AN ENERGY INVESTIGATION OF SIGNALIZED NETWORK OPTIMIZED BY TRANSYT 7

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CHAPTER 1

INTRODUCTION

This thesis examines the effect of various signal timing plans on the energy consumption of two signalized traffic networks. Also examined are the relationships of delay and stops to fuel consumption.

1.1 Review of the Energy Situation

In the fall of 1973 the Arab oil embargo brought to the attention of the world the seriousness of the energy crisis. At that time people began to realize that their energy supplies were limited and that they could not continue to use energy in the carefree manner they had been accustomed to. Here, in the United States, perhaps the shock was greater since a large amount of our development in urban areas had been centered around the automobile and an inexpensive, plentiful supply of gasoline. A 20-25 mile ride to work was of little concern when people were deciding where to live. The added costs of commuting for such trips were far outweighed by the benefits of suburban living.

Along with the growth and movement of population to the suburbs came the decline of the mass transit systems. The transit systems were no longer able to serve effectively. Most travel was being accomplished by private automobile. This shift in mode caused transit systems to lose revenue and consequently to reduce service. It produced a vicious cycle of loss of ridership, loss of revenue, poorer service, continued loss of ridership; etc. The mass transit systems in this country have moved from a profit making industry to a highly subsidized public service. Even after much investment by federal, state and local governments, the mass transit systems can effectively serve only a small percentage of the trips made today.

The oil embargo of 1973 highlighted the energy crisis, but the problem had been developing for some time. From 1947 to 1976 the annual energy consumption for the United States had increased in all but five of these years [1]. In the five years that consumption decreased, four were recession years. The average annual rate of growth of energy consumption was 3.2 percent for the period 1947-73. For 1973-74 there was a 2.8 percent decrease, and for 1974-75, a 2.4 percent decrease. Before 1974, there had been a 20 year period of continuous growth in gross energy consumption. With the combination of the oil embargo and a recession, the trend was reversed in 1974 and 1975. However, in 1976 consumption was 4.8 percent higher than 1975. These figures are presented in Table 1.1.

Since the oil embargo there has been a much greater concern for our energy supplies and ways in which they may be conserved. One area of particular interest is the conservation of energy in the transportation sector. "Nationally, transportation represents about 26% of the total U. S. energy consumption and 58% of the petroleum consumption" [2]. In the transportation sector, passenger travel by automobile accounts for 69 percent of the transportation petroleum consumption [3].

Internationally, the United States consumes 31% of the world's oil usage while having only six percent of the world's population [2].

TABLE 1.1 - United States Gross Energy Consumption For Selected Years

Year	Gross Energy Inputs (Quadrillion BTU)	Average Annual Growth Rate (Percent)
1950	34.0	-
1955	39.7	3.1
1960	44.6	2.3
1965	53.3	3.6
1970	67.4	4.8
1975	70.6	0.9
1976	74.0	4.8

Source: Dupree, W. G., "The United States Energy Scene 1976-85" Effects of Energy Constraints on Transportation Systems, Proceedings of the Fourth National Conference Held at Union College.

"Usually left unsaid is that the United States produces about 30 percent of the world's Gross National Product, and it is not pure happenstance that the proportion of world energy use and the proportion of world Gross National Product are similar" [4]. If the United States is going to continue to produce a large share of the world's goods and provide jobs for its citizens, it will have to continue to consume large amounts of energy. It takes energy to provide jobs.

Even though the United States is in an energy shortage, it is not energy poor. It is estimated that the United States has nearly one-third of the world's coal, enough to last for centuries [4]. The shale beds of the Rocky Mountains contain more oil than all of the Arab nations in the Middle East. "The dissolved methane contained in geopressured water strata underlying the northern Gulf of Mexico and coastal regions of Louisiana and Texas is estimated at as much as 50 thousand trillion cubic feet - much more than all the conventional natural gas so far discovered" [4]. There is enough Uranium in this country to fuel all present and future planned nuclear reactors for their 40-year life span. There is a potential ten to twenty trillion dollars worth of Uranium 238 presently stored in this country. In the absence of development in breeder reactor technology in the United States, the Uranium 238 has no value but has costs as a waste product [4].

The problem being faced today is that oil and gas represent only six percent of our total energy resources, but account for 75 percent of current energy usage [4]. It is also expected that world oil production will peak near the end of this century [5]. The Electric Power Research Institute estimates that new technologies such as solar, geothermal, wind, ocean thermal gradients, biomass, and nuclear fusion will account for only about 10 percent of the total U. S. energy supply at the turn of the century. Present oil production techniques recover only about one-third of the oil from the reservoir. It is possible to increase the output from existing wells with new, more costly methods of production.

Increased government regulation in the energy field is perhaps creating more problems than it is solving. Floyd Lewis of Middle South Utilities, Inc. gives an illustration of government regulation with respect to coal that occured some time back.

> Simultaneously, three congressional groups were meeting: the first, with respect to the Fuel Use Act, which mandates the use of coal for generating electricity; the second, on the Strip Mining bill, which makes it virtually impossible to mine some substantial coal reserves and extremely difficult and costly with respect to other reserves; and the third group, on the Clean Air Act amendments, which make it virtually impossible to use large quantities of U. S. coal, particularly that with high sulfur content, even if you are able to mine it under the other laws. The Congress passed all three laws [4].

