99	2.	2.	0.
11	1	7.99	13	5.01	25.05	3.	2.	1.
12	2	15.99	26	10.01	100.21	6.	4.	2.
13	3	23.98	22	1.98	3.94	5.	6.	0.
14	3	23.98	29	5.02	25.16	7.	6.	1.
15	2	15.99	19	3.01	9.06	5.	4.	1.
16	2	15.99	17	1.01	1.02	4.	4.	0.
17	3	23.98	13	10.98	120.66	3.	6.	-3.
18	2	15.99	17	1.01	1.02	4.	4.	0.
19	2	15.99	21	5.01	25.10	5.	4.	1.

SUM ABS DIFF = 139.
SUM SQU DIFF = 1345.
DIF IN DRAWN GRAPHS = 31
NUMBER OF OBSERVED CARS = 1061
NUMBER OF PREDICTED CARS = 1055.

Figure 5.1 A sample output of the program "CALIB."

5.3.2 Calibration results.

Applying the previous procedure for any link, one can find that PDF value whose flow profile satisfies (i.e. minimizes) the sum of the absolute differences criterion.

Figure 5.2 shows how the sum of absolute differences changes with different values of PDF for the first link serving the northbound traffic in Al-Khobar. With the aid of such a graph, the PDF value that satisfies the sum of the absolute differences criterion can be readily identified, which in this case is 31. The general "U" shape of this graph was found to be a common characteristic in all of the investigated links. Similar graphical representations for all other links are given in Appendix D. Figure 5.3 shows the observed traffic flow pattern (for the same first northbound link) drawn over the simulated one using the best fit PDF value of 31. It is clear from this figure that the two flow profiles are very similar, as one would expect.

Table 5.5 summarizes the results of the calibration effort. As can be seen from this table, there is a clear tendency for the best PDF value to be greater than the one suggested by the TRANSYT-7F manual for both low and moderate friction categories. More specifically, the best PDF values ranged between 26 and 31 for low friction links, and it was exactly 40 for the links with moderate friction, while the suggested values were 25 and 35, respectively. The average

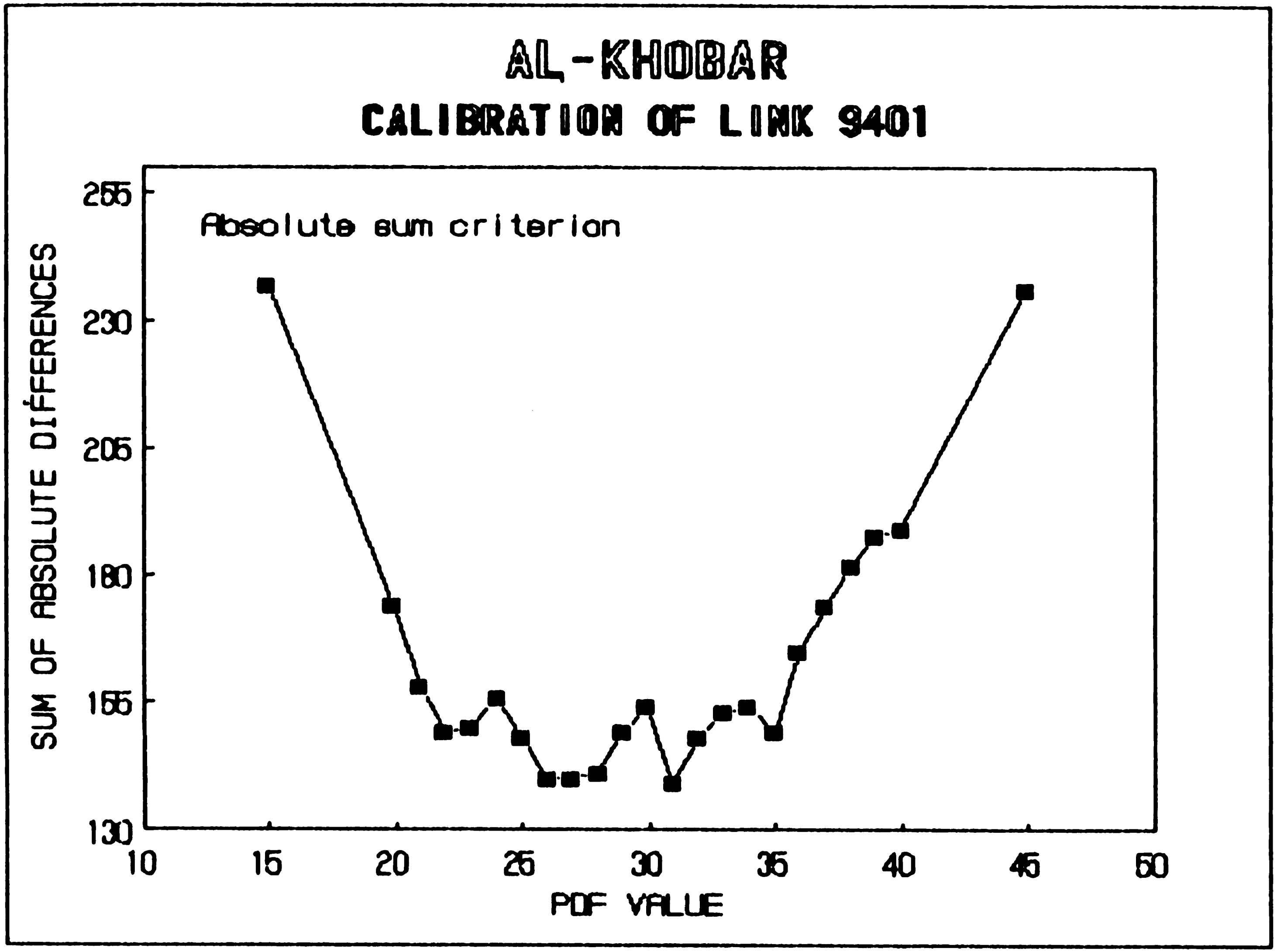


Figure 5.2 Calibration of link 9401.

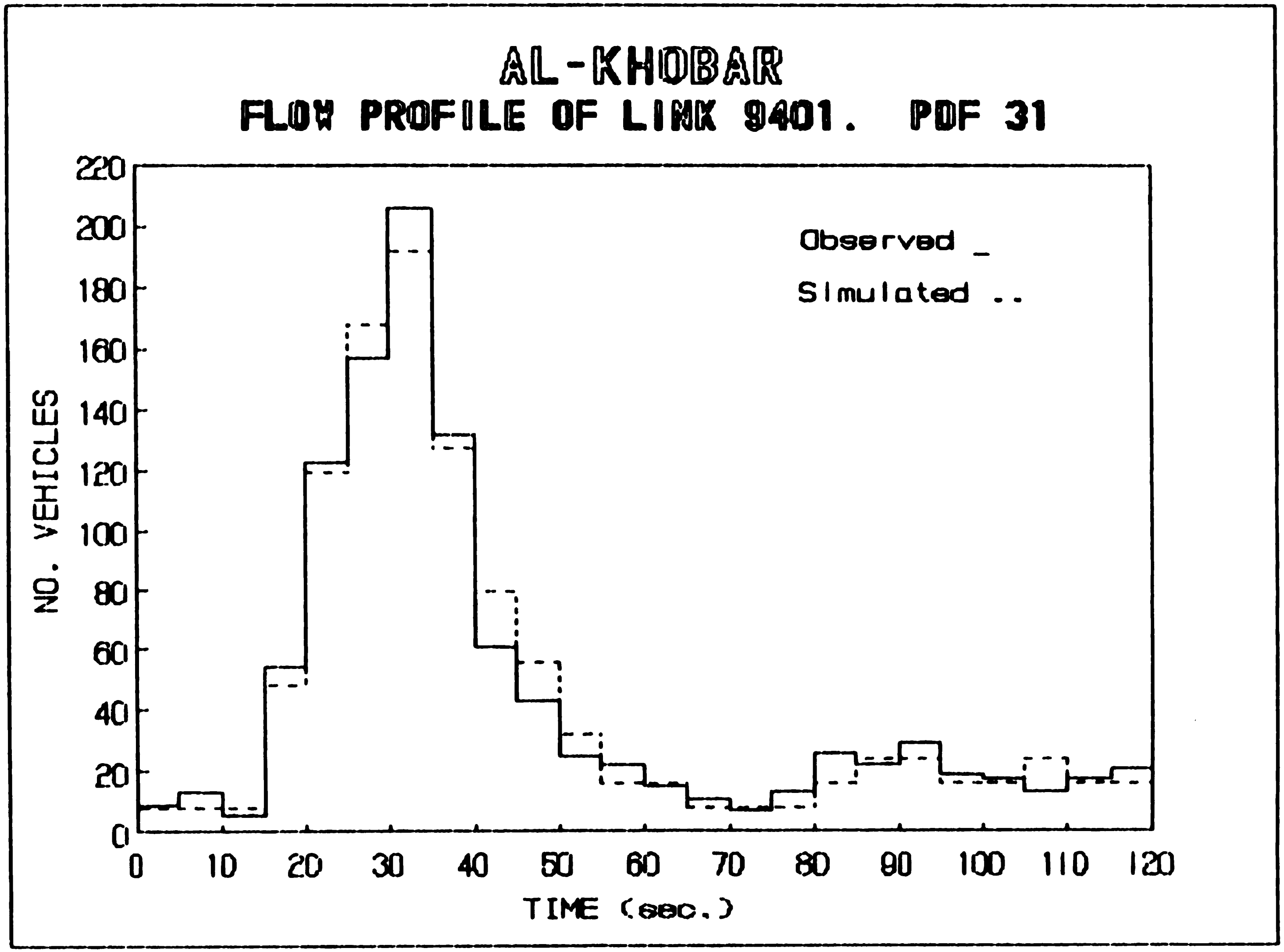


Figure 5.3 Observed and simulated flow profiles of link 9401.

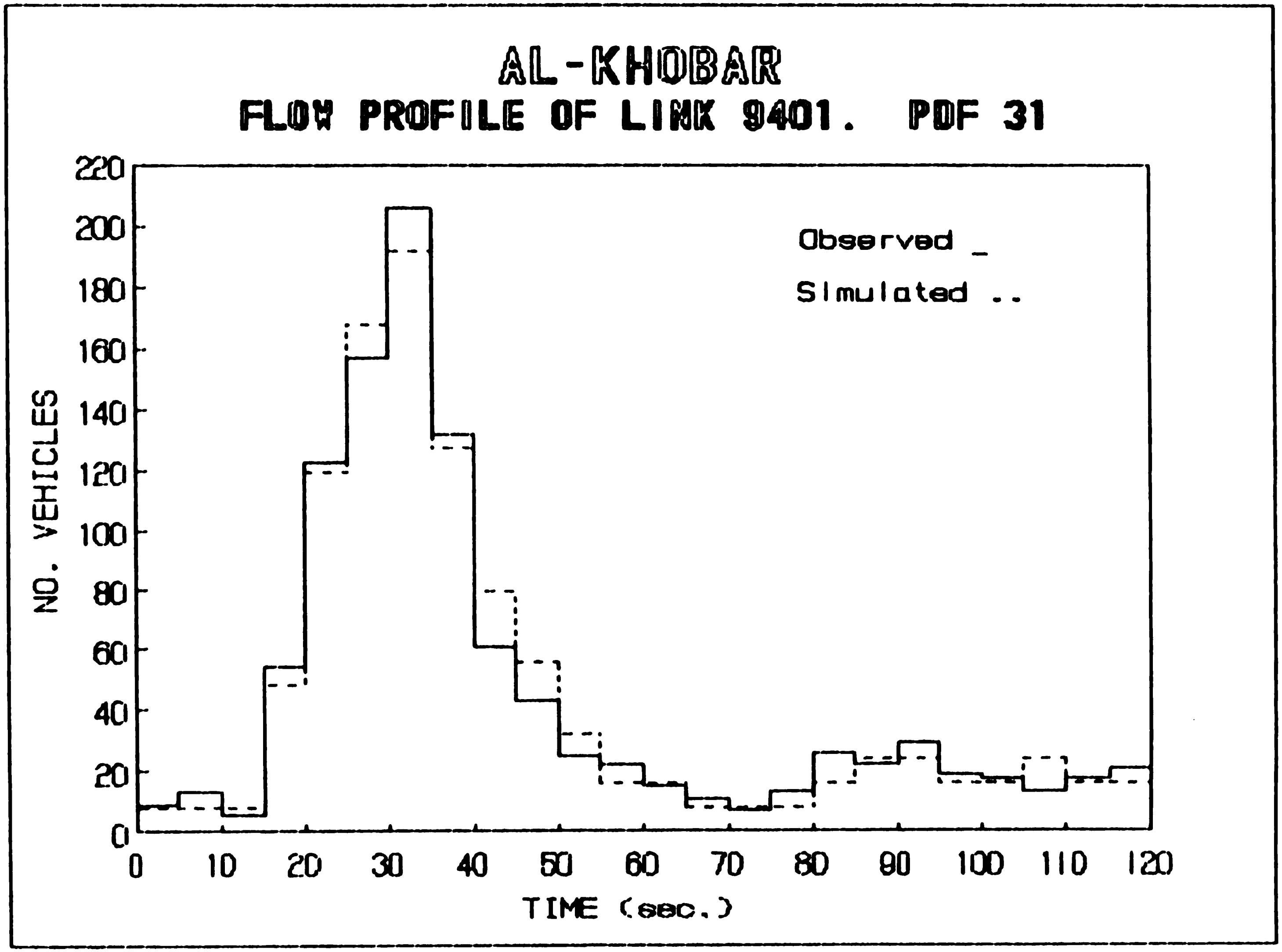


Figure 5.3 Observed and simulated flow profiles of link 9401.

Table 5.5 Calibration results.

[1]% error in volume	[2]Sum of Absolute Difference	[3]Best PDF Value	[4]Suggested PDF Value	[5]Roadway Characteristics	City and Direction	Link # (Node-Node)
13.1	139	31	25	Low friction	Al-Khobar N.B.	9401 (24 - 23)
12.1	125	27	25	Low friction	Al-Khobar N.B.	9201 (23 - 22)
13.4	146	40	35	Moderate friction	Al-Khobar N.B.	9001 (22 - 21)
13.4	115	26	25	Low friction	Dammam N.B.	9101 (12 - 6)
18.1	118	29	25	Low friction	Dammam N.B.	9201 (6 - 7)
14.4	117	40	35	Moderate friction	Dammam N.B.	9301 (7 - 1)

1: (Sum of absolute difference/observed volume) * 100. Observed volume is given in Table 5.3.
2: Sum of absolute difference between observed flow profile and the one predicted by the best PDF (column 3).
3: The PDF that minimizes the absolute difference between observed and predicted flow profiles.
4: From TRANSYT-7F manual recommendations.
5: From TRANSYT-7F manual recommendations.

best PDF values were 28 and 40, for the low and moderate friction links respectively.

5.4 Validation of the model.

Using the calibrated PDF values found in the previous section (28 and 40), the flow along each validation link was simulated. The resulting flow profiles were then compared to those observed in the field.

The flow along each of the above links was also simulated using the PDF values suggested by the TRANSYT-7F manual and the resulting flow profiles were compared to those observed in the field. This was done to compare the calibrated PDF values with those suggested by the manual. The results of this validation effort is summarized in Table 5.6.

Considering the "sum of absolute differences" as the comparison criterion between the results obtained using the calibrated and recommended PDF values, the following conclusions were reached:

1. With the exception of the last link in Dammam (# 9603), the calibrated PDF values provided superior results.
2. The differences are not large. The improvement in the comparison criterion is less than 2% of the observed volume along any link.

Table 5.6 Validation results.

Calibrated value found in the studies			TRANSYT-7F recommendation			Roadway Characteristics	City and Direction	Link Number
% error*	Sum** Abs. Diff.	PDF Value	% error*	Sum** Abs. Diff.	PDF Value			
13.6	137	28	15.0	151	25	Low Friction	Al-Khobar S.B.	9103
14.3	147	28	14.6	150	25	Low Friction	Al-Khobar S.B.	9303
16.0	170	28	17.3	184	25	Low Friction	Al-Khobar S.B.	9503
21.3	132	40	22.4	139	35	Moderate Friction	Dammam S.B.	9403
22.3	117	40	24.0	126	35	Moderate Friction	Dammam S.B.	9503
15.7	115	28	15.0	110	25	Low Friction	Dammam S.B.	9603

*: (Sum of absolute difference/volume along the link) * 100, volume is given in Table 5.3.
**: Sum of absolute difference between observed and predicted flow profile.

3. The reason why the last link in Dammam (# 9603) is an exception is the fact that the best fit PDF value for this link (see Table 5.7) is equal to the recommended value (25), where the value used in the validation was 28, the average value for all low friction links. The difference (in terms of the comparison criterion) between the results obtained using the calibrated and recommended PDF values for this link is small.

Because the number of links used in the calibration and validation processes were relatively small (6 links in each), it was thought that confidence in the resulting values would be enhanced if one can demonstrate that the calibrated PDF values would not change if the calibration and validation links are reversed, or if all the links are used in the calibration process. Thus, the links which were originally used in the validation process were calibrated and their best fit PDF values were determined. These values are reported in Table 5.7. For convenience, the table also re-summarizes the results of the original calibration process which were previously reported in Table 5.5. Consequently, Table 5.7 contains the results of calibrating and validating all links serving both northbound and southbound traffic in the study area. A study of Table 5.7 leads to the following conclusions:

1. If the links serving southbound traffic are used in the calibration process, then the average best fit

Table 5.7 Comparison between the flow profiles obtained using the best[1], calibrated[2], and recommended[3] PDF values.

Volume (vph)	Best PDF[1]			Calibration[2]			TRANSYT-7F Recommendation[3]			Originally used in[4]	Roadway Friction	City and Direction	Link #
	% error•	Sum* Abs. Diff.	PDF Value	% error•	Sum* Abs. Diff.	PDF Value	% error•	Sum* Abs. Diff.	PDF Value				
857	13.4	115	26	15.8	135	28	15.2	130	*25	Calib.	Low	Dammam N.B.	*9101
651	18.1	118	29	18.4	120	28	20.3	132	25	Calib.	Low	Dammam N.B.	9201
811	14.4	117	40	14.5	118	40	17.0	138	35	Calib.	Moderate	Dammam N.B.	9301
621	20.8	129	41	21.3	132	40	22.4	139	35	Valid.	Moderate	Dammam S.B.	9403
524	22.3	117	39	22.3	117	40	24.0	126	35	Valid.	Moderate	Dammam S.B.	9503
734	15.0	110	25	15.7	115	28	15.0	110	*25	Valid.	Low	Dammam S.B.	*9603
1061	13.1	139	31	13.3	141	28	13.9	148	25	Calib.	Low	Al-Khobar N.B.	9401
1036	12.1	125	27	12.5	130	28	13.0	135	25	Calib.	Low	Al-Khobar N.B.	9201
1090	13.4	146	40	13.4	146	40	16.1	176	35	Calib.	Moderate	Al-Khobar N.B.	9001

1: The PDF value that minimizes the sum of the absolute differences between observed and predicted flow profiles for each link separately.
2: The average PDF value found in this study for each type of roadway friction.
3: Recommended PDF value in the TRANSYT-7F manual.
4: Calib. = calibration, and valid. = validation.
•: (Sum of absolute difference/volume) * 100.
*: Recommended PDF better than the calibrated one.