One of the factors that will affect the future supplies of energy will be the cost. At present prices, many of the previously mentioned energy sources are uneconomical to produce. Many economists and oil experts believe that if the government removed all regulations on pricing, supplies of energy would be plentiful. The price of energy also appears to be the greatest factor influencing people to conserve. In

1979 and early 1980, there was a drastic increase in the price of gasoline. This price increase and uncertain supplies contributed to 1979 gasoline consumption dropping 400,000 barrels a day, or roughly 5 percent below 1978 figures. Through the first two months of 1980 gasoline use was down 4.2 percent [5].

Unless there is a major breakthrough in developing a new energy source, the United States will continue to be very dependent on oil as a major energy source. This dependence on an uncertain supply and the ever increasing cost of energy make it necessary to conserve whenever and however possible.

1.2 Organization

The goals and objectives of this thesis are presented in the second chapter. Chapter Three gives a review of some of the literature involving energy consumption and traffic signalization. A description of the two computer programs used, and the two networks analyzed are presented in Chapter Four. Chapter Five contains the analysis of the data. Chapter Six presents conclusions and recommendations.

CHAPTER 2

GOALS AND OBJECTIVES

2.1 Background

In the traffic engineering field today, much attention is being given to the area of intersection control. The intersection is the "location where most accidents occur, where the greatest delay occurs, where the most fuel is wasted, where congestion is the greatest and where adjacent land use tends to be in greatest conflict with the highway" [7].

The most critical element in intersection control is the timing of traffic signals. Inefficient timing of intersections causes unnecessary delay and wasted fuel. In the past few years there have been several computer programs developed to aid the traffic engineer in timing traffic signals. Also, many metropolitan areas have installed computerized, traffic responsive control systems to improve the operation of their intersections.

2.2 TRANSYT Analysis

The overall objective of this thesis is to analyze the effect that signal settings from one of the more widely used computer programs, TRANSYT [8], have on traffic operations in signalized networks. Many traffic engineers are using TRANSYT without any real understanding of how the program works. To many, it is just a "black box" that they put their data into, and TRANSYT gives them back a signal timing plan.

TRANSYT, for a given cycle length, generates a timing plan which minimizes a performance index. This performance index is a combination of delay, in vehicle-hours/hour, and a weighted measure of stops. The weighting on stops, referred to as the stop penalty, is provided by the user. One objective of this thesis is to investigate the effect that the stop penalty has on fuel consumption. According to the TRANSYT user's guide [8], "there is some evidence that values up to 20 tend to minimize fuel consumption". A number of stop penalties ranging from zero to 1000 were tested for different cycle lengths to ascertain whether or not there is a particular stop penalty which can be used to minimize fuel consumption. With the present emphasis on energy conservation, it would be very beneficial for traffic engineers to have an easy, reliable method of determining signal settings which minimize fuel consumption.

2.3 Alternative Programs

Of the traffic signalization computer programs available to the traffic engineer, TRANSYT appears to have the most potential. PASSER II [9] is limited to arterial progression analysis. It has no ability to handle a closed network, and is only concerned with maximizing bandwidth. PASSER II does not consider stops or delay. SOAP [10] includes a fuel consumption model in its package, but its accuracy is questionable and the program is restricted to isolated intersections. NETSIM [11] has the capability to accomodate open and closed networks and also to provide values of fuel consumption. However, NETSIM is only an evaluation program, with no ability to generate a signalization strategy. Furthermore, the costs of using NETSIM make it impractical for use in most signalization design. SIGOP [12], another network signalization program has generally been found to be inferior in performance to TRANSYT. TRANSYT's low operating costs and its flexibility make it the most practical program for engineers to implement.

2.4 Effect of Cycle Length on Fuel Consumption

Another point of interest is the relationship between cycle length and fuel consumption. There have been numerous previous studies concerning the relationships of cycle length to delay, and travel time or speed, but little has been done with regard to energy consumption. From the research that has been done, the relationship between cycle length and fuel consumption is not evident, particularly for signal systems. This thesis attempts to show a more definite relationship between cycle length and energy consumption.

2.5 Network Analysis

Most of the previous work in signal timing, besides being confined to studying delay, involved only single, isolated intersections. This thesis studies the effects of signalization in a network of intersections. Networks provide a great potential for saving fuel, due to vehicle interaction between intersections, and the large volume of traffic they carry. Because of the time required to hand calculate signal timings for a network, more and more cities are using the computer to develop their signalization strategies. Since TRANSYT is one of the more widely used programs for network timing, it was first decided to determine whether or not TRANSYT performs as claimed. That is: Does increasing the stop penalty really reduce the number of stops and increase the delay, and does the program operate in a consistent, accurate manner?