Table 5.7 (cont'd.).

Volume (vph)	Best PDF[1]			Calibration[2]			TRANSYT-7F Recommendation[3]			Originally used in[4]	Roadway Friction	City and Direction	Link #
	% error•	Sum* Abs. Diff.	PDF Value	% error•	Sum* Abs. Diff.	PDF Value	% error•	Sum* Abs. Diff.	PDF Value				
1007	13.6	137	28	13.6	137	28	15.0	151	25	Valid.	Low	Al-Khobar S.B.	9103
1028	14.3	147	28	14.3	147	28	14.6	150	25	Valid.	Low	Al-Khobar S.B.	9303
1065	13.6	145	33	16.0	170	28	17.3	184	25	Valid.	Low	Al-Khobar S.B.	9503

1: The PDF value that minimizes the sum of the absolute differences between observed and predicted flow profiles for each link separately.
2: The average PDF value found in this study for each type of roadway friction.
3: Recommended PDF value in the TRANSYT-7F manual.
4: Calib. = calibration, and valid. = validation.
•: (Sum of absolute difference/volume) * 100.
*: Recommended PDF better than the calibrated one.

PDF values are 28 and 40 for low and moderate friction links, respectively. These are the same values obtained in section 5.3, when the best PDF values of the links serving northbound traffic were averaged. The same is also true when links serving both northbound and southbound traffic are used collectively.

2. Using the "sum of absolute differences" as a comparison criterion between results obtained by different PDF values, the best results are obtained for the best fit PDF value for each link.
3. Except for two links marked by an "*" in the table, the calibrated PDF values provided superior results (in terms of the above comparison criterion), for all the links in the study area. Nevertheless, the degree of this superiority is not large. The improvement in the comparison criterion (as defined above) was less than 3% of the observed volume for any link.
4. The reason the recommended PDF values provided better results than the calibrated ones for the two links (marked by * in Table 5.7), is the fact that the best fit PDF value for each of these link is closer to the suggested PDF value than it is to the average calibrated one. However, the difference (in terms of the above comparison criterion) between the

results obtained using the calibrated and recommended PDF values for these links is very small. This difference never exceeded 0.7% of the observed volume for any links.

Consequently, one can conclude that, on average, the best PDF values in the study area are 28 and 40 for low and moderate friction, respectively. Furthermore, it has been shown that these best fit PDF values provide some improvement over the PDF values suggested by the TRANSYT-7F manual.

5.5 Sensitivity analysis.

It has been shown in previous sections that, in terms of reducing the discrepancies between simulated and observed traffic flow patterns, the calibrated PDF values provided slightly better results than those recommended by the manual. However, this difference is only important if the consequences of developing and implementing an optimal signal timing plan differ depending on which set of PDF values are used. More specifically, it is more important to determine if the performance measures (i.e. delay, stops, etc.) would be improved by using the calibrated PDF values over the recommended ones in optimizing a network in the study area. It is also important to determine if such improvement is large enough to justify the considerable amount of time, money, and effort spent in developing the calibrated PDF values.

To make these determinations, the performance measures resulting from using different sets of PDF values in optimizing the studied arterials have to be compared and evaluated. This comparison will indicate the significance of the calibrated PDF values in improving the traffic performance. Nevertheless, this will not be sufficient to draw conclusions on the importance of the calibrated PDF values in optimizing traffic along other arterials or networks in the study area. The two studied arterials do not cover the variety of network configurations in the study area. To overcome this dilemma, the two arterials were used in developing a large number of hypothetical network configurations. Since any network configuration is described by four principal parameters, namely, length, volume, friction, and complexity (arterial, or two-dimensional), different levels of these parameters were used in developing the hypothetical networks. These networks were used collectively in evaluating the significance of the calibrated PDF values.

5.5.1 Procedure.

The following specific procedure was followed throughout the sensitivity analysis:

1. The calibrated PDF values (i.e. 28 and 40 for low and moderate friction, respectively) were used in developing an optimal signal timing plan for the network under consideration. To assess the

reasonability of the optimal timing plans provided by TRANSYT-7F for the two networks (mentioned above), optimal time-space diagrams are provided in Appendix E for selected routes in the two networks.

2. The optimal signal timing plan (signals splits and offsets) was simulated using the same calibrated PDF values. Thus, the performance measures (i.e. delay, stops, PI, etc.) resulting from implementing the optimal signal plan were determined. For convenience, these performance measures will be referred to as $PM_{28\&40}$.

3. Using the recommended PDF values (i.e. 25 and 35 for low and moderate friction, respectively), another optimal signal timing plan was developed for the same network. This plan will represent the result that would be obtained by not using, or knowing, the appropriate PDF values of the study area.

4. To evaluate the non-optimal plan (part 3), the network was simulated using the appropriate (i.e. calibrated) PDF values. Consequently, the above plan was developed using the recommended PDF values and simulated using the calibrated ones. The performance measures resulting from simulating this plan are referred to as $PM_{25\&35}$.

5. Comparing the performance measures obtained in part four ($PM_{25\&35}$) to those found in part two ($PM_{28\&40}$), will indicate how much improvement can be achieved by using the calibrated (i.e. the appropriate) PDF values. More specifically, the following criterion was used to determine the level of improvement;

$$[\{(PM_{25\&35} - PM_{28\&40}) / PM_{28\&40}\} * 100]$$

Positive values of the above criterion, means that the calibrated PDF values provided better results (positive improvement), and vice versa. This is true for all performance measures except system speed. Since higher system speed means better performance, negative values of the above criterion represents positive improvement, and vice versa.

Three major parameters were studied in the sensitivity analysis: friction, volume, and length of links. Each variable was investigated on the maximum possible range that could be achieved without violating any of the following criteria;

- The value can not exceed the published TRANSYT-7F acceptable range.
- The value will not produce a volume to capacity ratio (V/C) greater than 95% on any link.
- The value will not produce a spill over situation (i.e. queue longer than link) on any link.

To include the effect of geometric complexity in the analysis, these factors were investigated over a hypothetical arterial, and then over a two-dimensional grid network. The characteristics of the hypothetical arterial and the grid network are discussed in the next section.

Changing the level of volume and friction was, conveniently, accomplished via the usage of cards number 36, and 39, respectively. However, the model does not have such a facility for changing the link length. Since changing the length of all links manually is tedious, a FORTRAN program was developed to accomplish this task. This program reads the original data, changes the length of links by whatever percentage needed, and then rewrites the whole data deck with the new link lengths. This program is given in Appendix C under the name "LONG".

There is an implicit assumption in conducting the sensitivity analysis that the calibrated PDF values will not change with different levels of the investigated factors. In other words, the calibrated (i.e. best fit) PDF values found for the original arterials will still be the best fit PDF values if the volume or length of links are altered. This assumption (which may, or may not be valid) is essential to the conduct of the sensitivity analysis.

5.5.2 Networks used in the analysis.

To cover a variety of link characteristics and traffic patterns, the two arterials used previously in the validation and calibration process were connected together to form a single hypothetical arterial consisting of eight signalized intersections. Furthermore, to include the effect of network complexity in the analysis, a two-dimensional grid network was made up from the same two arterials. In this hypothetical network, each arterial was used twice in an alternated way, and they were all oriented parallel in the East-West direction. All intersections of these four arterials were interconnected from the North-South direction with hypothetical links to form a grid network consisting of 16 signalized intersections. A sketch of this network is given in Figure 5.4. The hypothetical arterial and the grid network are referred to as the one and two dimensional network, respectively. It should be mentioned that a minor adjustment was introduced in the two-dimensional network when used in analyzing volume sensitivity. This modification was to increase the volume along a few links to 40 vehicles per hour. Since the minimum volume accepted by the model is 10 vehicles per hour, this increase (to 40 vph) was essential to study the effect of reducing the volume along all links by 75%.

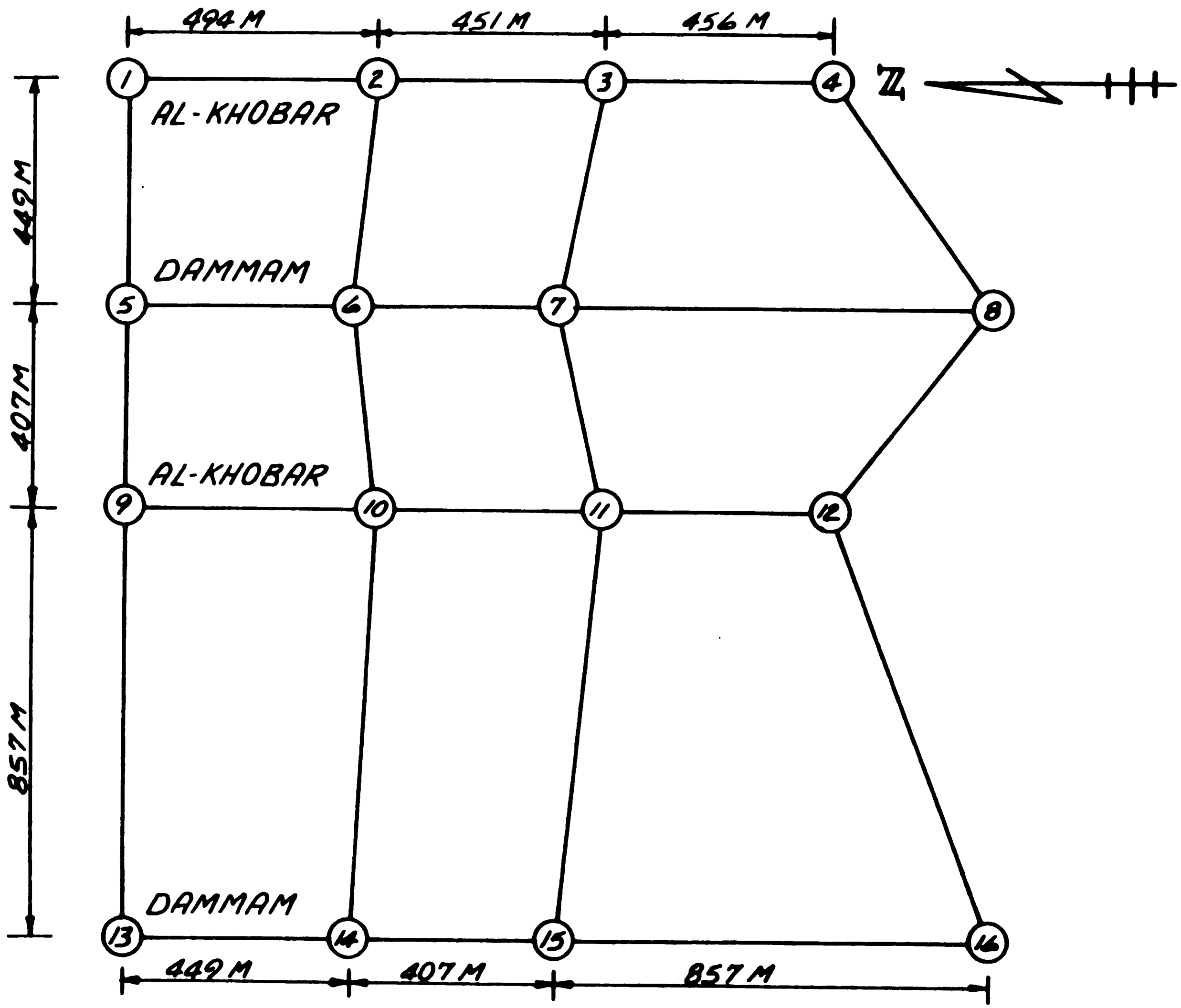


Figure 5.4 Sketch of the two-dimensional network.

5.5.3 Sensitivity results.

Although the behavior of all performance measures were investigated in this study, a special emphasis was placed on the behavior of the performance index (PI) throughout the study. The reason behind this emphasis is the fact that the performance index is the only criterion recognized and used in the optimization process. Furthermore, the performance index is, as discussed in previous chapters, a linear combination of delay and stops to which all other performance measures are related. More importantly, the fact that it is a combination of delay and stops provides the user with an average or overall assessment of the traffic performance.

A: Length of links

Values of this investigated factor ranged from 45% to 260% of the original length of each link. The performance measures resulting from optimizing and simulating the networks with each investigated value are documented in Tables 5.8, and 5.9.

Using the procedure and criterion discussed previously in section 5.5.1, Table 5.10 shows the percentage improvement in performance measures resulting from using the calibrated (rather than those suggested by the manual) PDF's. A pictorial representation of this improvement is also provided for delay, stops, and the performance index in Figures 5.5, 5.6, and 5.7, respectively.

Table 5.8 Optimization of results of different percentages of original length.

Part A: Arterial

Row No.	[a]Length Multiplier	[b]Run Descrip.	PDF Value	[c]Source of PDF	Cycle Length (sec)	Total Delay (v/hr)	Avg. Delay (sec/v)	Uniform Stops (v/hr)	Fuel Cons. (li)	System Speed (km/hr)	Performance Index (PI)
1	260%	opt	25 & 35	TRAN	85	161.13	14.0	16439	3705.52	49.35	320.95
2		opt	28 & 40	CALIB	65	140.67	12.2	17899	3703.48	51.04	314.69
3	220%	opt	25 & 35	TRAN	75	142.48	12.4	16475	3260.50	48.78	302.65
4		opt	28 & 40	CALIB	70	147.42	12.8	16805	3291.23	48.32	310.81
5	180%	opt	25 & 35	TRAN	65	130.50	11.3	17229	2861.38	47.25	298.00
6		opt	28 & 40	CALIB	65	131.59	11.4	17227	2864.86	47.14	299.08
7	130%	opt	25 & 35	TRAN	65	142.11	12.3	17718	2427.03	41.14	314.37
8		opt	28 & 40	CALIB	65	141.11	12.2	17834	2427.87	41.25	314.50
9	100%	opt	25 & 35	TRAN	80	150.26	13.0	15053	2041.53	35.96	296.61
10		opt	28 & 40	CALIB	85	150.70	13.1	15256	2046.17	35.91	299.02
11	80%	opt	25 & 35	TRAN	70	135.55	11.8	15075	1814.07	33.96	282.11
12		opt	28 & 40	CALIB	70	138.37	12.0	15266	1828.63	33.62	286.79
13	45%	opt	25 & 35	TRAN	65	131.86	11.4	16356	1503.71	25.00	290.87
14		opt	28 & 40	CALIB	65	131.52	11.4	16784	1518.90	25.04	294.70

a: The factor which multiplies the original link length.
b: Opt: optimization.
c: TRAN: PDF value recommended by TRANSYT-7F; CALIB: PDF value found by calibration.

Table 5.8 (cont'd.).

Part B: Network

Row No.	[a]Length Multiplier	[b]Run Descrip.	PDF Value	[c]Source of PDF	Cycle Length (sec)	Total Delay (v/hr)	Avg. Delay (sec/v)	Uniform Stops (v/hr)	Fuel Cons. (li)	System Speed (km/hr)	Performance Index (PI)
1	233.3%	opt	25 & 35	TRAN	65	269.21	15.4	32703	6681.93	49.84	587.16
2		opt	28 & 40	CALIB	65	272.50	15.6	32951	6699.19	49.69	592.86
3	180%	opt	25 & 35	TRAN	65	255.97	14.6	33126	5608.31	47.12	578.03
4		opt	28 & 40	CALIB	65	259.48	14.8	33542	5634.73	46.94	585.58
5	100%	opt	25 & 35	TRAN	80	276.85	15.8	29206	3950.42	36.99	560.79
6		opt	28 & 40	CALIB	80	275.45	15.7	29354	3957.82	37.07	560.83
7	45%	opt	25 & 35	TRAN	65	234.97	13.4	31427	2856.16	26.58	540.51
8		opt	28 & 40	CALIB	65	236.45	13.5	31573	2876.55	26.48	543.41

a: The factor which multiplies the original link length.
b: Opt: optimization.
c: TRAN: PDF value recommended by TRANSYT-7F; CALIB: PDF value found by calibration.

Table 5.9 Simulation results of different percentages of original length.

Part A: Arterial

[a]Row No.	[b]Length Multiplier	PDF value used in obtaining the optimal signal plan	PDF value used in simulating the optimal signal plan	Cycle length (sec)	[c]Performance measures obtained from simulation runs					
					Total Delay (v/hr)	Avg. Delay (sec/v)	Uniform stops (v/hr)	Fuel cons. (li)	System speed (km/h)	Performance Index (PI)
1	260%	25 & 35	28 & 40	85	163.58	14.2	16551	3716.80	49.16	324.49
2		28 & 40	28 & 40	65	143.56	12.4	18137	3724.84	50.80	319.89
3	220%	25 & 35	28 & 40	75	148.48	12.9	16874	3286.84	48.23	312.53
4		28 & 40	28 & 40	70	146.85	12.7	16792	3288.36	48.38	310.11
5	180%	25 & 35	28 & 40	65	133.28	11.6	17309	2876.86	46.96	301.56
6		28 & 40	28 & 40	65	132.87	11.5	17337	2876.72	47.00	301.43
7	130%	25 & 35	28 & 40	65	143.88	12.5	17878	2441.86	40.94	317.69
8		28 & 40	28 & 40	65	142.59	12.4	18007	2442.97	41.09	317.66
9	100%	25 & 35	28 & 40	80	151.77	13.2	15156	2049.69	35.80	299.12
10		28 & 40	28 & 40	85	151.45	13.1	15314	2052.67	35.83	300.33
11	80%	25 & 35	28 & 40	70	136.47	11.8	15132	1815.91	33.85	283.59
12		28 & 40	28 & 40	70	135.38	11.7	15048	1810.03	33.98	281.67
13	45%	25 & 35	28 & 40	65	133.70	11.6	16525	1518.59	24.78	294.36
14		28 & 40	28 & 40	65	131.96	11.4	16686	1521.07	24.99	294.19

a: Matches previous row numbers.
b: The factor which multiplies the original length of all links.
c: By simulating the optimal signal plan with the calibrated PDF (4th column).

Table 5.9 (cont'd.).

Part B: Network

[a]Row No.	[b]Length Multiplier	PDF value used in obtaining the optimal signal plan	PDF value used in simulating the optimal signal plan	Cycle length (sec)	[c]Performance measures obtained from simulation runs					
					Total Delay (v/hr)	Avg. Delay (sec/v)	Uniform stops (v/hr)	Fuel cons. (li)	System speed (km/h)	Performance Index (PI)
1	233.3%	25 & 35	28 & 40	65	272.69	15.6	32944	6699.85	49.68	592.97
2		28 & 40	28 & 40	65	272.54	15.6	32958	6699.56	49.69	592.96
3	180%	25 & 35	28 & 40	65	256.79	14.7	32875	5603.43	47.08	576.41
4		28 & 40	28 & 40	65	256.79	14.7	33138	5611.64	48.08	578.97
5	100%	25 & 35	28 & 40	80	284.99	16.3	29638	3998.88	36.51	573.14
6		28 & 40	28 & 40	80	277.26	15.8	29339	3962.99	36.96	562.50
7	45%	25 & 35	28 & 40	65	236.28	13.5	31434	2860.35	26.49	541.89
8		28 & 40	28 & 40	65	236.44	13.5	31571	2876.46	26.48	543.38

a: Matches previous row numbers.
b: The factor which multiplies the original length of all links.
c: By simulating the optimal signal plan with the calibrated PDF (4th column).