2.6 Delay, Stops, and Fuel Consumption

Early fuel consumption studies performed by Claffey [13] for a range of operating conditions, showed that speed change cycles are a major consumer of fuel. Claffey's data also showed that the fuel used for a speed change cycle is much greater than for a vehicle idling for the same amount of time. From this data it seems reasonable to assume that if one could minimize or lower the number of stops, without increasing delay significantly, fuel consumption could be minimized. Testing this assumption is another objective of this thesis; that is to find whether or not there is a consistent trade-off between stops and delay with respect to fuel consumption. This produces several questions that this research addresses. First; what is the relationship between vehicle delay and fuel consumption in a network? Second; what is the relationship between vehicle stops and fuel consumption? Third; what effect do vehicle stops have on vehicle delay? And fourth; can TRANSYT be used to minimize fuel consumption in a network?

2.7 Fuel Consumption as an Evaluation Base

In the past, delay has been the measure of effectiveness normally used in evaluating traffic signal systems. Total delay for a system would be calculated along with an associated cost to the users, and then the reduced user costs for certain improvements would be used for justifying their implementation. However, when these delays are calculated on an individual (or per vehicle) basis, the difference in delay may not be that significant. When evaluating on an energy basis, the total energy savings of an improvement may be a more reasonable measure of effectiveness rather than total delay. This is especially true when fuel consumption can be minimized with only a small increase in delay per vehicle. Another factor making energy analysis more important is the rising cost of fuel. As the cost of fuel increases, the user costs for fuel may reach or even outweigh the user travel time costs.

CHAPTER 3

LITERATURE REVIEW

This chapter presents a review of some of the research which has been performed in the area of intersection timing for energy conservation. Also presented are some of the research studying traffic flow in signalized networks. This chapter is divided into two sections. The first section examines the literature involving isolated intersections, and the second examines the studies involving networks.

3.1 Isolated Intersections

Bauer [14] has examined isolated pretimed intersection signal timing for its effect on energy conservation. Bauer developed a FORTRAN computer program to calculate energy consumption for different cycle lengths, and different total critical lane volumes. The computer program uses Webster's delay equation [15] to generate values of delay and stops to be used in calculating energy consumption. The values of delay and stops are multiplied by factors for idling energy consumption and the energy consumption for a 0 to 30 mph acceleration maneuver respectively. For the idling consumption factor, a value of 0.5 gallon/hour was used. For the 0 to 30 mph acceleration maneuver, four different values, 1/30, 1/50, 1/100, and 1/200 gallons were used and calculations made for each value.

The basic finding of Bauer's work was that the minimum energy cycle differs quite significantly from the minimum delay cycle. The calculations were made for total critical volumes ranging from 200 vph to 1400 vph at a two-phase, one lane per approach intersection. As the total critical volumes increased, so did the difference between the minimum energy cycle and the minimum delay cycle. Bauer's findings show, that for a total critical flow of 1400 vehicles/hour, there is little difference in the energy consumption for cycle lengths ranging from 180 to 300 seconds. The minimum energy cycle was 222 seconds, while the minimum delay cycle was 95 seconds. At or below the minimum delay cycle, Bauer found that energy consumption was much greater than the energy consumption in the 180 to 300 second range.

Cohen and Euler [16] have studied fuel consumption and emissions at isolated intersections with the NETSIM [11] traffic simulation model. Where Bauer's results were based on macroscopic flow characteristics, NETSIM is a microscopic flow model. The study by Cohen and Euler evaluated fuel consumption and emissions at a two-phase, pretimed intersection as was Bauer's intersection of study. Different scenarios were tested by changing the approach volumes and the percentage of left and right turns. For the different scenarios the cycle length was varied from 40 to 150 seconds, the normally accepted range for cycle lengths.

Cohen and Euler performed regression analysis on their data to study the correlation between average speed and fuel consumption. They found the two to be highly correlated. For their hypothetical intersection the regression equation for fuel consumption is:

$$FC = 0.695 + 0.471(\text{average speed}) - 0.0154(\text{average speed})^2.$$

In analyzing the effect of cycle length on traffic operations, Cohen and Euler found the minimum delay and minimum fuel cycle lengths to be the same. The minimum fuel consumption cycle length also produced the minimum emissions of HC and CO.

Tarnoff and Parsonson [17] analyzed the effect of pretimed, semi-actuated, fully-actuated and volume-density controllers on traffic flow characteristics such as speed, stops and delay. Also included in the analysis were fuel consumption, vehicle emissions and controller costs. The only information concerning fuel consumption that is presented by Tarnoff and Parsonson are fuel consumption factors for stops and delays. "In this manner the stops and delays estimated for a particular type of control can be translated directly into measure of emissions and fuel consumption" [17].

Hurley and Ball [18, 19, 20] have studied isolated intersections under both pretimed and actuated control on a net energy basis. Hurley [21] found for vehicles making a stop/go speed change cycle the other forms of energy consumption were almost equal to the fuel requirements, while at uniform speed the fuel requirement is almost 80% of the total energy required. The general model used by Hurley and Ball for determining hourly energy consumption for an approach at an intersection is given by:

$$E_i = E_{c_i} + E_{sg_i} + E_{I_i}$$

where E_i = total hourly energy consumption on approach i (BTU/hr)

E_{c_i} = hourly energy consumption on approach i for vehicles clearing the intersection without stopping (BTU/hr)

E_{sg_i} = hourly energy consumption on approach i due to stop/go speed change cycles (BTU/hr)

E_{I_i} = hourly energy consumed on approach i under idling conditions (BTU/hr)

Hurley and Ball define an "affected area" where the traffic flow is affected by the traffic signal. The energy consumption for the affected area is computed based on energy coefficients for constant speed, speed change cycle, and idling. Estimates of delay and probability of stopping are obtained from Webster's delay equation and probability of stopping formula [15].

Hurley and Ball found that Webster's optimum cycle length and splits produced energy consumption very close to the minimum values. Webster's optimum cycle length was particularly effective in minimizing energy consumption at high approach volumes. "The worst comparison occurs for small cross flows where use of Webster's cycle length 'costs' about ten percent" [18]. Another significant finding by Hurley and Ball was that as cycle length drops below Webster's optimum the energy consumption increases greatly.

In Hurley and Ball's [19] investigation of intersections with actuated control the NETSIM [11] computer simulation program was used to evaluate different control conditions. NETSIM provided estimates of delay and stops to be used in calculating net energy consumption for different minimum main street green settings and maximum extension intervals.

Hurley and Ball "found that for actuated control, minimum energy operation does not necessarily correspond to minimum delay operation" [19]. It was also found "that energy consumption is, for the most part, insensitive to maximum extension interval for both semi-actuated and fully-actuated control". Hurley and Ball also concluded that for semi-actuated control, energy consumption is very sensitive to minimum Main Street green time.

Ball [20] has examined the effect on energy consumption of using incorrect values of lost time and saturation headway in computing pretimed signal settings. Ball's findings were that energy consumption "is usually very insensitive to incorrectly assumed lost time and saturation headway values. Only when low values of these characteristics are assumed and high values actually occur is there appreciable excess energy consumed".

3.2 Networks

This section is divided into two parts. The first part presents some of the research concerning traffic flow characteristics in networks, but not on an energy or fuel consumption basis. The second part examines the work that has investigated fuel consumption in networks.

3.2.1. Traffic Flow Characteristics in Networks

Wagner, Barnes, and Gerlough [22] evaluated nine different concepts for generating signal timing plans for a network. The nine strategies evaluated were:

1. Webster's cycle and split optimization method;
2. the delay-difference method for optimizing signal offsets;
3. the volume-priority method of establishing a network offset plan;
4. the preferential street method of establishing a network offset plan;
5. the mixed-cycle method of signalized network operation;
6. Little's maximal bandwidth method for optimizing offsets;
7. the SIGOP traffic signal optimization method;
8. the British combination method for optimizing offsets; and
9. Allsop's graph theory method for optimizing offsets. [22]

After evaluating the different strategies, the authors concluded that the cycle length is the single most important variable affecting operation, whether it be an isolated intersection, along an arterial, or in an urban network. Wagner, Barnes and Gerlough's basic conclusion was that if "a network of signalized intersections that has not recently been the subject of intensive traffic engineering attention devoted specifically to signal operation improvements, it is highly probable that initiation of systematic study, analysis, and implementation of signal timing changes will produce significant upgrading of performance" [22]. There was little difference found between the different strategies, but all strategies provided a great improvement over the existing conditions.

In another study analyzing flow in a street network, Ponteer, Miller and Kraft [23] found the signal system of a network to be the most critical element of all traffic control alternatives available.

3.2.2 Fuel Consumption in Networks

Courage and Parapar [24] have analyzed a network for its fuel consumption and delay characteristics. The network studied was a system of 26 signals in the central business district of Gainesville, Florida. The network's fuel consumption and delay were estimated by the TRANSYT [25] computer model. The TRANSYT program was run for cycle lengths ranging from 70 to 160 seconds, and stop penalties from 0 to 60.

Using Claffey's values of fuel consumption for delay and stops [13], Courage and Parapar determined that each vehicle stop is equal to 60 vehicle-seconds of delay in terms of fuel consumption. Therefore, if a stop penalty of 60 is used in TRANSYT, then the performance index generated by TRANSYT will be proportional to the estimated fuel consumption. Using this strategy, Courage and Parapar found minimum delay to occur at a cycle length of approximately 90 seconds, while the fuel consumption was minimized at a 140 second cycle length.

Radwan and Benevelli [26] have investigated the use of different optimization schemes for an open urban network. The signal settings for the network of five intersections were obtained from TRANSYT [8]. The TRANSYT program was modified so that it would produce signal settings which would minimize one of four optimization strategies. The four strategies used were minimization of: a) Total Vehicle Delay; b) Total Passenger Delay; c) Excess Fuel Consumption Due to Idling and Speed Change Cycles; and d) Total Cost.

The optimum cycle lengths generated by TRANSYT were; 45 seconds for total vehicle delay, 40 seconds for total passenger delay, 65 seconds for excess fuel consumption, and 40 seconds for total cost. Radwan and Benevelli also evaluated the signal timings found by TRANSYT with the NETSIM simulation program. The optimum cycle lengths from the NETSIM data for the four strategies were; 45 seconds for total delay, 50 seconds for total passenger delay; 40 seconds for excess fuel consumption, and 40 seconds for total cost. As Cohen and Euler [16] found by using NETSIM, Radwan and Benevelli's NETSIM results show that when total delay is minimized, so is fuel consumption.