Table 5.10 Improvement in performance measures with different percentages of original length.

[a]Length Multiplier	PDF Values		[b]Network	[c]Percentage improvement in performance measures					
	TRANSYT-7F value	Calibration value		Total Delay	Avg. Delay	Uniform stops	Fuel cons.	System speed	Performance Index (PI)
260%	25 & 35	28 & 40	•1-dim (85 & 65)	+13.95	+14.52	-8.74	-0.22	+3.23	+1.44
233.3%	25 & 35	28 & 40	2-dim (65)	+ 0.06	0.00	-0.04	0.00	+0.02	0.00
220%	25 & 35	28 & 40	•1-dim (75 & 70)	+ 1.11	+ 1.57	+0.49	-0.05	+0.31	+0.78
	25 & 35	28 & 40							
180%	25 & 35	28 & 40	1-dim (65)	+ 0.31	+ 0.87	-0.16	0.00	+0.09	+0.04
	25 & 35	28 & 40	2-dim (65)	0.00	0.00	-0.79	-0.15	0.00	-0.44
130%	25 & 35	28 & 40	1-dim (65)	+ 0.90	+ 0.81	-0.72	-0.05	+0.37	+0.01
	25 & 35	28 & 40							
*100%	25 & 35	28 & 40	•1-dim (80 & 85)	+ 0.21	+ 0.76	-1.03	-0.15	+0.08	-0.40
	25 & 35	28 & 40	2-dim (80)	+ 2.79	+ 3.16	+1.02	+0.91	+1.22	+1.89

a: The factor which multiplies the original length of all links.
b: 1-dim: Hypothetical arterial; 2-dim: two-dimensional hypothetical network.
c: By using the calibrated PDF over the recommended ones if the calibrated PDF's are more appropriate.
*: Base case - i.e. no change in original length.
•: Optimal cycle length found by TRANSYT-7F recommended PDF values is different than the optimal cycle length found by using the calibrated PDF values; (# & #) optimal cycles obtained by using the recommended and calibrated PDF values, respectively.

Table 5.10 (cont'd.).

[a]Length Multiplier	PDF Values		[b]Network	[c]Percentage improvement in performance measures					
	TRANSYT-7F value	Calibration value		Total Delay	Avg. Delay	Uniform stops	Fuel cons.	System speed	Performance Index (PI)
80%	25 & 35 25 & 35	28 & 40 28 & 40	1-dim (70)	+ 0.81	+ 0.85	+0.56	+0.32	+0.38	+0.68
45%	25 & 35	28 & 40	1-dim (65)	+ 1.32	+ 1.75	-0.96	-0.16	+0.84	+0.06
	25 & 35	28 & 40	2-dim (65)	-0.07	0.00	-0.43	-0.56	-0.04	-0.27

a: The factor which multiplies the original length of all links.
b: 1-dim: Hypothetical arterial; 2-dim: two-dimensional hypothetical network.
c: By using the calibrated PDF over the recommended ones if the calibrated PDF's are more appropriate.
*: Base case - i.e. no change in original length.
•: Optimal cycle length found by TRANSYT-7F recommended PDF values is different than the optimal cycle length found by using the calibrated PDF values; (# & #) optimal cycles obtained by using the recommended and calibrated PDF values, respectively.

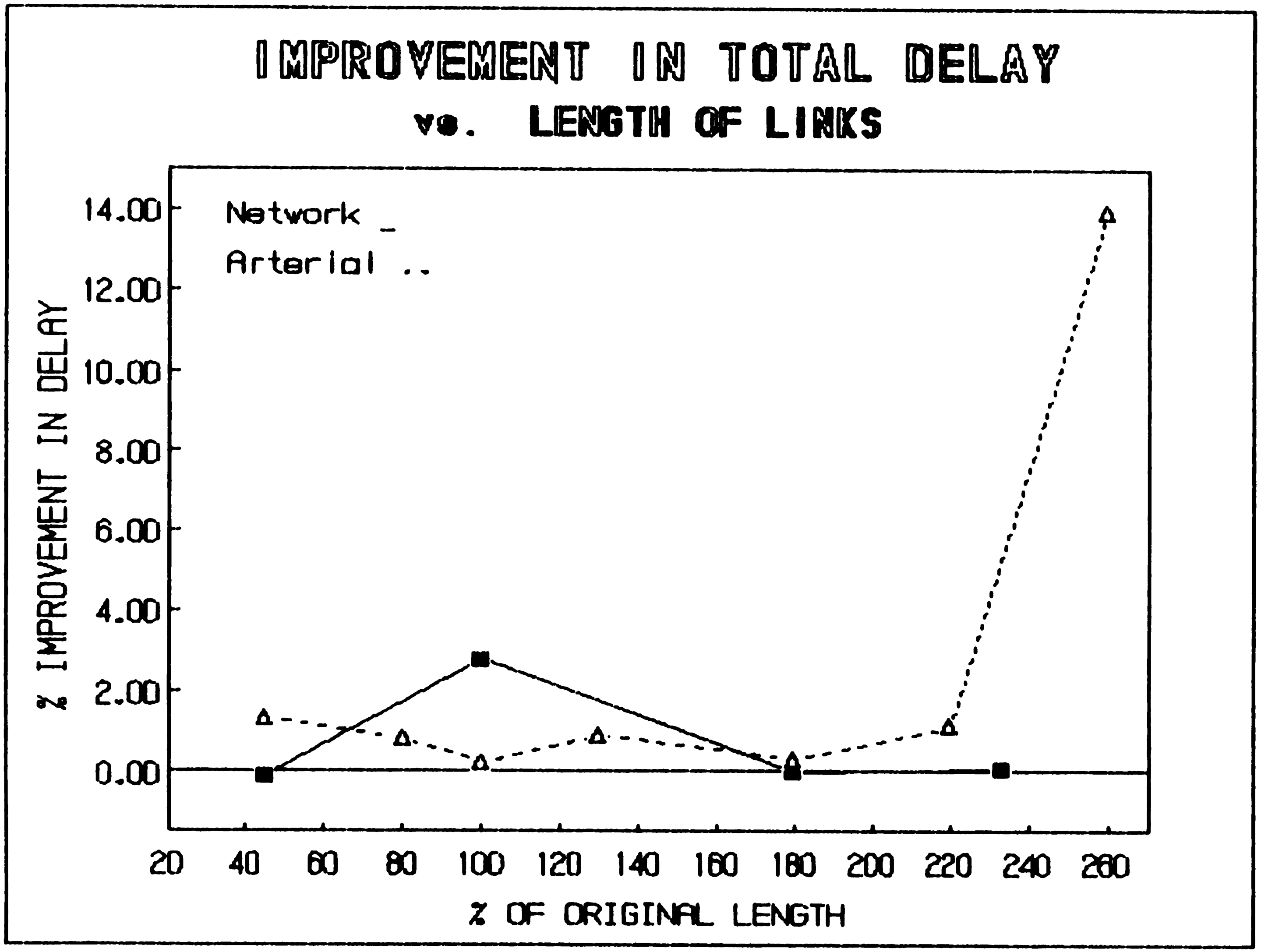


Figure 5.5 Improvement in total delay vs. length of links.

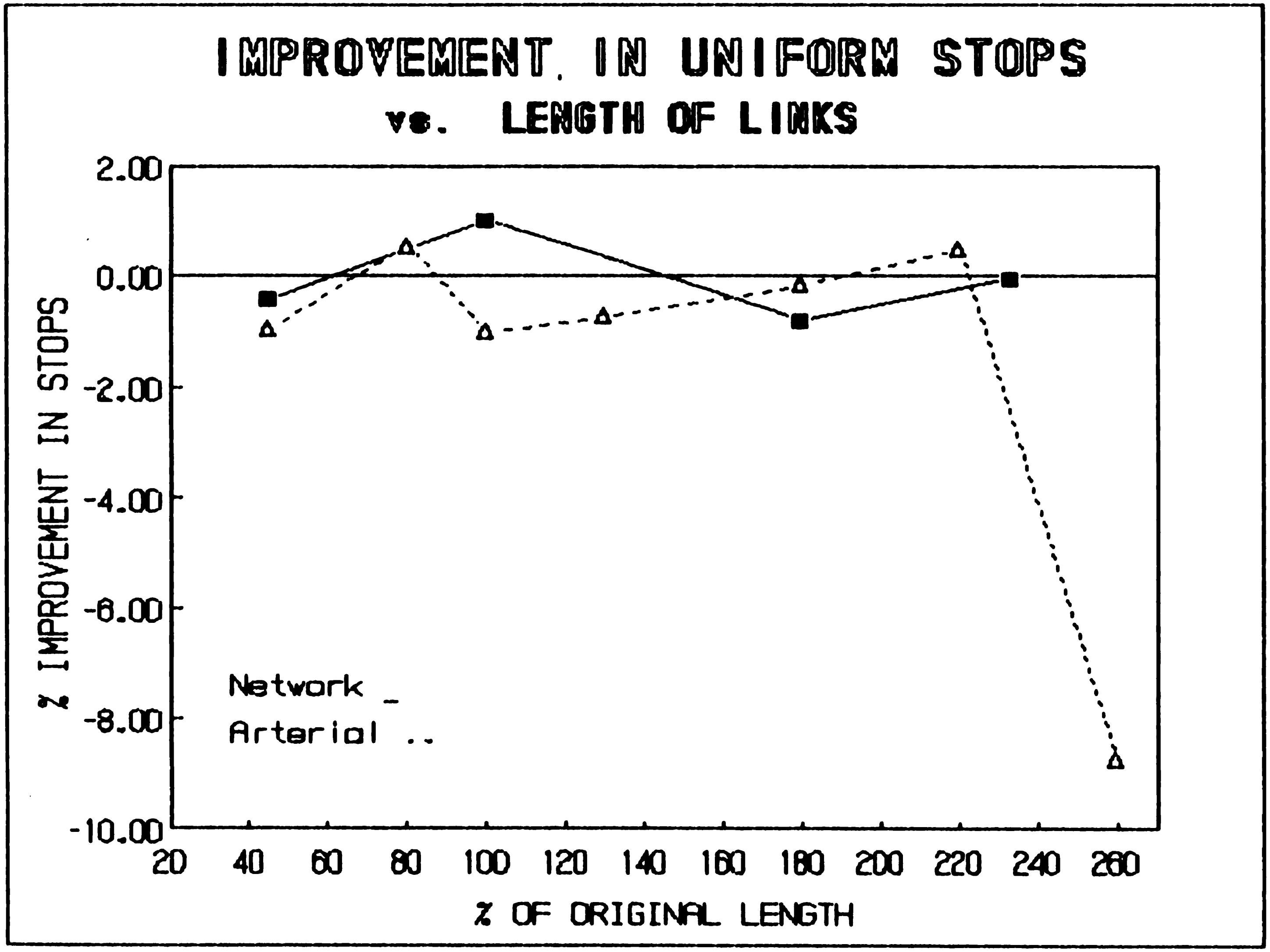


Figure 5.6 Improvement in uniform stops vs. length of links.

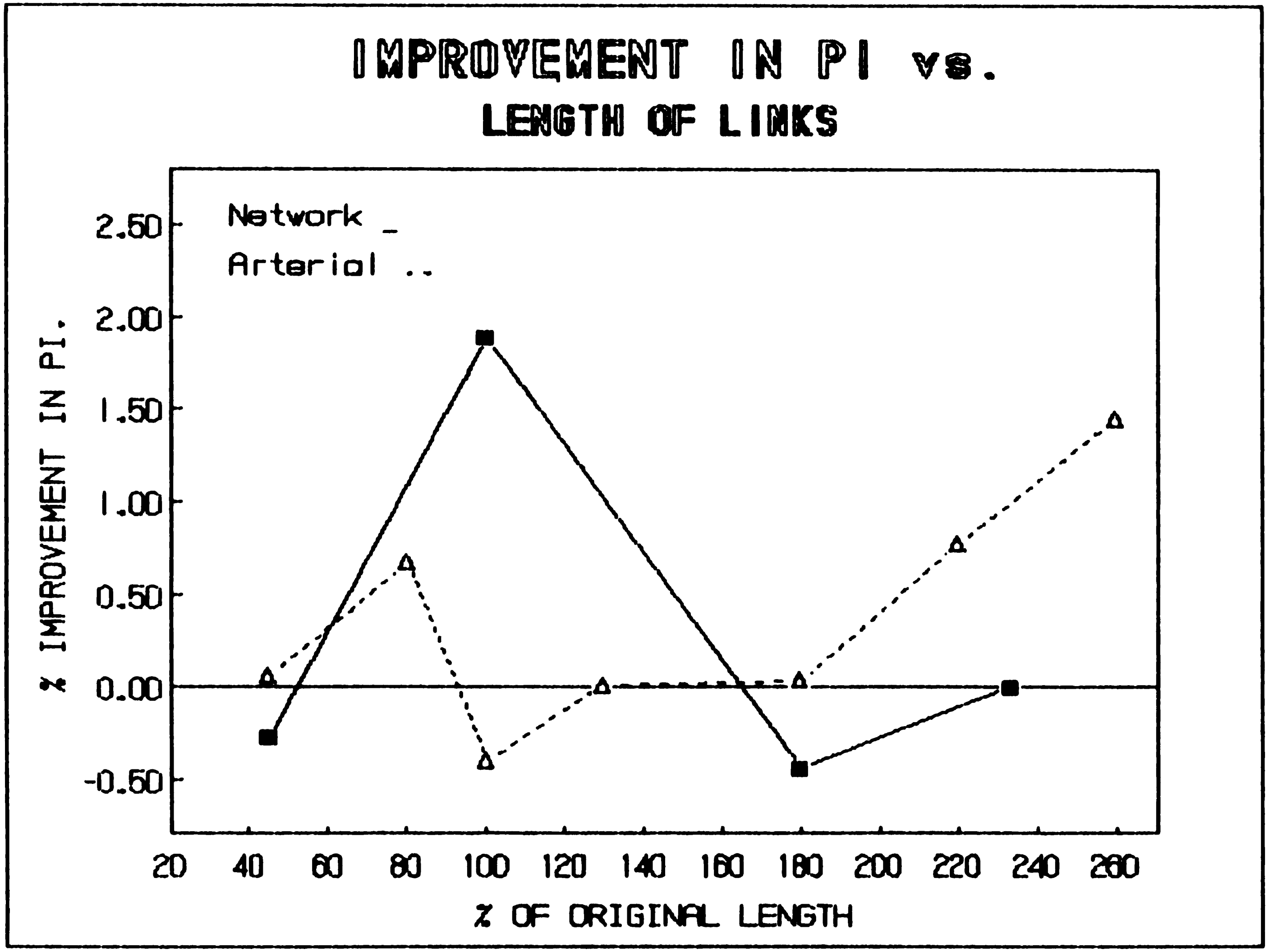


Figure 5.7 Improvement in PI vs. length of links.

It is clear from Table 5.10 and these figures that there is no specific pattern or general relationship between the improvement in any performance measure and the length of links. Furthermore, there is an inconsistency in the results from the arterial and the results from the network. It is also clear from Table 5.10 that with the exception of the case of "arterial at maximum length" (first row in the table), the change in any performance measure was less than 4% in all cases studied.

In the case of the "arterial at maximum length", where the largest difference in performance measures existed, the difference between the optimal cycle chosen (by the model) with the calibrated PDF values and the suggested ones was also the largest. This difference was twenty seconds. In all other cases such differences, if they exist, never exceeded five seconds. The relatively large difference in the arterial case at maximum length is mostly attributed to the difference between the two optimal cycles chosen by the model with different PDF values. Even in this case, the improvement in the performance index, which is the criterion used by the model in the calibration process, never exceeded 1.89%.

All of the above observations tend to indicate that using the calibrated PDF values does not consistently provide a better solution for all levels of length investigated.

B: Volume along links

Values of this factor investigated ranged from 25% to 114% of the original volume along each link. Table 5.11 shows the percentage change in performance measures resulting from using the calibrated platoon dispersion factors at each investigated value. As in the previous factor (i.e. length), Table 5.11 shows no specific pattern or a consistent relationship between improvement in any performance measure and volume. With the exception of the case of "network at minimum volume" (2nd row), the maximum change in any performance measure never exceeded 3.29%. With the same exception, the difference between the optimal cycle length chosen with the calibrated PDF values, and that chosen with the suggested ones, never exceeded five seconds.

For the network at minimum volume case, this difference was fifteen seconds. This relatively large difference between the two optimal cycles is the major reason why this particular case possesses the largest change in the performance measures. Even in this case, the largest change in performance index was less than 3.8%.

C: Friction level

The TRANSYT-7F model recognizes only three categories of friction, namely low, moderate and high. As discussed in previous sections, links with high friction characteristics did not exist in the studied arterials. Hence, calibrated PDF values were developed only for the low and moderate

Table 5.11 Improvement in performance measures with different percentages of original volume.

% of links volume	PDF Values		[a]Network	[b]Percentage improvement in performance measures					
	TRANSYT-7F value	Calibration value		Total Delay	Avg. Delay	Uniform stops	Fuel cons.	System speed	Performance Index (PI)
25%	25 & 35	28 & 40	1-dim (80)	+ 1.07	+ 1.00	-0.47	-0.07	+0.45	+0.26
	25 & 35	28 & 40	2-dim •(65 & 80)	-12.31	-12.31	+3.79	-0.68	-5.10	-3.77
65%	25 & 35	28 & 40	1-dim (85)	+ 0.06	0.00	-0.29	-0.06	+0.03	-0.11
	25 & 35	28 & 40	2-dim (85)	- 0.38	- 0.68	-0.58	-0.35	-0.18	-0.48
100%	25 & 35	28 & 40	1-dim •(80 & 85)	+ 0.21	+ 0.76	-1.03	-0.15	+0.08	-0.40
	25 & 35	28 & 40	2-dim *(80 & 85)	- 3.29	- 2.98	+1.12	-0.25	-1.53	-1.12
111%	25 & 35	28 & 40	1-dim (85)	0.00	0.00	0.00	0.00	0.00	0.00
	25 & 35	28 & 40							
114%	25 & 35	28 & 40	2-dim (95)	+ 1.85	+ 1.59	+0.01	+0.45	+0.91	+0.98
	25 & 35	28 & 40							

a: 1-dim: Hypothetical arterial; 2-dim: two-dimensional hypothetical network.
b: By using the calibrated PDF over the recommended ones if the calibrated PDF's are more appropriate.
•: Optimal cycle length found by TRANSYT-7F recommended PDF values is different than the optimal cycle length found by using the calibrated PDF values; (# & #) optimal cycles obtained by using the recommended and calibrated PDF values, respectively.
*: The network used here is not exactly the same one used in analyzing length and friction; see section 5.5.2.

friction categories. However, to increase the number of values over which the friction level could be studied, a calibrated PDF value was assumed for the high friction category. Since the calibrated PDF values were higher than the recommended ones by three and five points for low and moderate friction, respectively, it was assumed that the calibrated PDF value for high friction links would be higher than the recommended one by five points. This is only a hypothetical assumption, and should not be considered as a more appropriate PDF value of high friction links in the study area.