The Urban Traffic Control System (UTCS) Project [27] involved six tasks in its study of fuel consumption in urban networks. The six tasks of the UTCS study were:

1. One-Way/Two-Way Streets.
2. Pedestrian Scramble System.
3. Pre-Timed vs. Fully-Actuated Signal Systems.
4. Comparison of Cycle Lengths.
5. Variations in Traffic Demands.
6. Exclusive Bus Lanes [27].

The UTCS study found that converting some two-way to one-way streets resulted in an average increase of 12 percent in fuel consumption efficiency (FCE). The study warns that increased travel due to rerouting could cause this improvement to be reduced in other studies. The pedestrian scramble system was found to increase delay and reduce speed and FCE. It seems to have potential only in cases with very high pedestrian volumes. For the test case the pedestrian volume was 500 per hour. Fully-actuated control was found to be effective when cross street flows were minor (7 to 1 main to cross street flow ratio). In more evenly balanced networks the savings from fully-actuated control vs. pre-timed would not be as great.

In the task studying the effect of cycle length on fuel consumption two networks were analyzed. The first, Hawthorne Blvd. in Los Angeles, had low cross street volumes, few turning movements, and no pedestrian interference. For this case, longer cycle lengths produced better fuel consumption but with an increase in delay. The second network was a section in Washington, D.C. characterized by significant volumes on all approaches and high turning volumes. In this network the use of longer cycle lengths caused lower fuel efficiency and more delay. The UTCS study concluded that "the effect of longer cycle lengths is highly dependent on network characteristics, traffic volumes, and traffic patterns" [27].

In the task investigating effects of variation in demand, as would be expected, as demand increased so did fuel consumption. The use of exclusive bus lanes caused a decrease in network speed and FCE (vehicle miles per gallon). However, exclusive bus lanes did increase FCE when measured in passenger miles per gallon.

CHAPTER 4

MODEL AND NETWORK DESCRIPTION

This chapter describes the two computer programs, TRANSYT 7 and NETSIM, which were used for this thesis. Also discussed are the two traffic networks, Prices Fork Road in Blacksburg, Virginia and Arlington County, Virginia which were analyzed.

4.1 TRANSYT 7

TRANSYT (TRAffic Network StudY Tool) [8] is a computer program which generates fixed-time signal settings for a network of intersections. The program was developed by D. I. Robertson of the British Transport and Road Research Laboratory and was first released in 1967. Version 7 of TRANSYT, released in 1978, is the program used for this research.

TRANSYT consists of two main parts, the first, a traffic model which estimates delay and stops to be used in calculating a performance index for a given set of signal timings. The second part is a hill-climbing optimization process which adjusts the signal settings and tests the setting to determine whether or not the performance index has been improved. A flow chart illustrating the organization of the TRANSYT program and its six subroutines is presented in Figure 4.1. The performance index, which the hill-climbing procedure attempts to minimize, is given as:

$$\text{Performance index} = \sum_{i=1}^{i=n} (d_i + Kc_i)$$

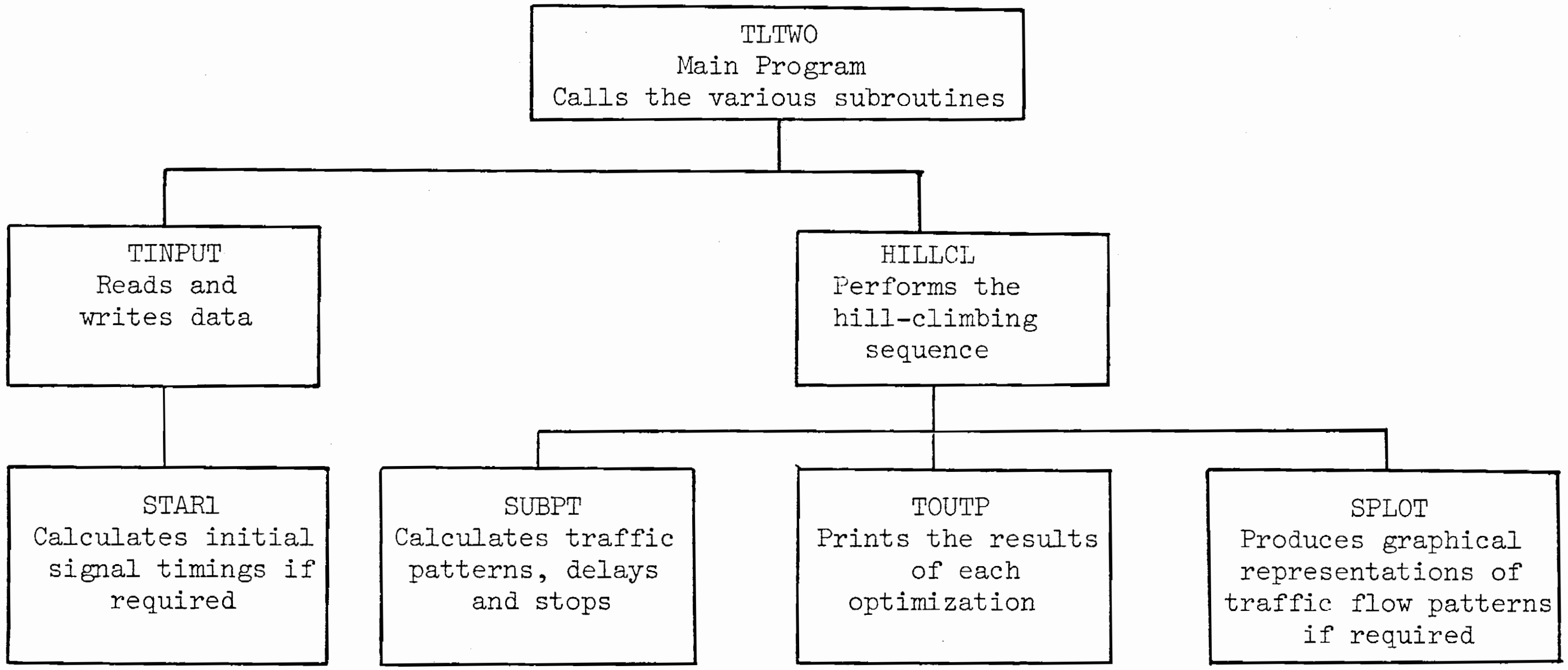

Figure 4.1 TRANSYT Flow Chart

where d_i is the average delay in vehicle-hours/hour on the i th link of the network;

c_i is the average number of vehicle stops per second on the i th link of the network;

K is a weighting factor

The stop penalty, K, which is specified by the user, may be anything from 0 to 10,000. If a value of zero is used, TRANSYT will attempt to minimize only delay. The higher the stop penalty, the more emphasis is placed on minimizing the number of stops. According to the TRANSYT user's guide, "values between 4 and 8 tend to reduce stops with little increase in delay. There is some evidence that values up to 20 tend to minimize fuel consumption".

As TRANSYT performs its calculations there are four basic assumptions made. These are:

1. All major intersections in the network have signals (or sign control).
2. All the signals in the network have a common cycle length or a cycle length of half this value.
3. Traffic entering the network does so at a constant specified rate on each approach.
4. The proportion of traffic turning right or left remains constant throughout the cycle.

TRANSYT is capable of evaluating an existing signal system if the assumptions above are satisfied. TRANSYT will then adjust the existing timing plan if it finds the adjustments to improve the performance index. All TRANSYT runs are executed for a specified cycle length. If comparisons of different cycle lengths are desired, as is generally the case, a run for each cycle length must be executed. Cycle lengths may then be compared on the basis of their respective performance indices.

In addition to the overall stop penalty, TRANSYT has link stop and delay weighting penalties. This allows the user to place a different emphasis on particular links. Geometric conditions of a link may make it desirable to reduce the number of stops on that link. The link stop penalty could be used for this purpose. The delay weighting penalty may be used to attempt to reduce delay on a particular link more than on other links. This may be beneficial in the case of a few high volume links.

TRANSYT's traffic model estimates delay in two parts, uniform and random. The uniform delay is obtained from an input/output process. The queue length for a particular time interval is determined from the inflow and outflow patterns TRANSYT has generated. The queue length multiplied by the time interval gives an estimate of the uniform stopped time delay. The random delay is based only on the degree of saturation at the stop line. The equation for random delay is:

$$D_r = \frac{X^2}{4(1-X)}$$

where D_r = random delay in vehicle-hours/hour

X = degree of saturation

"The average number of stops per cycle is derived by totalling the number of vehicles which arrive while a queue is present" [23].

TRANSYT has the capability to optimize up to 50 intersections in a single run. Each intersection may be fed by up to 50 links. This feature allows different flows on a single approach to be separated. Each intersection may have up to seven different phases. Intersections with a cycle length one-half of the network cycle length are limited to three phases per cycle.

TRANSYT requires that a cycle length for the entire network be input. Also required is the phasing at each intersection in the network. TRANSYT only optimizes the splits and offsets. Additional data required by TRANSYT includes; lost time, link length, stopline saturation flow, travel time or speed, link flowrates, and turning movements for each link. TRANSYT is also able to incorporate bus travel into its traffic model. Performance of bus traffic is separated from that of other vehicles in the final output. A new feature of version 7 allows TRANSYT to model a bottleneck situation. TRANSYT 7 also produces a much faster solution time than earlier versions, thereby reducing the computer costs to the user.

4.2 NETSIM

NETSIM [11] is a microscopic simulation model used to evaluate different control strategies in an urban network. NETSIM, formerly called UTCS-1, was developed for the Federal Highway Administration by Peat, Marwick, Mitchell & Company and KLD Associates, Inc. "The model is designed primarily to serve as a vehicle for testing relatively complex network control strategies under conditions of heavy traffic flow" [11].

NETSIM has the ability to simulate traffic controls ranging from a simple "Stop" or "Yield" sign to a dynamic, real-time traffic control system. The basic NETSIM model has the capacity to handle 99 intersections, 160 links, and 1600 vehicles at any one time. These limits may be increased by changing the dimensions of the arrays defining the size of these parameters. Due to the saturation of one of the networks studied in this thesis, the maximum-occupancy was increased from 1600 to 2500 vehicles.

For program input purposes, the network must be broken down into a group of links and nodes. Each link represents one direction of travel on a street connecting two intersections. Each link may have up to five moving lanes, with the channelization being specified for each lane. Individual intersections may have up to nine different phases per cycle.

The input data for each link and intersection necessary to execute the program includes:

- link geometry;
- intersection type;
- network connectivity;
- intra-link target speed;
- intersection turning movements;
- pedestrian volumes;
- signal timings;
- entry link flow rates;
- source/sink node flow rates; and

- traffic composition

The basic NETSIM model generates vehicles according to a uniform statistical distribution and enters them into the network through entry links and source nodes. For this thesis a modified version of NETSIM [28] incorporating a shifted negative exponential headway model was used to more accurately represent vehicle arrivals. As each vehicle is generated it is stochastically assigned a set of performance characteristics, such as; vehicle type, average discharge headway, average acceptable gap, etc. Each vehicle's movement through the network is then controlled by its assigned performance characteristics and microscopic car-following, queue-discharge and lane-switching algorithms [11]. The status of each vehicle in the network is updated and statistics accumulated once every second.

In updating the status of each vehicle, seven basic functions are performed every second. The seven functions are:

1. All vehicles that were located in queue at the commencement of the time step are processed;
2. All remaining vehicles already on the network, but not in queue are processed;
3. Any new vehicles are emitted onto the network via entry links in accordance with the specified flow rates for each entry link;
4. Any new vehicle to be emitted onto the network from the internal source nodes are processed;
5. The status of all traffic signals in the network is updated;

6. The set of standard vehicle and link statistics contained within the vehicle-array and link-array are accumulated and a series of diagnostic checks performed;
7. Finally, if a point has been reached in the simulation run where a statistical output is called for the necessary results are printed [11].

At the end of each specified sub-interval the accumulated statistics are printed for each internal link. Statistics are not given for entry or exit links.

For each internal link the statistics generated are:

- vehicle miles travelled;
- vehicle trips;
- moving time (vehicle-minutes);
- delay time (vehicle-minutes);
- moving time/total travel time;
- total travel time (vehicle minutes);
- total travel time/vehicle (seconds);
- total travel time/vehicle-mile (seconds/mile);
- delay time/vehicle (seconds)
- delay time/vehicle-mile (seconds/mile)
- percent stop delay;
- average speed (MPH);
- average occupancy;
- stops/vehicle;
- average saturation percentage;

- cycle failures;
- fuel consumption (gallons & MPG);
- vehicle emissions of HC, CO and NO X (grams/mile)

Measurements of delay are calculated by subtracting the ideal travel time of an unimpeded vehicle on a link from the actual travel time for that link.

Network statistics are accumulated and printed at the end of the link statistics. These include:

- vehicle miles;
- vehicle-minutes;
- vehicle-trips;
- stops/vehicle;
- moving/total trip time;
- average speed (MPH);
- mean occupancy (vehicles);
- average delay/vehicle (seconds);
- total delay (minutes);
- delay/vehicle-mile (minutes/vehicle-mile);
- travel time/vehicle-mile (minutes/vehicle-mile);
- stopped delay as a percentage of total delay
- fuel consumption (gallons & MPG);
- vehicle emissions of HC, CO, and NO X (grams/mile).

Since NETSIM does not generate statistics for entry links, it is necessary to incorporate dummy nodes into the network. For this thesis, a dummy node was placed upstream of each node on the boundary of the networks being studied.

4.3 Prices Fork Road Arterial

The first network investigated is an open network of four intersections along Prices Fork Road, located in Blacksburg, Virginia. Prices Fork Road is a four lane divided street with exclusive left turn bays at all intersections. The TRANSYT link-node diagram is shown in Figure 4.2. Node 3, the intersection of Prices Fork and Tom's Creek Road is the critical intersection in the system. The critical lane volume of Tom's Creek Road is more than five times that of Prices Fork Road. Nodes 1 and 4 have cross street critical lane volumes equal to or greater than the Prices Fork Road critical lane volumes.

The TRANSYT link-node diagram was developed so it would give an accurate representation of the actual traffic flow conditions. Significant left turn volumes were separated from the through and right turn volumes by giving them a separate link. For the case of very small left turn volumes (under five vph), left turns were added to the through movements and saturation flow rates were based only on the through lanes.

The NETSIM link-node diagram is shown in Figure 4.3. Nodes 801-808 are entry nodes through which vehicles are generated into the network. Nodes 1, 3, 5, 6, 8, 9, 11 and 12 are "dummy" nodes which were added so that statistics would be generated for vehicles entering the network.