By using combinations of these three categories, five friction levels were investigated as shown in Table 5.12. There is no systematic pattern or general relationship between improvement in performance measures and level of friction. This conclusion is true whether we include or exclude the last two levels (i.e. level 4 and 5), where the calibrated PDF value for the high friction links was assumed and not determined. It is also clear from Table 5.12 that the change in performance index never exceeded 4.27%.

This percentage change in performance index (i.e. 4.27%) is the largest value obtained in the sensitivity study. To determine whether such a value has practical significance, a simple experiment was conducted. In this experiment, the arterial case with its original parameters was optimized twice. The only difference between the two optimization runs

Table 5.12 Improvement in performance measures with different levels of friction.

Friction level	PDF Values: TRANSYT-7F value	PDF Values: Calibration value	[a]Network	[b]Percentage improvement in performance measures: Total Delay	Avg. Delay	Uniform stops	Fuel cons.	System speed	Performance Index (PI)
Level 1. All low	25	28	1-dim (85)	- 1.07	- 1.53	+1.14	-0.08	-0.47	+0.02
			*2-dim (90 & 80)	+ 9.09	+ 9.09	-0.50	+1.86	+3.94	+4.27
** Level 2. Low and med.	25 & 35	28 & 40	*1-dim (80 & 85)	+ 0.21	+ 0.76	-1.03	-0.15	+0.08	-0.40
			2-dim (80)	+ 2.79	+ 3.16	+1.02	+0.91	+1.22	+1.89
Level 3. All med.	35	40	1-dim (85)	+ 2.03	+ 1.48	+1.31	+0.61	+0.93	+1.68
			*2-dim (85 & 95)	- 3.62	- 3.33	+2.01	-0.17	-1.75	-0.94
Level 4. Med. and high	35 & 50	40 & •55	*1-dim (95 & 85)	+ 2.65	+ 2.14	-6.61	-1.58	+1.26	-1.95
			*2-dim (80 & 95)	- 5.58	- 5.59	+3.29	-0.12	-2.72	-1.31
Level 5. All high.	50	•55	*1-dim (95 & 65)	+16.89	+16.54	-7.98	+0.37	+7.11	+3.61
			*2-dim (95 & 65)	+16.68	+16.88	-7.56	+0.63	+6.93	+3.75

a: 1-dim: Hypothetical arterial; 2-dim: two-dimensional hypothetical network.
b: By using the calibrated PDF over the recommended ones if the calibrated PDF's are more appropriate.
•: An assumed value only.
*: Optimal cycle length found by TRANSYT-7F recommended PDF values is different than the optimal cycle length found by using the calibrated PDF values; (# & #) optimal cycles obtained by using the recommended and calibrated PDF values, respectively.
**: Base case.

is the node (i.e. intersection) order used by the model in the optimization process. In the first run, the nodes were ordered as they were faced by the northbound traffic. Thus, the model first optimized the most upstream (external) node in the northbound direction. Then, moving in the same northbound direction, the second node was optimized, and so on. In the second run, the nodes were ordered as they were faced by southbound traffic. Consequently, the node order of each run is a mirror image of the other, as can be seen in Table 5.13. This table shows that just reversing the node order produced a 3% change in the performance index. Theoretically speaking, using either node-order is equally correct. Recalling that 4.27% is the maximum change in the performance index encountered in the sensitivity study, it appears that the model is relatively insensitive to volume, link length, and PDF values when compared to the 3% that can result by just reversing the node order in the optimization process.

It is interesting to note that the negative changes, which were very frequent throughout the sensitivity study, are contradictory to common sense. A negative change means that if two optimal signal timing plans were developed for a given network, the first using the wrong PDF values and the second using the correct ones, the traffic performance resulting from implementing the first optimal plan will be better than that resulting from implementing the second one.

Table 5.13 Results of reversing the node order in optimizing the hypothetical arterial (original case).

PDF	Node order in optimization	Direction	Total Delay (v/hr)	Avg. Delay (sec/v)	Uniform stops (v/hr)	Fuel cons. (li)	System speed (km/h)	Performance Index (PI)
25 & 35	•12, 6, 7, 1, 24, 23, 22, 21	[b]North bound	145.04	12.6	14675	2019.28	36.55	287.71
25 & 35	21, 22, 23, 24, 1, 7, 6, 12	[a]South bound	150.26	13.0	15053	2041.53	35.96	296.61
% Difference between performance measures of the first and second row			*+3.47	+3.08	+2.51	+1.09	+1.64	+3.00

a: The direction used throughout the study.
b: The reversed direction.
c: (Southbound - Northbound value)/Southbound value.
*: The sign means optimizing in the Northbound direction is better than the South.
•: This is the exact order of nodes in the field, i.e. node 6 is between nodes 12 and 7, etc.

5.5.4 Conclusions

The general conclusion of the sensitivity study can be summarized as follows;

1. There is no specific pattern or general relationship between the change in performance measures and any of the investigated parameters.
2. The change in the performance index, which is the most important performance measure, never exceeded 4.27%. It has been shown that even this maximum percentage appears to have no practical significance.
3. With a very few exceptions, the changes in all other performance measures were less than 4%.
4. The exceptional cases existed at the extreme values of the investigated factors. For example, minimum volume in the two dimensional network and maximum length in the arterial case. In each of these situations, the difference between the optimal cycle chosen (by the model) with the calibrated PDF values and that chosen with the suggested ones is relatively large. Consequently, it seems that the change in the performance measures is mostly attributable to the relatively large difference between the two optimal cycles chosen by the model with different PDF values.

From the above four points and from the detailed discussion in the previous section, it appears that the changes in performance measures are within the accuracy of the model, and there is no evidence to consider such changes as significant "improvements" resulting from using the calibrated PDF values over the suggested ones.

In summary, the sensitivity study tends to indicate that the calibrated PDF values do not provide significant practical improvement in the overall traffic performance, regardless of link length, volume, friction or complexity of the networks investigated.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Traffic optimization is the act of developing a signal timing plan in which the signalized intersections in a given network are operated to minimize delay and stops. Several studies showed that this minimization of delay and stops in a network provides a convenient driving environment, improves the network capacity, and reduces excess fuel consumption.

The main objective of this study was to select a candidate tool for optimizing the traffic in Saudi Arabia, and then to test and assess the applicability of this tool to the traffic conditions in the cities of Dammam and Al-Khobar, Saudi Arabia.

With the increasing complexity and magnitude of urban signal networks, manual traffic optimization is an impossible task to perform. An exhaustive research of the literature was conducted to identify signal network optimization models. The features of these models were compared, and it was concluded that the TRANSYT-7F model is the best candidate for application to the traffic in Saudi Arabia.

In any optimization or simulation model, there are a number of parameters (constants) that represent the driver performance characteristics in the country where the model was originally introduced and calibrated. It is well known that such characteristics can vary significantly from one society to another. Therefore, the successful utilization of any traffic model depends on selecting the proper values of the parameters that describe the driver performance characteristics in the area where the model is to be used.

In the TRANSYT-7F model, these parameters are average vehicle spacing, start-up lost time, extension of the green phase into the clearance interval, and saturation flow rates. In addition to these parameters, the platoon dispersion algorithm used in the TRANSYT-7F model has to be calibrated for the traffic conditions existing in the area where the model will be applied. This algorithm portrays the need of individual drivers to maintain a safe and comfortable headway as they progress along network links. Hence, the platoon dispersion algorithm is also affected by the driver performance characteristics. Consequently, to assess the applicability of the TRANSYT-7F model in optimizing the traffic flow in the cites of Dammam and Al-Khobar, Saudi Arabia, the above four factors had to be measured in the study area and the platoon dispersion algorithm had to be calibrated for the local traffic conditions.

To select study sites for this analysis, the entire road network in each city was investigated. One criterion used in selecting the study sites was that the chosen networks have only one cycle length or a multiple of this common cycle length. Since the TRANSYT-7F model can not be used to simulate traffic (and consequently can not be calibrated) in a network possessing different cycle lengths, this criterion was essential to the conduct of this research. Only one arterial in each city was found which satisfied this requirement. Each arterial consisted of four signalized intersections with four approaches in each, three lanes in each direction with curb parking, and they were both located in areas of mixed residential and commercial activities. All intersections had 120 second cycle lengths divided into four separate phases.

The required traffic and operational data for both cities were collected near the morning peak in the summer of 1988. Other physical and geometric data were collected either in the early morning, or late in the afternoon during the same period.

It was found that the values of the extension of the effective green and the start-up lost time were three and two seconds, respectively. The average value of the saturation flow rates of both cities were 1750 vph and 1670 vph for through and protected turns traffic, respectively. The average vehicle spacing was seven meters. Comparing the values of these parameters with those documented in the TRANSYT-7F manual for different categories of drivers indicates that the drivers in the study area can be classified somewhere between normal and aggressive. Therefore, the value of these parameters are not very different from what is usually encountered in the United States.

The calibration of the TRANSYT-7F model consists of determining that value of "PDF" (α) which when used in the platoon dispersion algorithm, produces best agreement between the simulated and observed flow profiles. To accomplish this, the observed arrival flow pattern (profile) was obtained for every link of the studied arterials. Using different values of "PDF", a large number of simulated flow profiles was obtained for each link. With the aid of a FORTRAN program, the value of "PDF" which minimizes the value of the absolute difference between the observed and simulated flow profiles (i.e. best-fit) was determined for each link.

The average best-fit PDF values were 28 and 40 for the low and moderate friction links, respectively. On the other hand, the TRANSYT-7F manual suggests a value of 25 for low friction links and 35 for moderate friction links. The flow along all the links were simulated using both sets of "PDF" values and the resulting profiles were compared to the observed ones. It was concluded that the average best-fit "PDF" values provide some improvement over those suggested by the TRANSYT-7F manual. More specifically, the improvement in terms of reducing the value of the absolute difference between the observed and predicted flow profiles was less than 3% of the observed volume for any link.

To determine if the consequences of developing and implementing an optimal signal timing plan differ depending on which set of "PDF" values are used, a sensitivity analysis was conducted. In this analysis, a large number of hypothetical networks were coded using data from the two studied arterials. To do this, the two arterials were connected together to form a single hypothetical arterial consisting of eight signalized intersections. Furthermore, to include the effect of network complexity in the analysis, the same two arterials were used in making a two-dimensional grid network consisting of sixteen signalized intersections. Following that, the length, volume, and friction of links, in both the arterial and the network, were varied systematically (one factor at a time) to produce a large number of hypothetical network configurations. For each hypothetical configuration, an optimal signal timing plan was developed using the average best-fit "PDF" values. This plan was then simulated with the same "PDF" values. The performance measures resulting from this simulation reflect the consequences of implementing an optimal signal timing plan developed with the average best-fit "PDF" values. For the same network, a second optimal plan was developed using the suggested "PDF" values. This plan was also simulated using the average best-fit "PDF" values. The performance measures resulting from simulating the second optimal plan indicates the consequences of implementing an optimal signal plan which was developed using the suggested "PDF" values. Comparing the performance measures of the two simulation runs is an indicator of how much improvement can be achieved by using the average best-fit "PDF" values.

It was concluded from the sensitivity analysis that the change in the performance index, which is the most important performance measure, never exceeded 4.27%. To prove that even this maximum percentage has very little practical significance, an experiment was conducted. In this experiment, the hypothetical arterial was optimized twice. The only difference between the optimization runs is the intersection order used by the model in the optimization process. It was found that just reversing the intersection order produced a 3% change in the performance index. Comparing this 3% change to the maximum change in the performance index encountered in the sensitivity analysis (4.27%) clearly shows that the change has little practical significance.

It was also concluded that, with a very few exceptions, the change in all other performance measures was less than 4.0%. In each of the exceptional cases, the difference between the optimal cycle chosen (by TRANSYT-7F) with the average best fit "PDF" values and that chosen with the suggested ones is relatively large. Consequently, it seems that the change in the performance measures is mostly attributable to the relatively large difference between the two optimal cycles chosen by the model with different sets of "PDF" values.

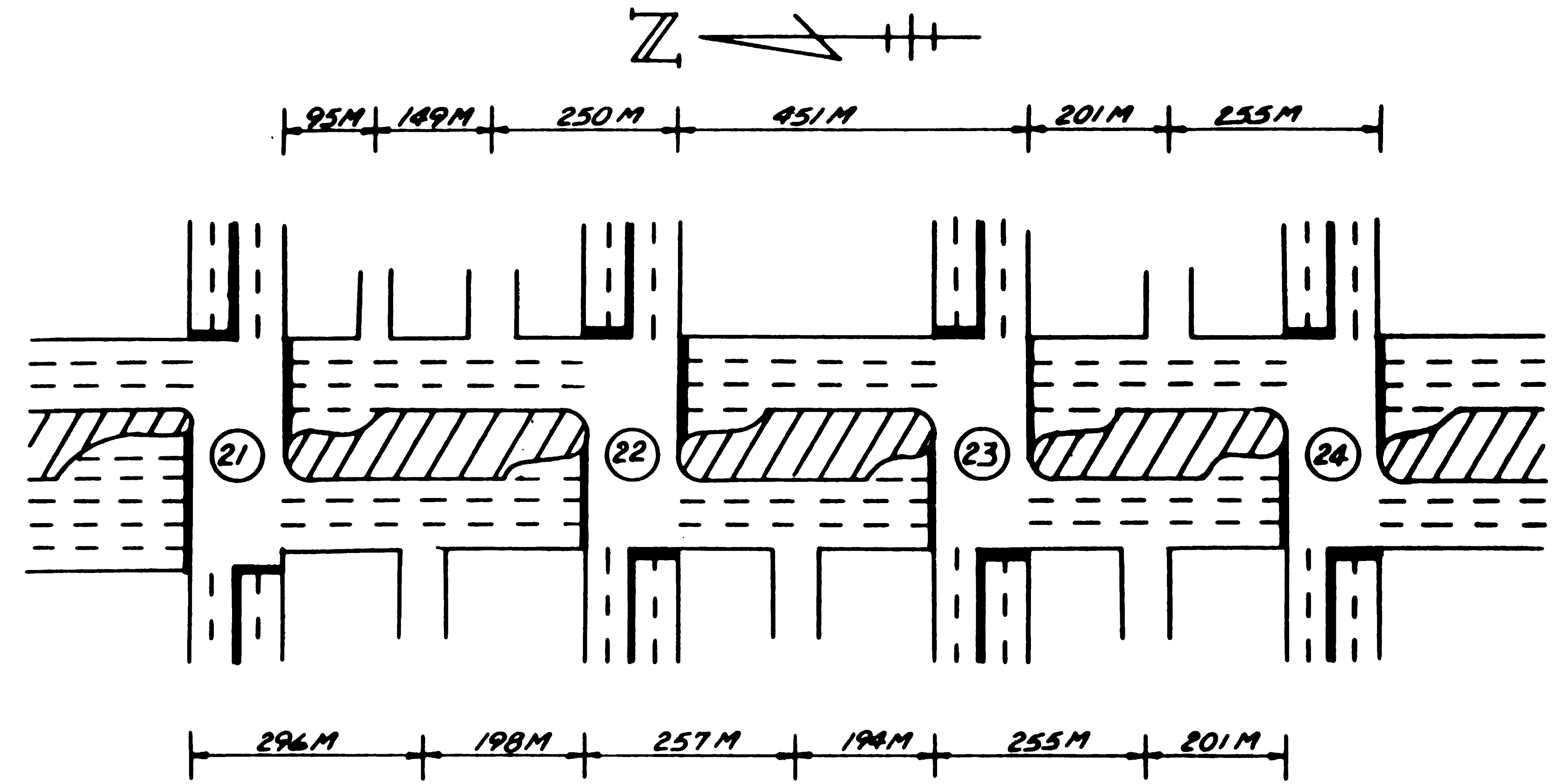
In summary, this study indicates that there is little value in developing a calibrated set of "PDF values for use in the cities of Dammam and Al-Khobar. Since this study was conducted on a small sample of the road network in these two cities, this conclusion should not be taken for granted in other networks in Saudi Arabia. It is suggested that similar work be done in other major cities such as Riyadh and Jeddah.

Working with the TRANSYT-7F program in this study demonstrated that the program is easy to understand and use. Consequently, its introduction to traffic engineers in Saudi Arabia should not yield major problems. The program is flexible and can be applied to almost any network configuration in Saudi Arabia. However, its data requirements are immense, especially since traffic and operational data are not readily available for the user. Presentation of the required data in an acceptable format to the program is another tedious task. Nevertheless, the TRANSYT-7F program is still the best network optimization tool and its usage should be encouraged throughout Saudi Arabia.

APPENDICES

APPENDIX A

NETWORK DIAGRAMS



NOT TO SCALE
NOT ALL FEATURER SHOWN
CURB PARKING IS ALLOWD

Figure A.1 Sketch of King Abdul Aziz Street.

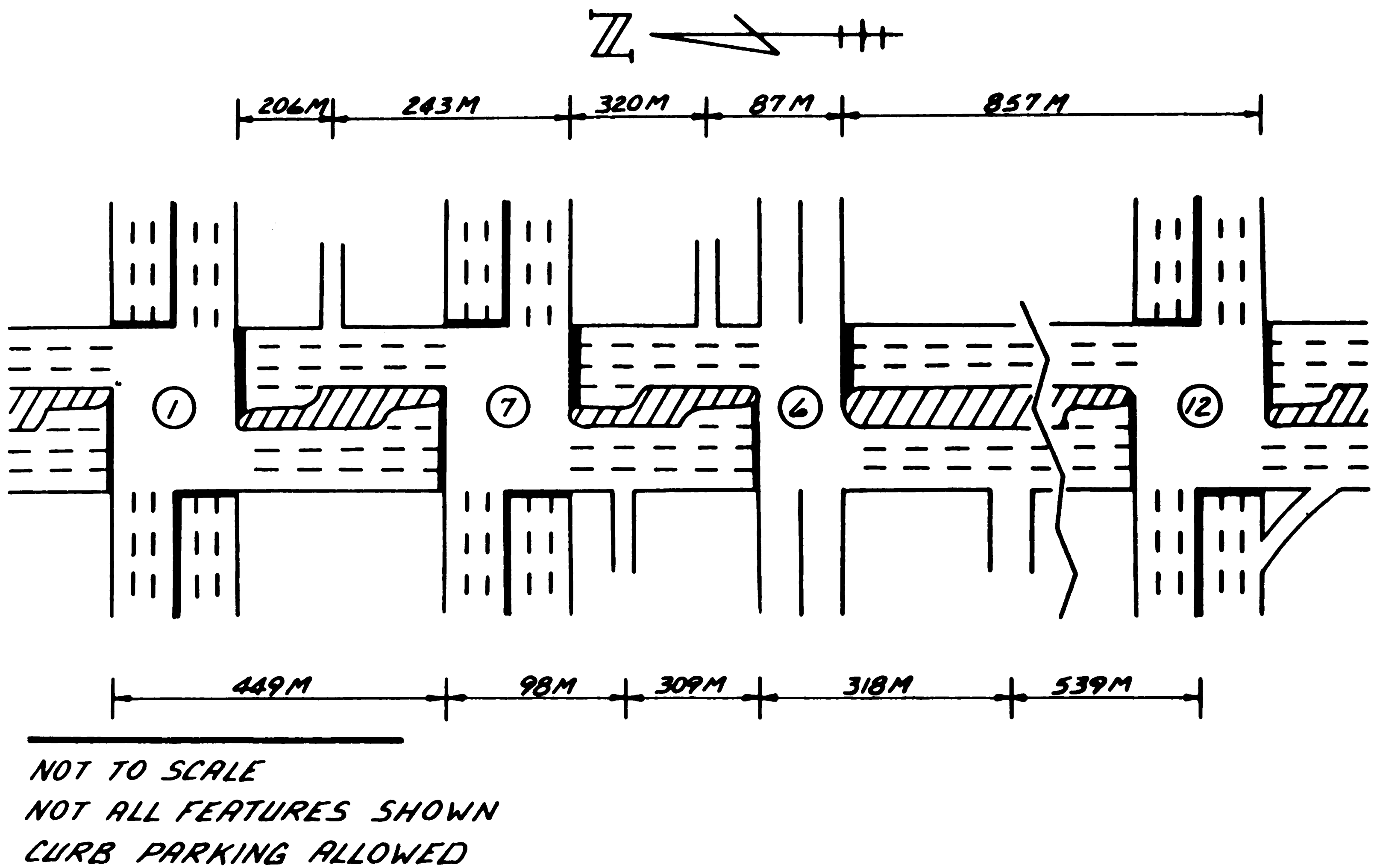
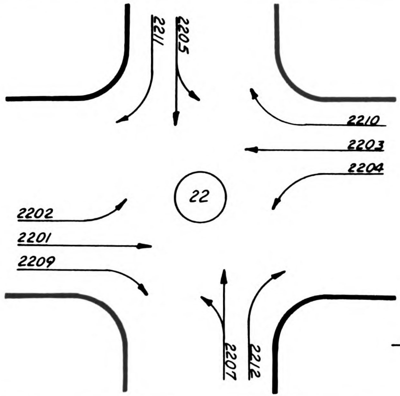


Figure A.2 Sketch of First Street (Dammam).



INTERSECTION #22 (AL-KHOBAR)

PHASE NUMBER	1	2	3	4
PHASE LENGTH (Sec.)	30	30	30	30
LINKS MOVING	2210	2202	2212	2205
	2203	2201	2207	2211
	2204	2209	2209	2210
	2212	2211		

Figure A.3 Typical phase sequence in the study area.

APPENDIX B

SPEED DATA

Table B.1 Speeds in the study area.

City	Intersections	Link Number	Direction	Number of speed samples	*Mean speed (KPH)	95% confidence interval
Dammam	12 - 6	9101	North	14	83	±1.8
Dammam	6 - 7	9201	North	14	66	±3.2
Dammam	7 - 1	9301	North	14	60	±1.8
Dammam	1 - 7	9403	South	14	65	±2.1
Dammam	7 - 6	9503	South	14	64	±2.1
Dammam	6 - 12	9603	South	14	82	±1.8

*: By floating car technique.

Table B.1 (cont'd.).

City	Intersections	Link Number	Direction	Number of speed samples	*Mean speed (KPH)	95% confidence interval
Al-Khobar	24 - 23	9401	North	12	64	±2.5
Al-Khobar	23 - 22	9201	North	12	63	±2.5
Al-Khobar	22 - 21	9001	North	12	66	±2.5
Al-Khobar	21 - 22	9103	South	12	66	±2.0
Al-Khobar	22 - 23	9303	South	12	64	±2.3
Al-Khobar	23 - 24	9503	South	12	64	±2.4

*: By floating car technique.

APPENDIX C

LISTING OF THE FORTRAN PROGRAMS USED IN THIS STUDY

```
*********************************************************************
*                                                                   *
*                              CALIB                                *
*                                                                   *
*********************************************************************
*     This is the program "CALIB".  It was used in the calibration *
*     process.                                                      *
*                                                                   *
*     Required input files;                                         *
*       1.   SCL: Includes scale (SCAL) for manually plotting the   *
*                 profiles, and the conversion factor (CONVF) to    *
*                 convert the simulated profile to number of        *
*                 vehicles observed in each interval of the cycle   *
*                 over the study period.                            *
*       2.   PRE: The simulated length of the vertical line ( # of  *
*                 vertical symbols) for each interval of the cycle  *
*                 and maximum link flow as reported by the TRANSYT  *
*                 model.  Also includes PDF value and link number.  *
*       3.   ACT: The observed number of vehicles in each interval  *
*                 over the study period.  Also includes data set    *
*                 name.                                             *
*                                                                   *
*     Output files;                                                 *
*       1.   DRO: For the program use.                              *
*       2.   OUT: The results.                                      *
*                                                                   *
*     Glossary;                                                     *
*       INTR:  Interval number.                                     *
*       NPVS:  Number of simulated symbols (simulated length of     *
*              the vertical line) of each interval.                 *
*       NPCR:  Number of simulated vehicles in each interval.       *
*       NACR:  Number of observed vehicles in each interval.        *
*       ABDF:  Absolute difference between NPCR & NACR.             *
*       SQDF:  The difference between NPCR & NACR squared.          *
*       ACT SCALE:  Scale for manually plotting the observed        *
*                   flow profile.                                   *
```

```
*       PRE SCALE:  Scale for manually plotting the simulated         *
*                   flow profile.                                      *
*       DIF SCALE:  Difference between the above two scales.          *
*       SUM ABS DIFF:  Sum of all ABDF.                               *
*       SUM SQU DIFF:  Sum of all SQDF.                               *
*       DIF IN DRAWN GRAPHS:  Sum of all DIF SCALE.                   *
**********************************************************************
**********************************************************************
      CHARACTER DATSET*14
      INTEGER PDF
      REAL*8 NPCR,SCAL,DF,ABDF,SMABDF,SQDF,SMSQDF,ASCAL,PSCAL,CONVF
      OPEN (1,FILE='SCL' ,STATUS='OLD')
      OPEN (2,FILE='PRE' ,STATUS='OLD')
      OPEN (3,FILE='ACT' ,STATUS='OLD')
      OPEN (4,FILE='OUT' ,STATUS='NEW')
      OPEN (5,FILE='DRO' ,STATUS='NEW')
**********************************************************************
      SCAL=0.0
      PDF=0
      MAXF=0
      LINK=0
      I=0
      K=0
      INTR=0
      NACR=0
      NPVS=0
      NPCR=0.0
      DF=0.0
      ABDF=0.0
      SMABDF=0.0
      SQDF=0.0
      SMSQDF=0.0
      ASCAL=0.0
      PSCAL=0.0
      SUMP=0.0
      ISUMA=0
```

```
*********************************************************************
      REWIND(1)
      REWIND(2)
      REWIND(3)
*********************************************************************
      READ(1,111,END=99)SCAL,CONVF
99    CONTINUE
      READ(2,222,END=88)PDF,MAXF,LINK
      READ(3,100)DATSET
      WRITE (4,100)DATSET
      WRITE(4,999)LINK,PDF,MAXF,SCAL
      WRITE(4,888)
*********************************************************************
      DO 1 I=1,24
           READ(2,444,END=88)NPVS
           READ(3,333,END=88)INTR,NACR
           NPCR=(MAXF*NPVS)/CONVF
           SUMP=SUMP+NPCR
           ISUMA=ISUMA+NACR
           DF=(NACR*1.00)-NPCR
           SDF=DF/SCAL
           ABDF=ABS(DF)
           SMABDF=SMABDF+ABDF
           SQDF=DF**2
           SMSQDF=SMSQDF+SQDF
           ASCAL=NACR/SCAL
           PSCAL=NPCR/SCAL
           WRITE(4,555)INTR,NPVS,NPCR,NACR,ABDF,SQDF,ASCAL,PSCAL,SDF
           WRITE(5,101)ASCAL,PSCAL
1     CONTINUE
88    CONTINUE
      WRITE(4,666)SMABDF,SMSQDF
      CLOSE(5,STATUS='KEEP')
      OPEN (5,FILE='DRO'  ,STATUS='OLD')
      REWIND(5)
      DO 7 K=1,24
```

```
      READ(5,102,END=77)IA,IP
      IDF=IA-IP
      IABS=ABS(IDF)
      ISUM=ISUM+IABS
7     CONTINUE
77    CONTINUE
      WRITE(4,103)ISUM
      WRITE(4,501)ISUMA
      WRITE(4,502)SUMP
*******************************************************************
14    CONTINUE
      CONTINUE
*******************************************************************
101   FORMAT(2F10.0)
102   FORMAT(I9,1X,I9)
103   FORMAT(/2X,'DIF IN DRAWN GRAPHS = ',I9)
100   FORMAT(1X,A14)
111   FORMAT(2F16.9)
222   FORMAT(3I6)
333   FORMAT(2I6)
444   FORMAT(I6)
501   FORMAT(///2X,'NUMBER OF OBSERVED CARS = ',I6)
502   FORMAT(2X,'NUMBER OF PREDICTED CARS = ',F8.0)
555   FORMAT(2I5,F9.2,I6,2F10.2,3F10.0)
666   FORMAT(//2X,'SUM ABS DIFF =',F12.0
     +,//2X,'SUM SQU DIFF =',F10.0)
888   FORMAT(/1X,'INTR',2X,'NPVS',3X,'NPCR'
     +,3X,'NACR',5X,'ABDF',6X,'SQDF',3X,'ACT SCALE',3X,'PRE SCALE'
     +,3X,'DIF SCALE')
999   FORMAT(1X,'LINK # ',I6,/1X,'PDF',I6,/1X,'MAX FLOW',I6
     +,/1X,'SCALE USED : 1/8 inch represents',F12.9,'  vehicles')
      STOP
      END
*******************************************************************
*******************************************************************
*                      END OF PROGRAM "CALIB"                     *
```

```
*********************************************************************
*                                                                   *
*                              LONG                                 *
*                                                                   *
*********************************************************************
*     This the program "LONG".  It was used for changing the        *
*     length all of links.                                          *
*                                                                   *
*      Input files;                                                 *
*          1.  MFOL:  The factor which multiplies the original      *
*                     length of links.                              *
*          2.  ODAT:  The original TRANSYT-7F data.                 *
*                                                                   *
*      Output files;                                                *
*          1.  RDAT:  For the program use.                          *
*          2.  NDAT:  The results (new data set for TRANSYT-7F).    *
*********************************************************************
      CHARACTER TITLE*80
      INTEGER PDF,I1,I2,I3,I4,I5,I6,I7,I8,I9,I10,
     +I11,I12,I13,I14,I15,I16
      REAL*8 LMF,R3
      OPEN (1,FILE='MFOL' ,STATUS='OLD')
      OPEN (2,FILE='ODAT' ,STATUS='OLD')
      OPEN (3,FILE='RDAT' ,STATUS='NEW')
*********************************************************************
      LMF=0.0
      REWIND(1)
      REWIND(2)
*********************************************************************
      CONTINUE
      READ(1,222,END=22)LMF
22    CONTINUE
      READ(2,111,END=11)TITLE
      WRITE(3,111)TITLE
4     CONTINUE
      CONTINUE
```

```
      I1=0
      I2=0
      I3=0
      I4=0
      I5=0
      I6=0
      I7=0
      I8=0
      I9=0
      I10=0
      I11=0
      I12=0
      I13=0
      I14=0
      I15=0
      I16=0
      R1=0.0
      R2=0.0
      R3=0.0
      R4=0.0
      R5=0.0
      R6=0.0
      R7=0.0
      R8=0.0
      R9=0.0
      R10=0.0
      R11=0.0
      R12=0.0
      R13=0.0
      R14=0.0
      R15=0.0
      R16=0.0
    CONTINUE
    READ(2,333,END=11)I1,I2,I3,I4,I5,I6,I7,I8,I9,I10,
   +I11,I12,I13,I14,I15,I16
    CONTINUE
```

```
      IF(I1 .EQ. 28 .OR. I1 .EQ. -28)THEN
              R3=LMF*(1.0*I3)
      ELSE
              R3=1.0*I3
      END IF
      CONTINUE
          R1=1.0*I1
          R2=1.0*I2
          R4=1.0*I4
          R5=1.0*I5
          R6=1.0*I6
          R7=1.0*I7
          R8=1.0*I8
          R9=1.0*I9
          R10=1.0*I10
          R11=1.0*I11
          R12=1.0*I12
          R13=1.0*I13
          R14=1.0*I14
          R15=1.0*I15
          R16=1.0*I16
      CONTINUE
        WRITE(3,444)R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,
     +R12,R13,R14,R15,R16
      CONTINUE
      GO TO 4
11    CONTINUE
      CONTINUE
      CLOSE(1,STATUS='KEEP')
      CLOSE(2,STATUS='KEEP')
      CLOSE(3,STATUS='KEEP')
      OPEN (4,FILE='NDAT' ,STATUS='NEW')
      OPEN (3,FILE='RDAT' ,STATUS='OLD')
      REWIND(3)
      CONTINUE
      READ(3,111,END=77)TITLE
```

```
      WRITE(4,111)TITLE
88    CONTINUE
      I1=0
      I2=0
      I3=0
      I4=0
      I5=0
      I6=0
      I7=0
      I8=0
      I9=0
      I10=0
      I11=0
      I12=0
      I13=0
      I14=0
      I15=0
      I16=0
      R1=0.0
      R2=0.0
      R3=0.0
      R4=0.0
      R5=0.0
      R6=0.0
      R7=0.0
      R8=0.0
      R9=0.0
      R10=0.0
      R11=0.0
      R12=0.0
      R13=0.0
      R14=0.0
      R15=0.0
      R16=0.0
      READ(3,444,END=77)R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,
     +R11,R12,R13,R14,R15,R16
```

```
      I1=R1
      I2=R2
      I3=R3
      I4=R4
      I5=R5
      I6=R6
      I7=R7
      I8=R8
      I9=R9
      I10=R10
      I11=R11
      I12=R12
      I13=R13
      I14=R14
      I15=R15
      I16=R16
      WRITE(4,333)I1,I2,I3,I4,I5,I6,I7,I8,I9,I10,
     +I11,I12,I13,I14,I15,I16
      GO TO 88
77    CONTINUE
      CONTINUE
      CLOSE(3,STATUS='DELETE')
      CLOSE(4,STATUS='KEEP')
**********************************************************************
111   FORMAT(1X,A80)
222   FORMAT(F10.3)
333   FORMAT(16I5)
444   FORMAT(16F6.0)
      STOP
      END
**********************************************************************
**********************************************************************
*                       END OF PROGRAM "LONG"                        *
**********************************************************************
```

APPENDIX D

GRAPHS OF "SUM OF ABSOLUTE DIFFERENCES VS. PDF VALUES"

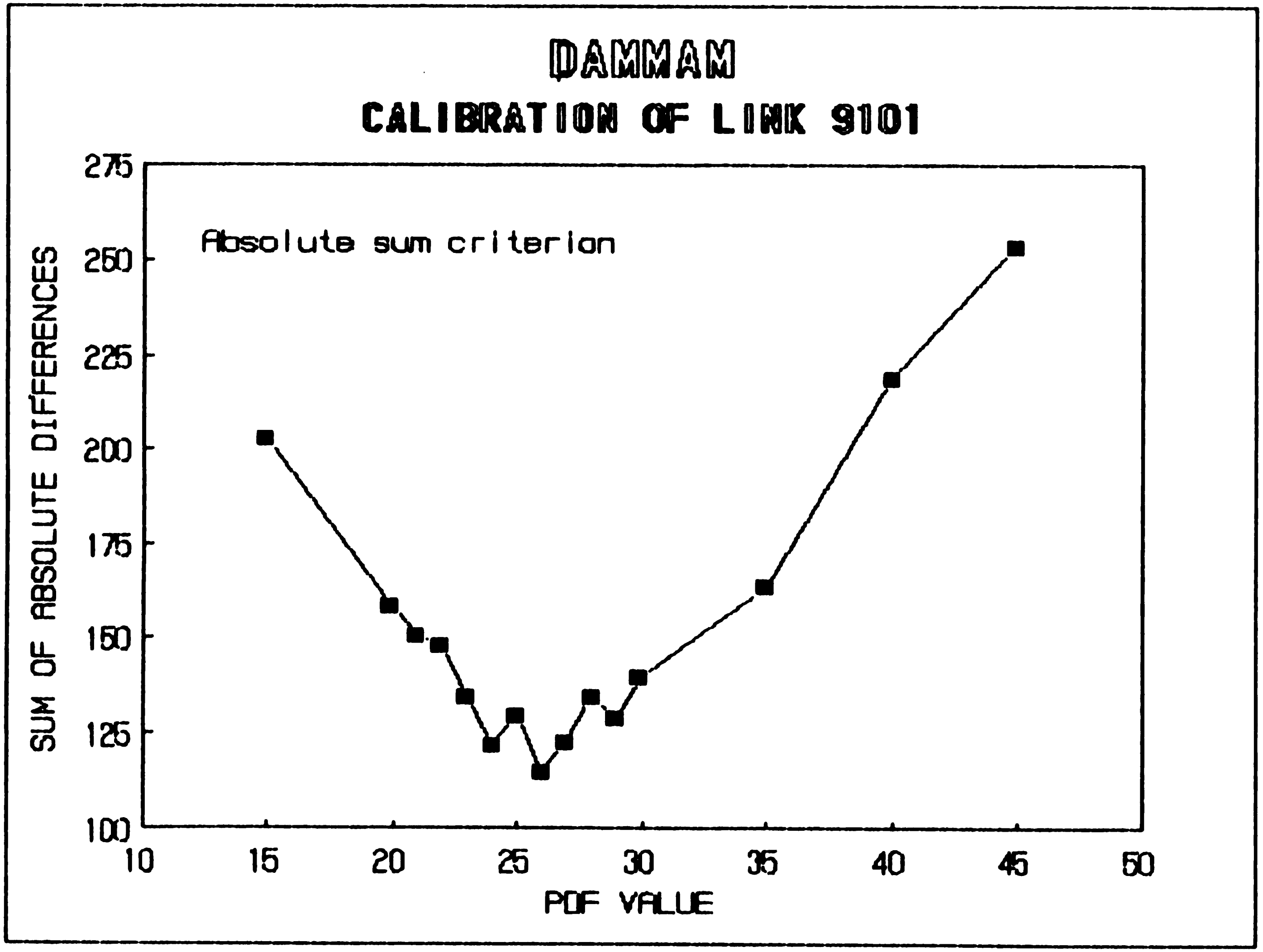


Figure D.1 Calibration of link 9101, Dammam.

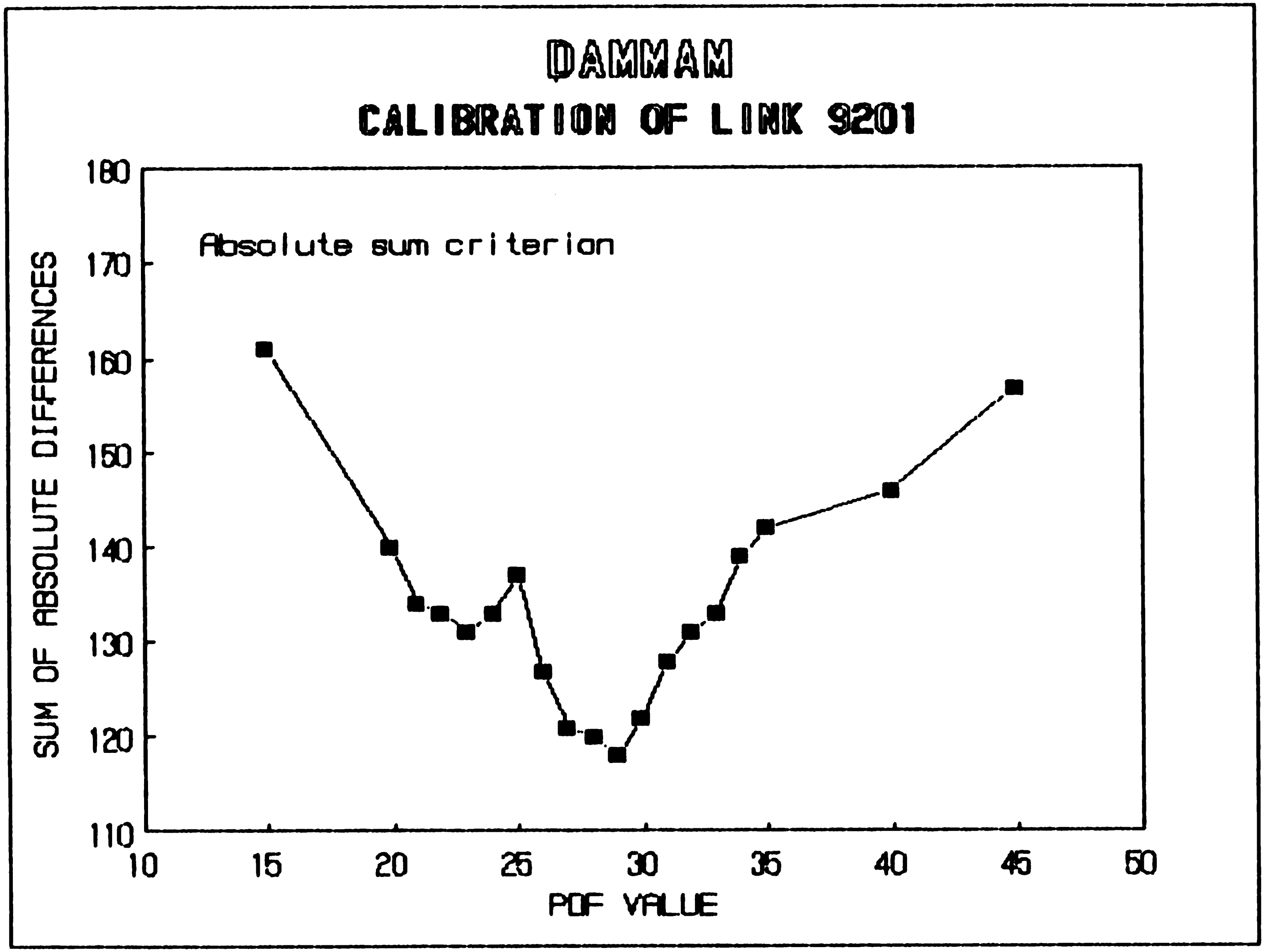


Figure D.2 Calibration of link 9201, Dammam.

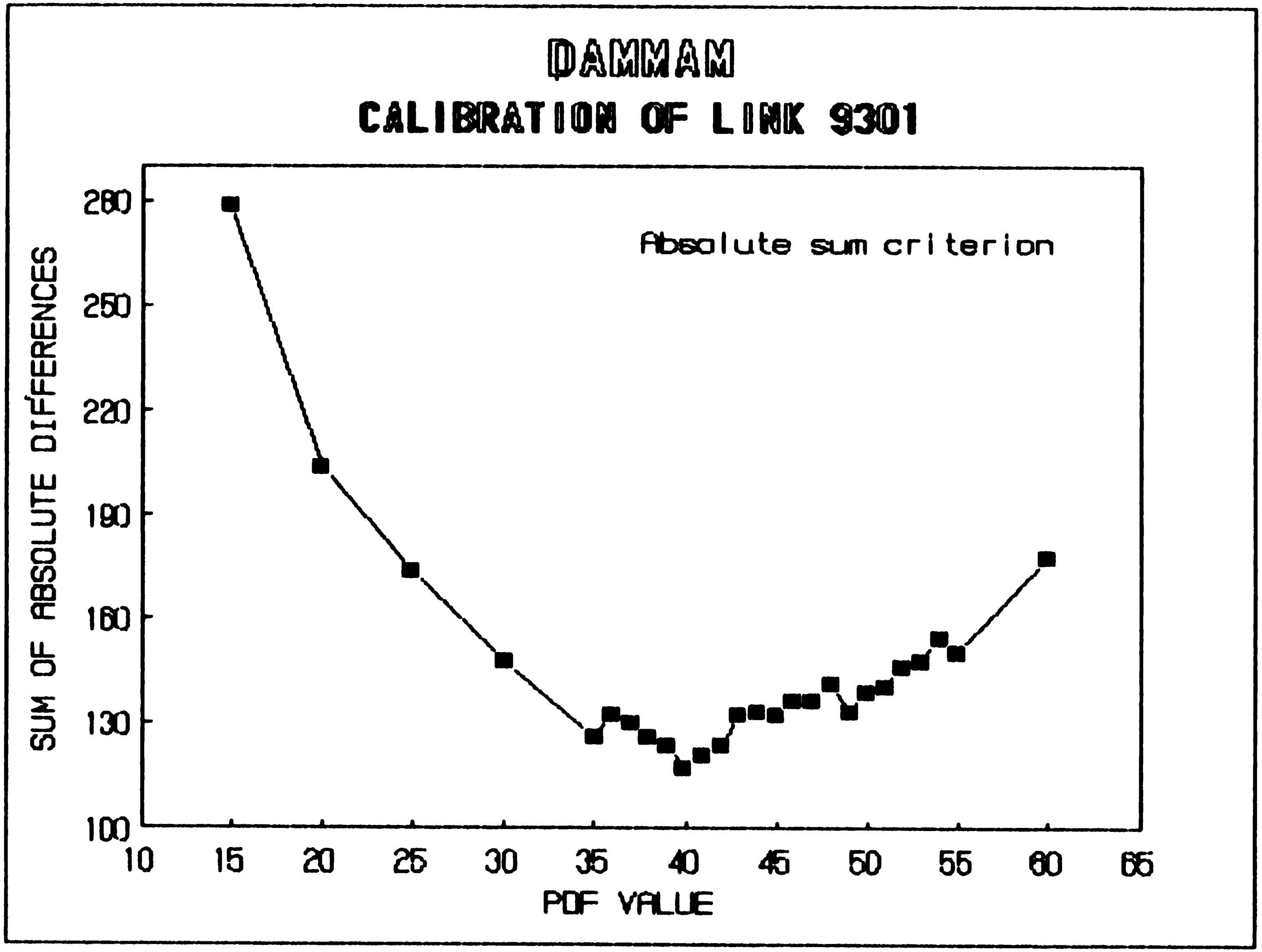


Figure D.3 Calibration of link 9301, Dammam.

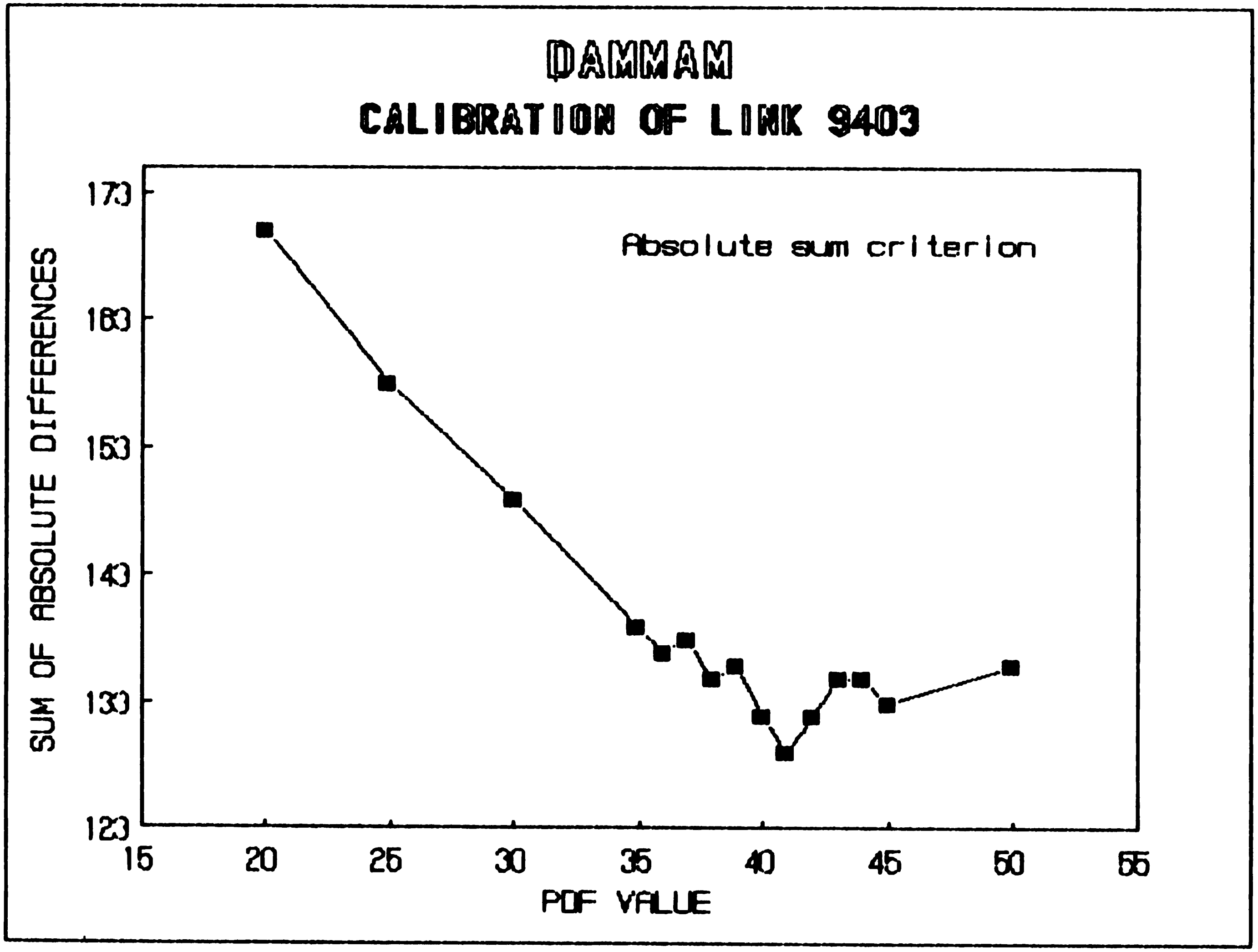


Figure D.4 Calibration of link 9403, Dammam.

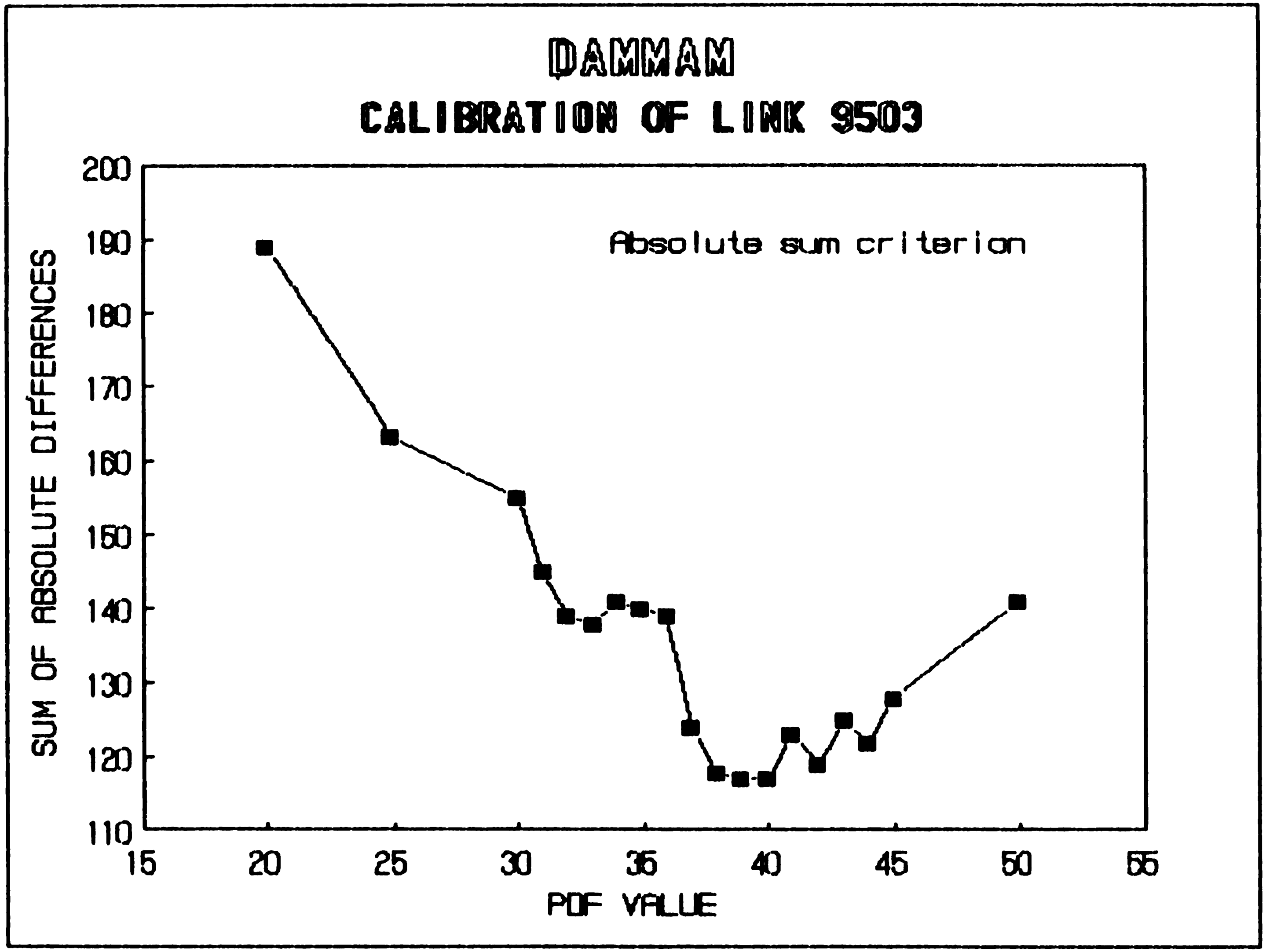


Figure D.5 Calibration of link 9503, Dammam.

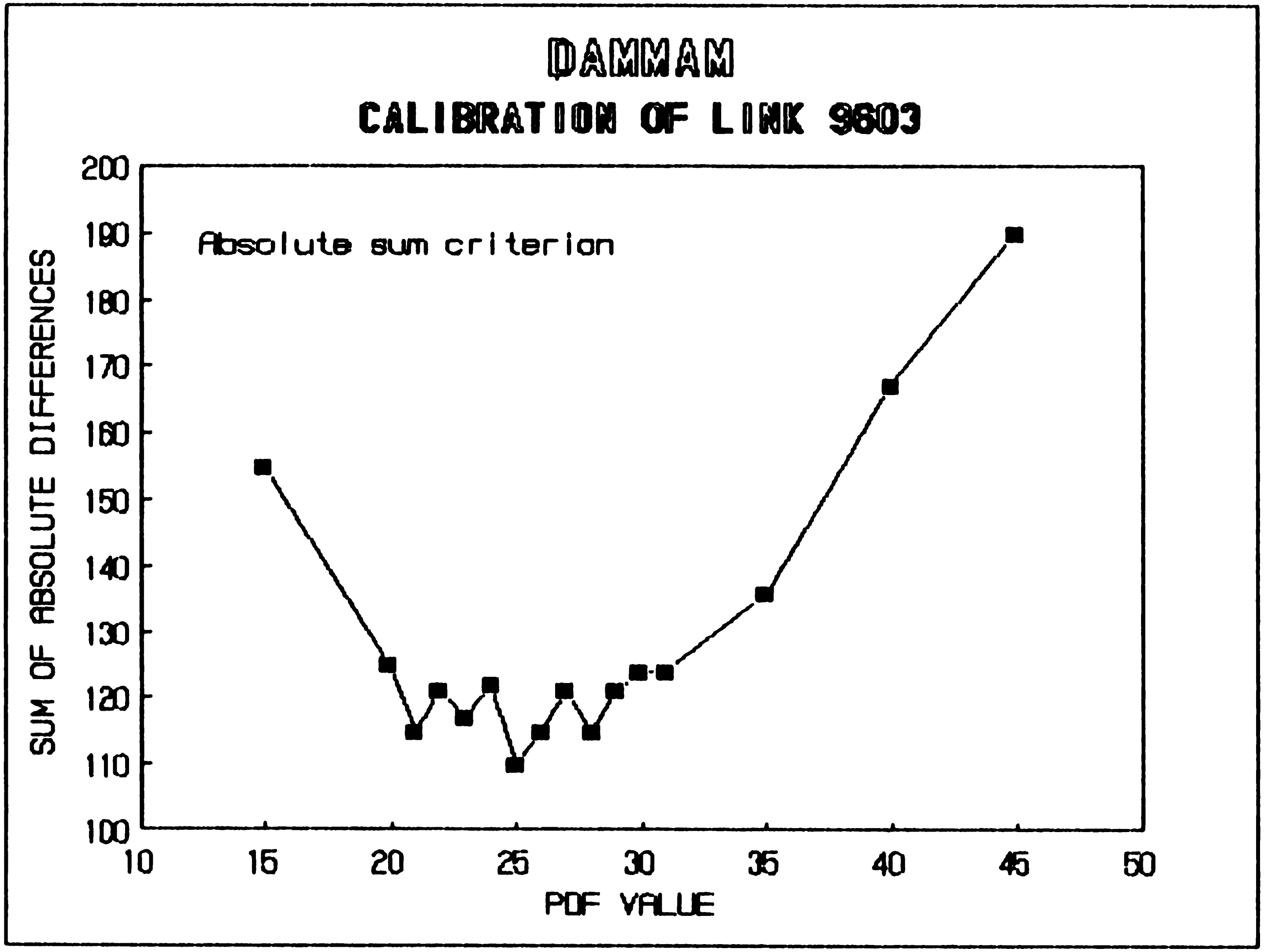


Figure D.6 Calibration of link 9603, Dammam.

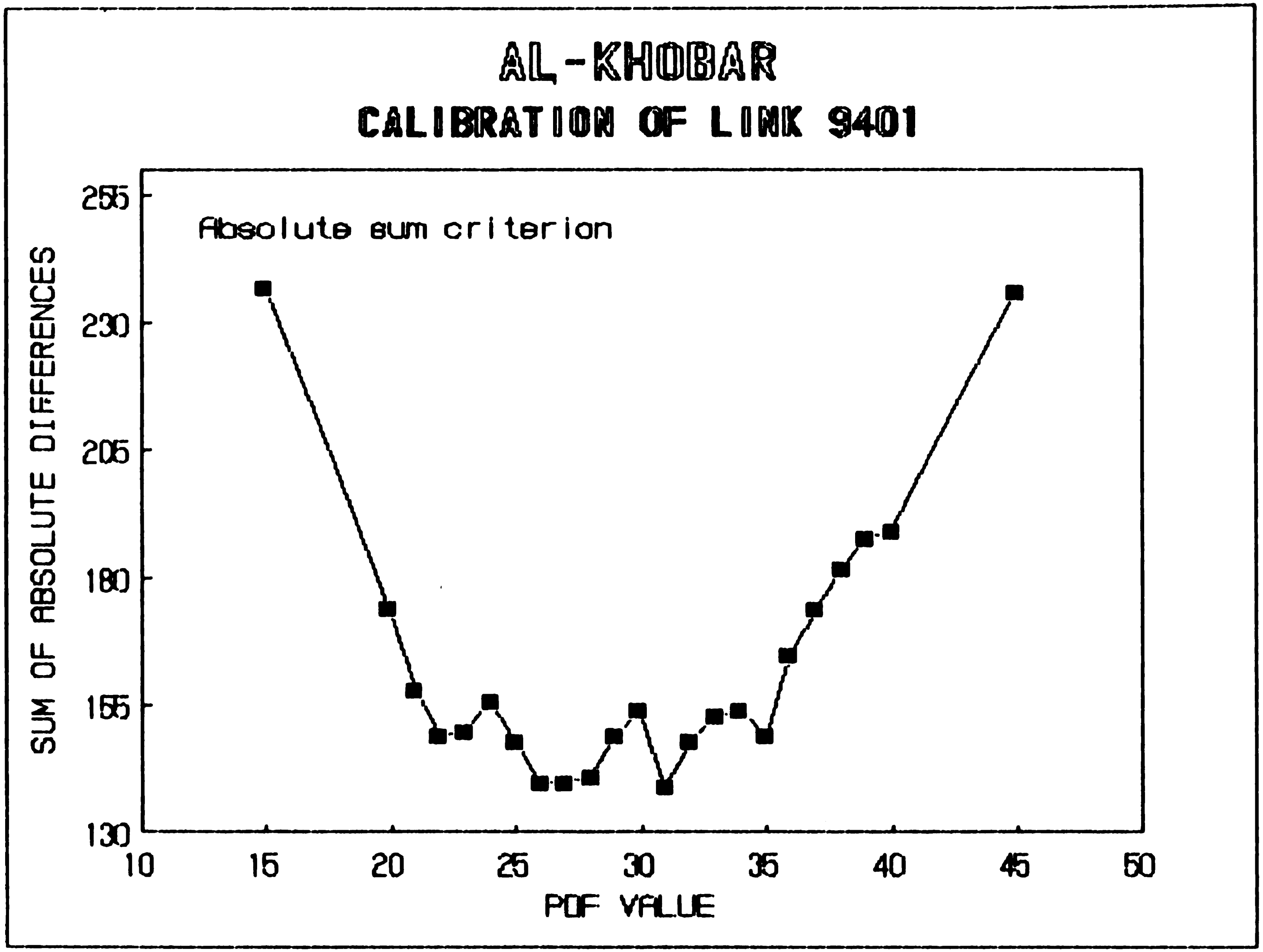


Figure D.7 Calibration of link 9401, Al-Khobar.

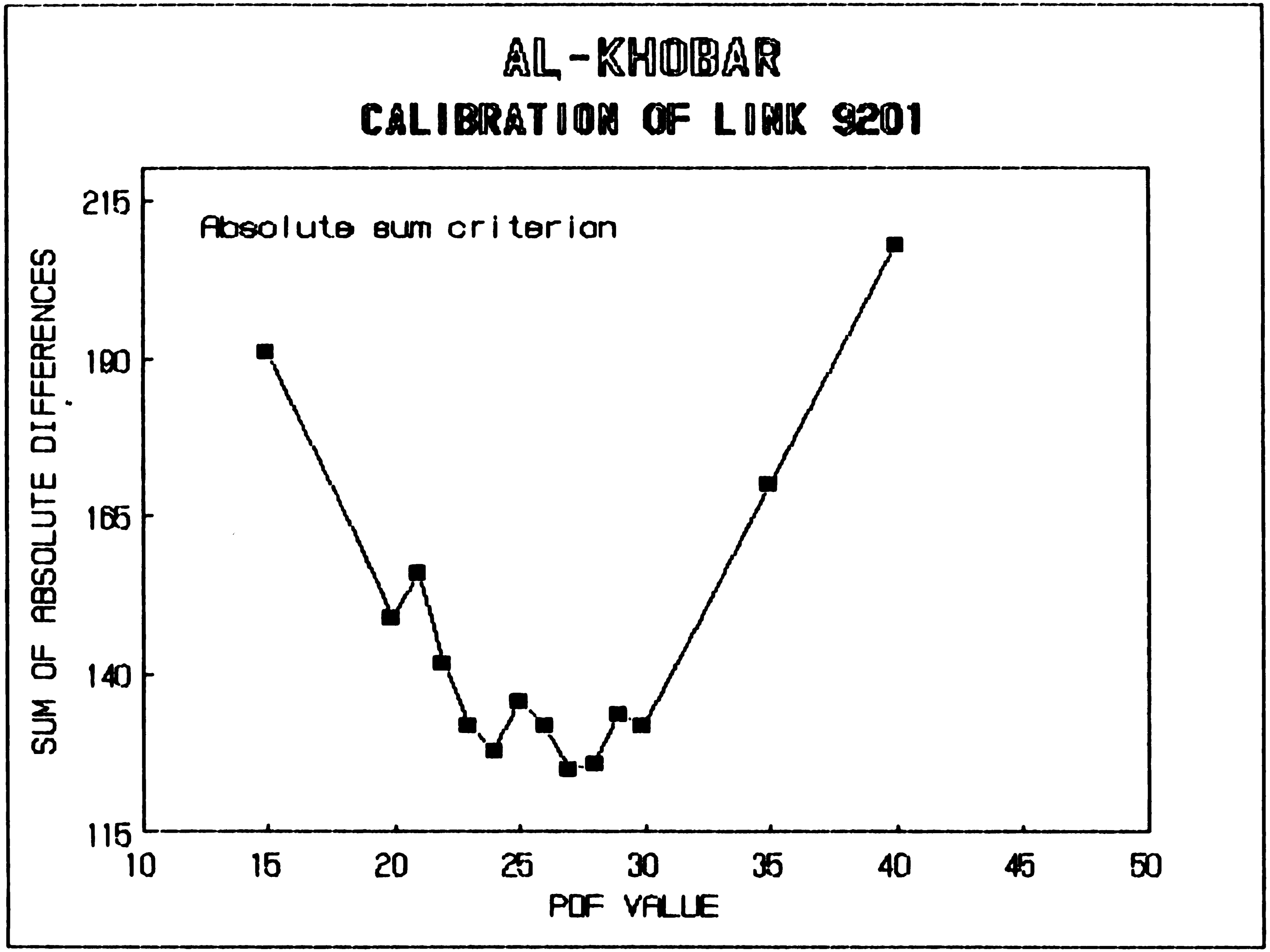


Figure D.8 Calibration of link 9201, Al-Khobar.

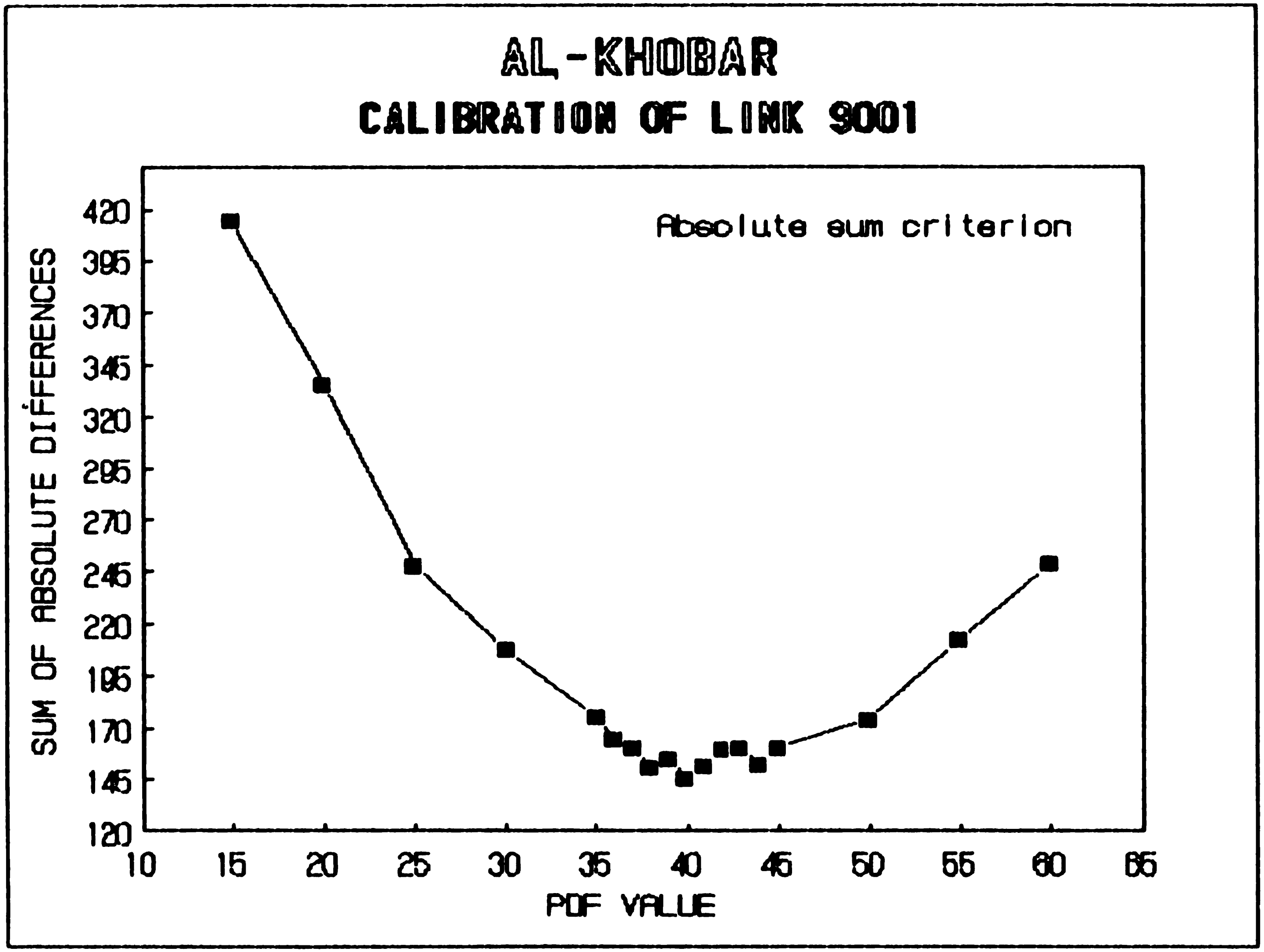


Figure D.9 Calibration of link 9001, Al-Khobar.

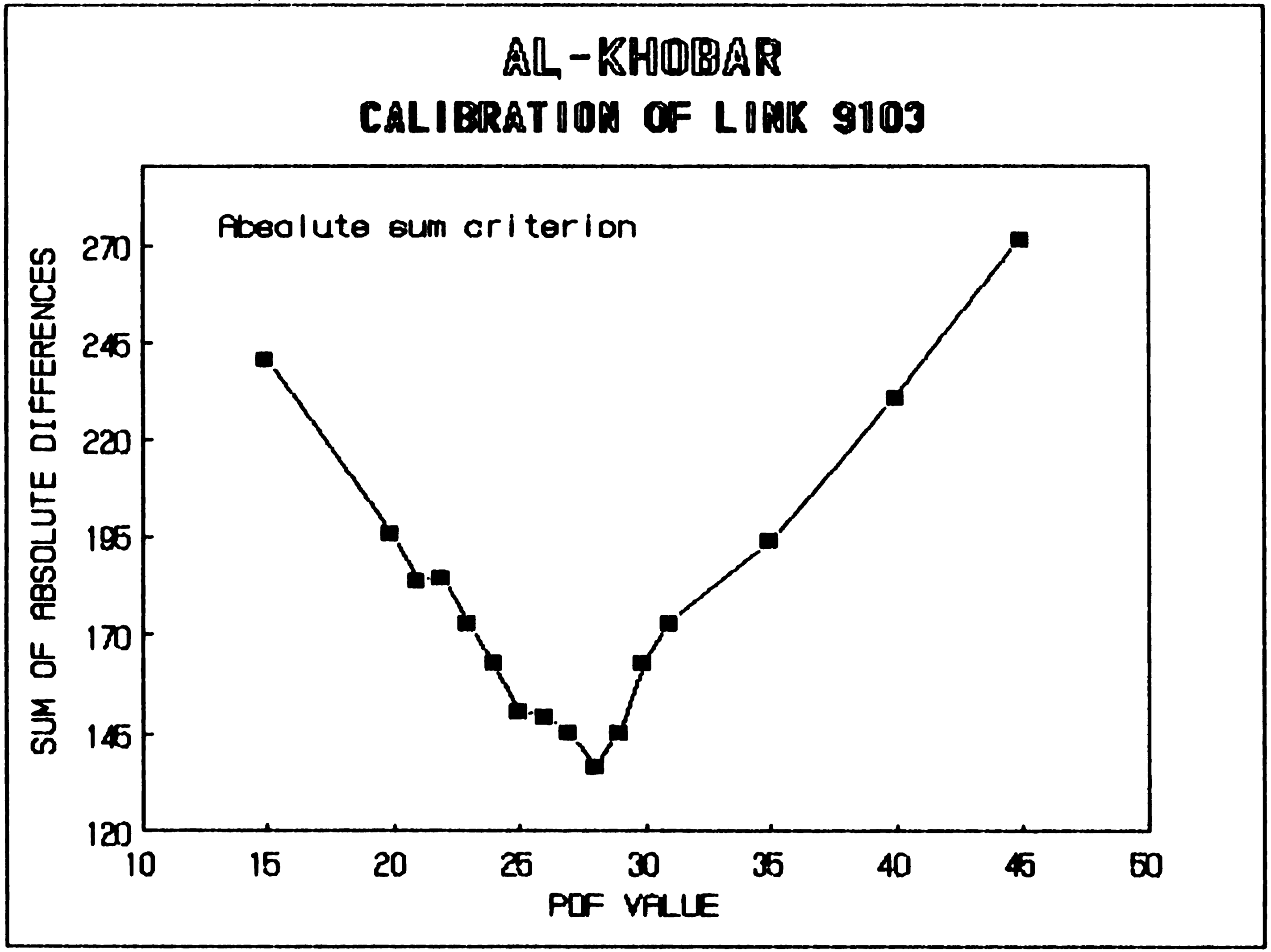


Figure D.10 Calibration of link 9103, Al-Khobar.

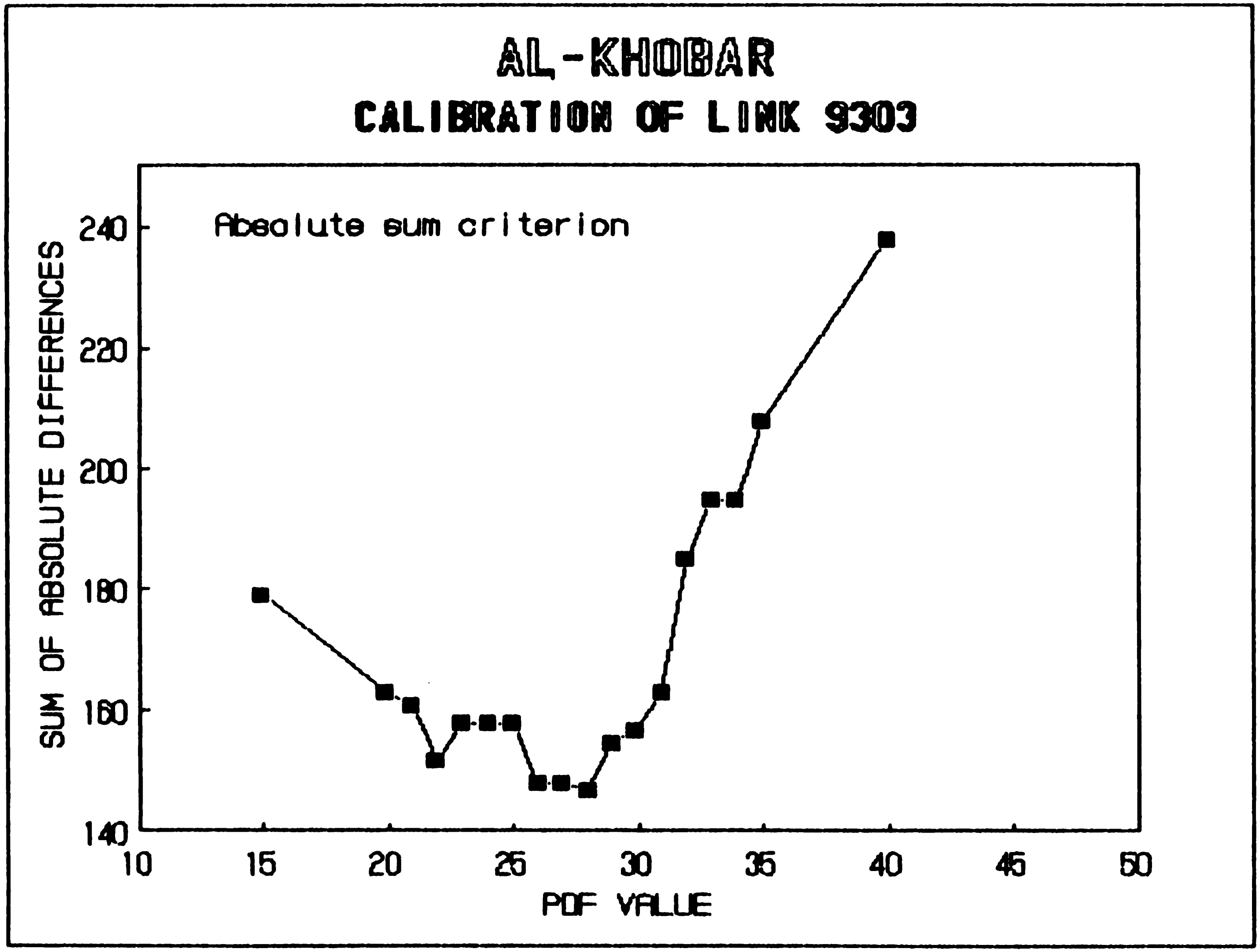


Figure D.11 Calibration of link 9303, Al-Khobar.

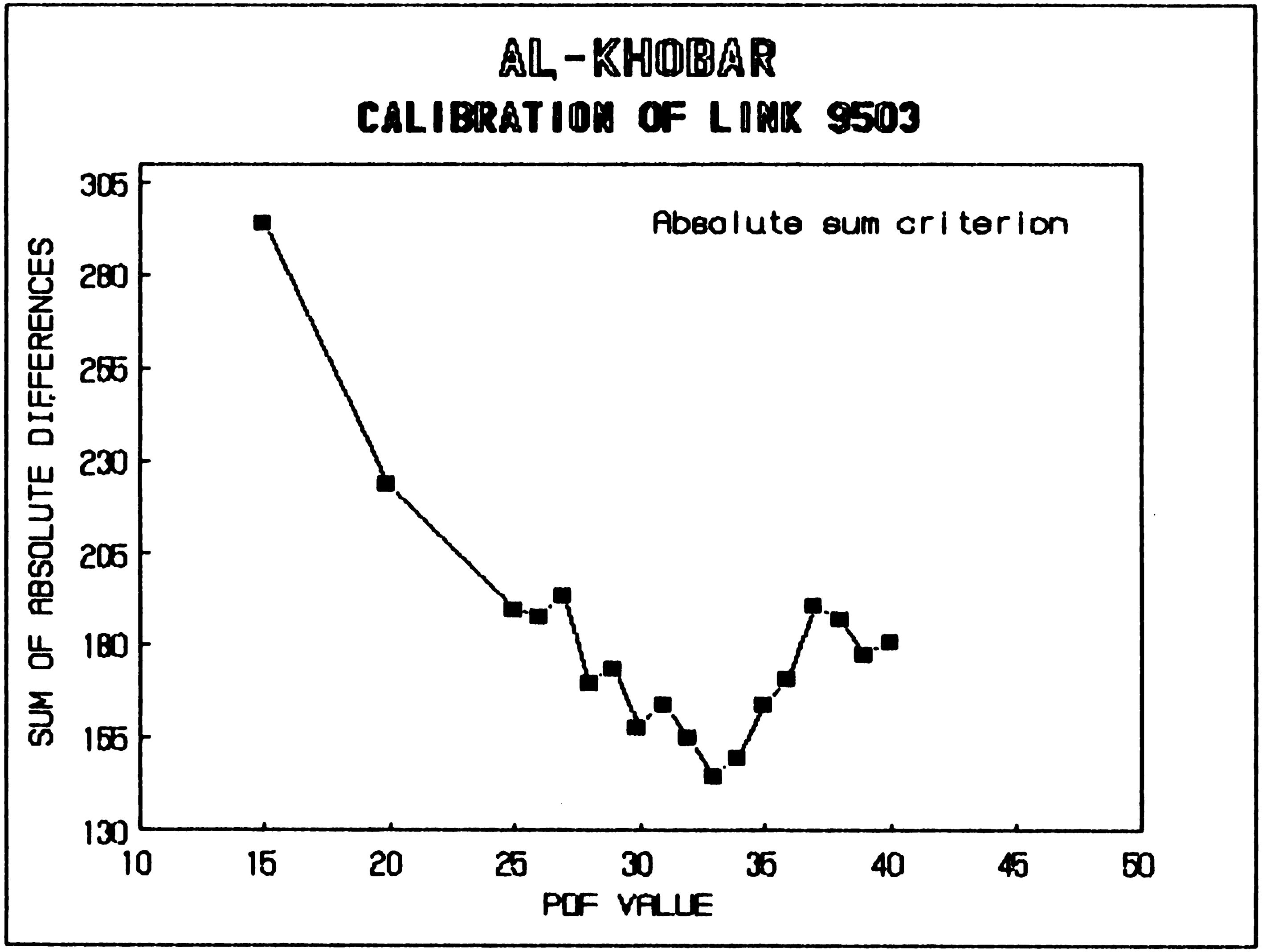


Figure D.12 Calibration of link 9503, Al-Khobar.

APPENDIX E

TIME-SPACE DIAGRAMS

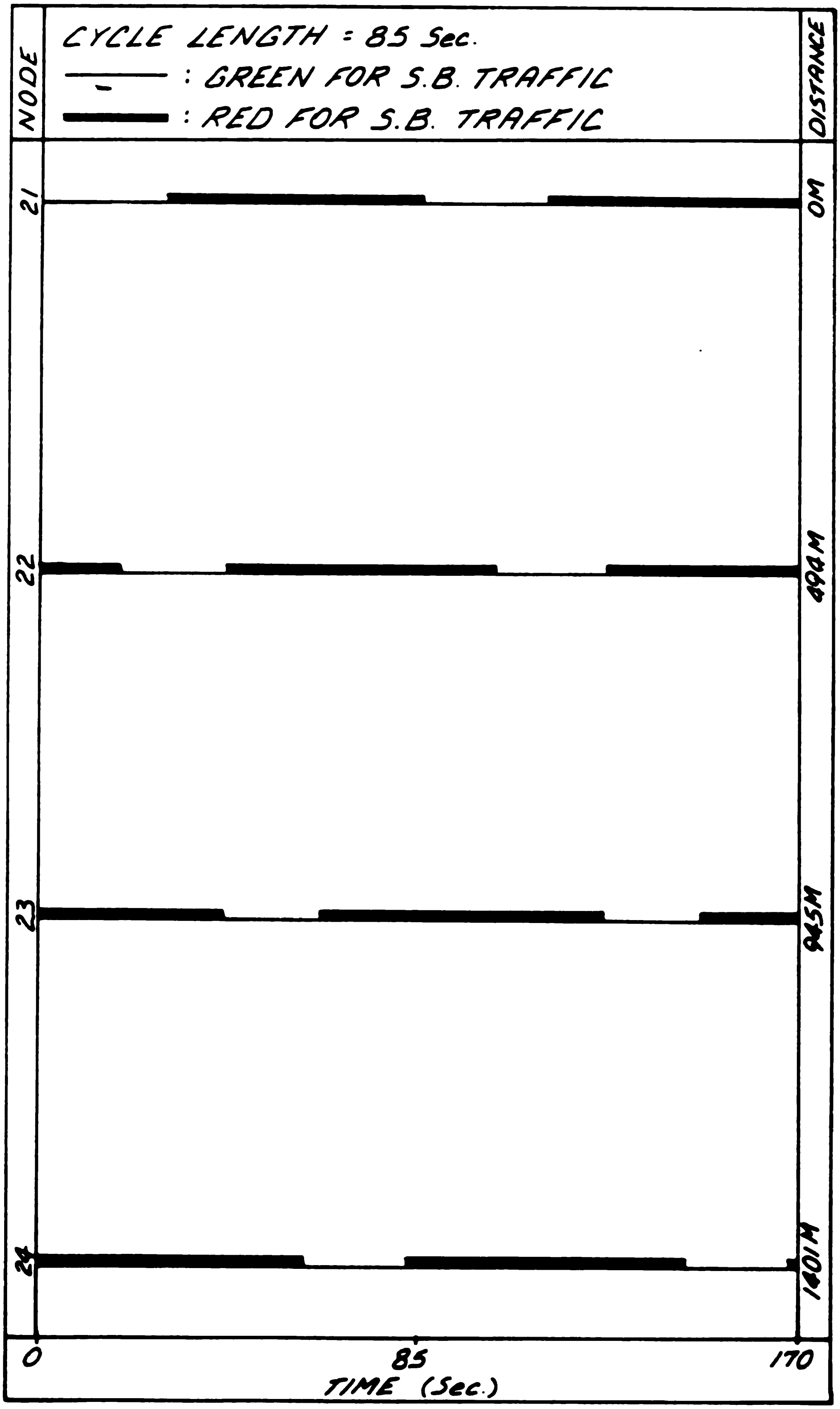


Figure E.1 Optimal time-space diagram for the linear network.
(a) Southbound traffic along Al-Khobar arterial.

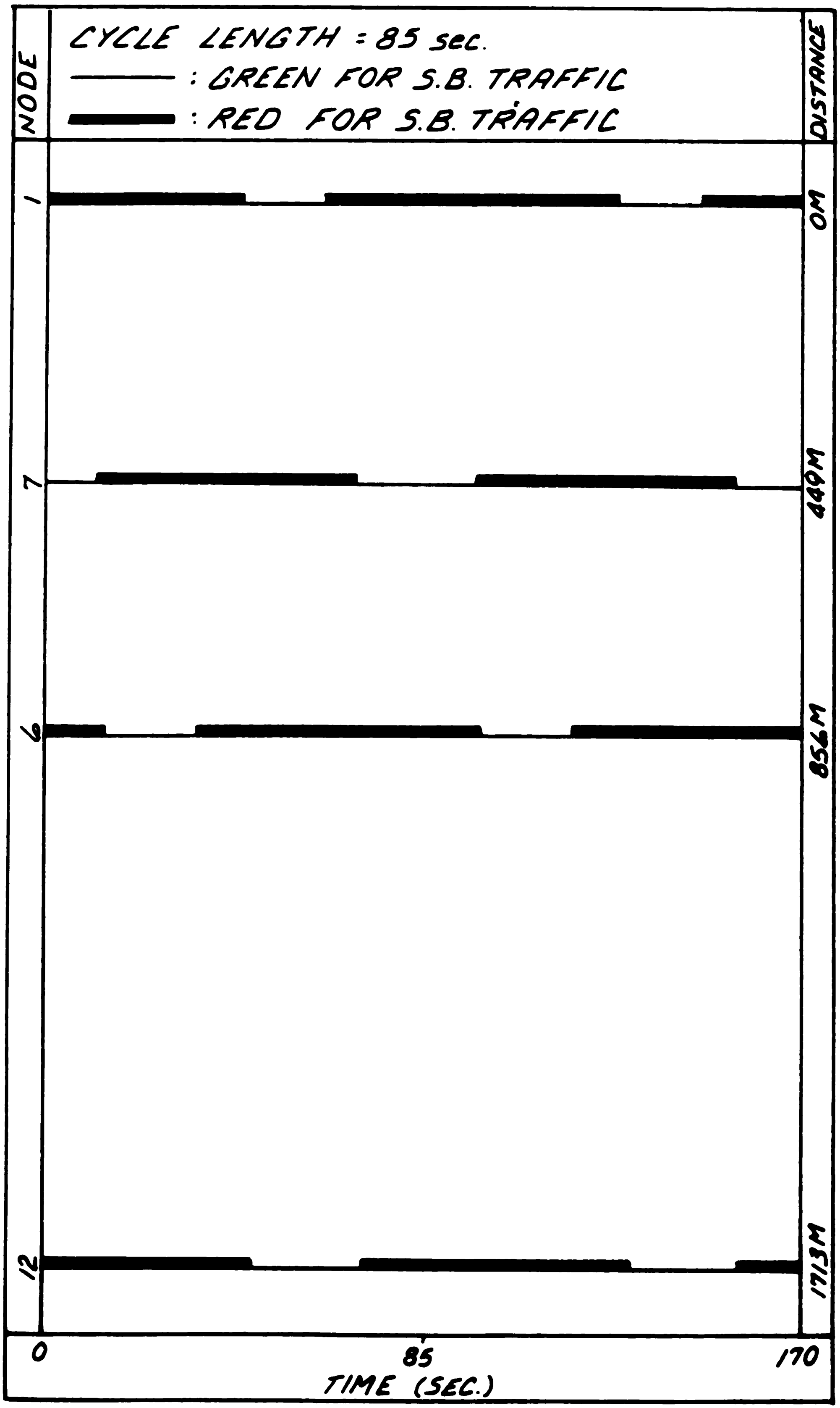


Figure E.1 (cont'd.).
(b) Southbound traffic along Dammam arterial.

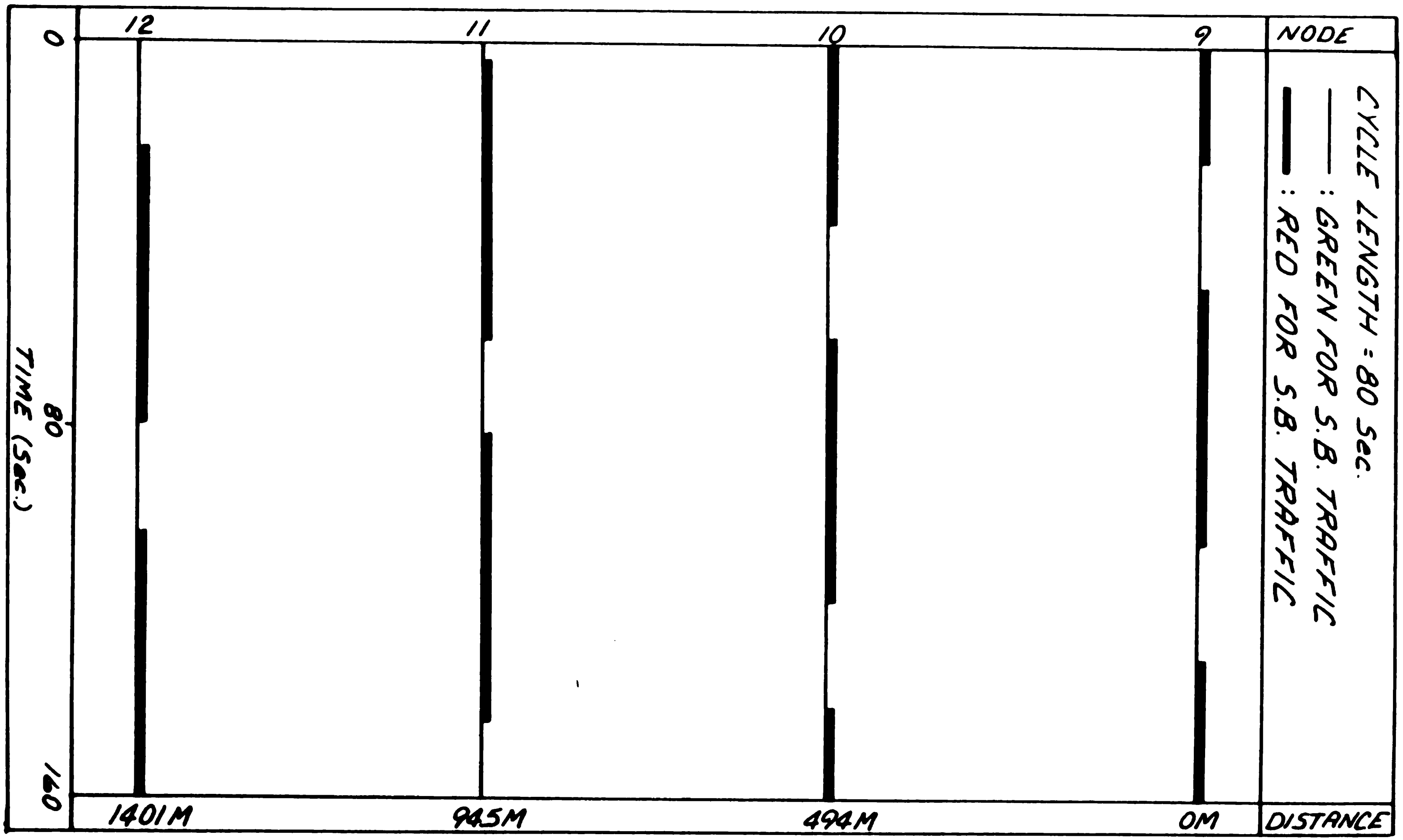


Figure E.2 Optimal time-space diagram for the two-dimensional network.
(a) Southbound traffic along Al-Khobar arterial.

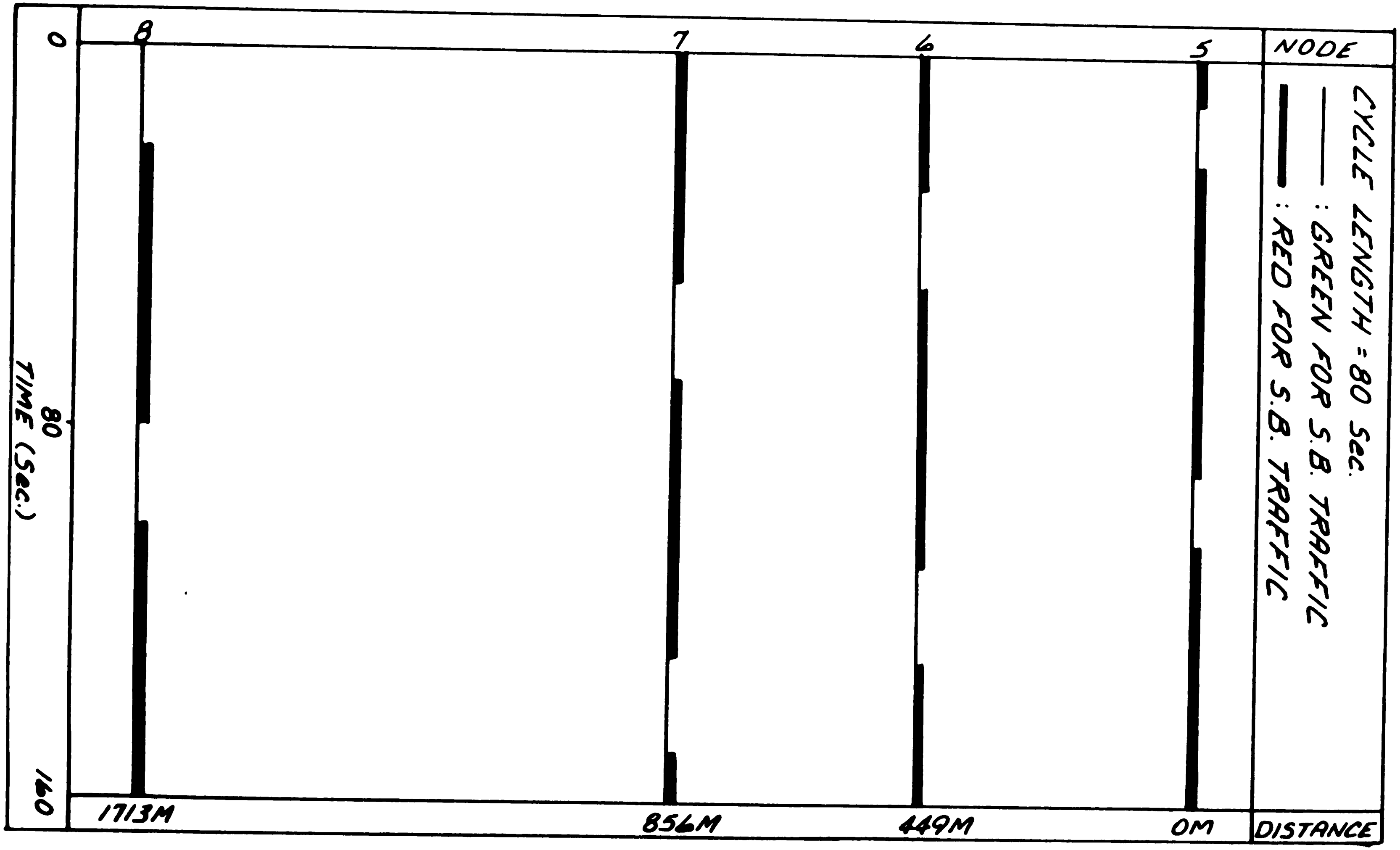


Figure E.2 (cont'd.).
(b) Southbound traffic along Dammam arterial.

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