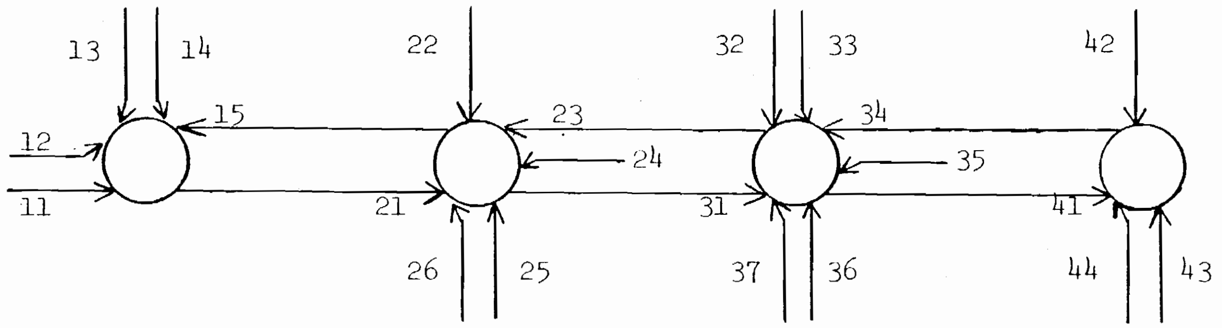

Figure 4.2 TRANSYT LINK-NODE DIAGRAM
(Prices Fork Road)

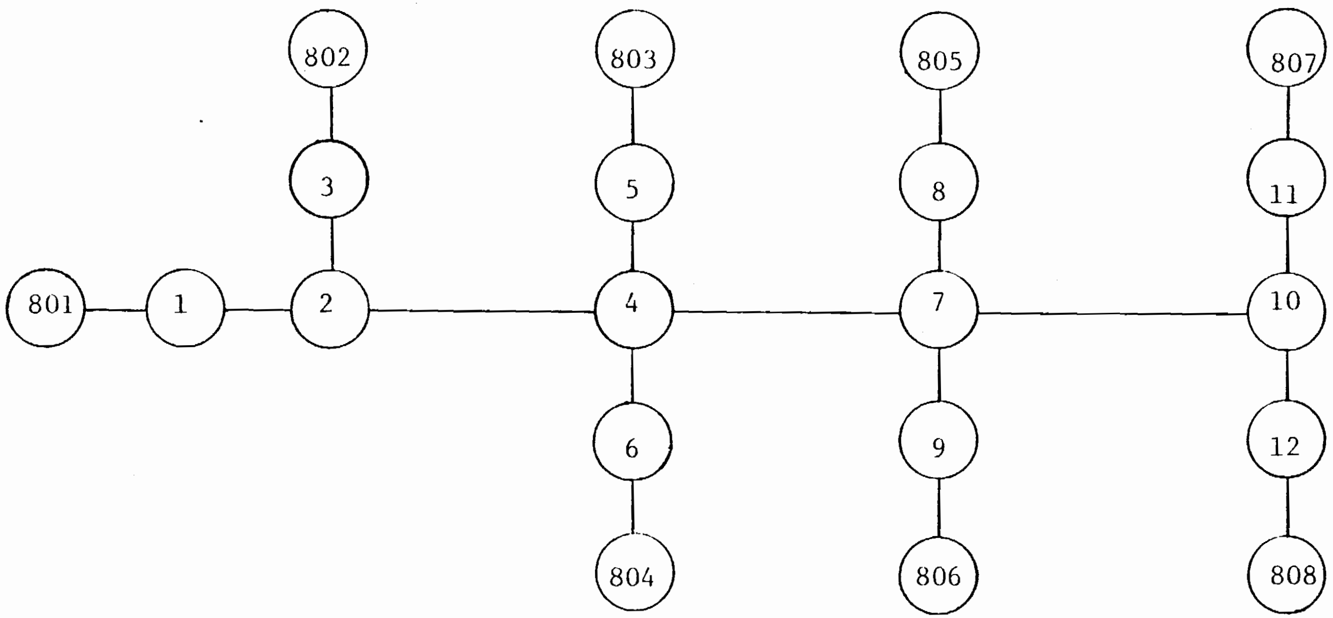

Figure 4.3 NETSIM LINK-NODE DIAGRAM
(Prices Fork Road)

4.4 Arlington County

The second network analyzed is a section of Arlington, Virginia, consisting of a total of 24 intersections, 20 of which are signalized. The section studied is the Wilson Boulevard - Rosslyn area of Arlington County. This area is on the border of Washington, D.C. and handles a large amount of traffic entering and exiting the Nations Capital. Most of the traffic in the network is funneled onto Key Bridge, one of the five bridges linking Northern Virginia and the District of Columbia.

The TRANSYT link-node diagram is presented in Figure 4.4. For the A.M. peak studied, there are three major flows of traffic through the network. The first is along Wilson Boulevard from node 118 (Wilson Blvd. & No. Veitch St.) to node 110 (Wilson Blvd. & N. Lynn St.). The second flow is along North Lynn St. from node 147 (N. Lynn St. & Fairfax Dr.) to node 154 (N. Lynn St. & W.B. Lee Highway). At node 110, 54% of the volume travelling along Wilson Blvd. (links 1102 & 1103) turn left into the major flow on N. Lynn St. (link 1481). The third major flow is along E.B. Lee Highway (link 2531). Lee Highway and Wilson Boulevard are two of the five arterials and expressways which carry traffic East and West across Arlington County. At node 253, 38% of the traffic from Lee Highway turn left onto N. Lynn St. The traffic along N. Lynn St. exits the network through node 154 onto Key Bridge and into Washington, D.C.

The NETSIM link-node diagram is presented in Figure 4.5. Due to the necessity of "dummy" nodes, the NETSIM network required a total of 71 nodes. As was mentioned previously, the Arlington network was

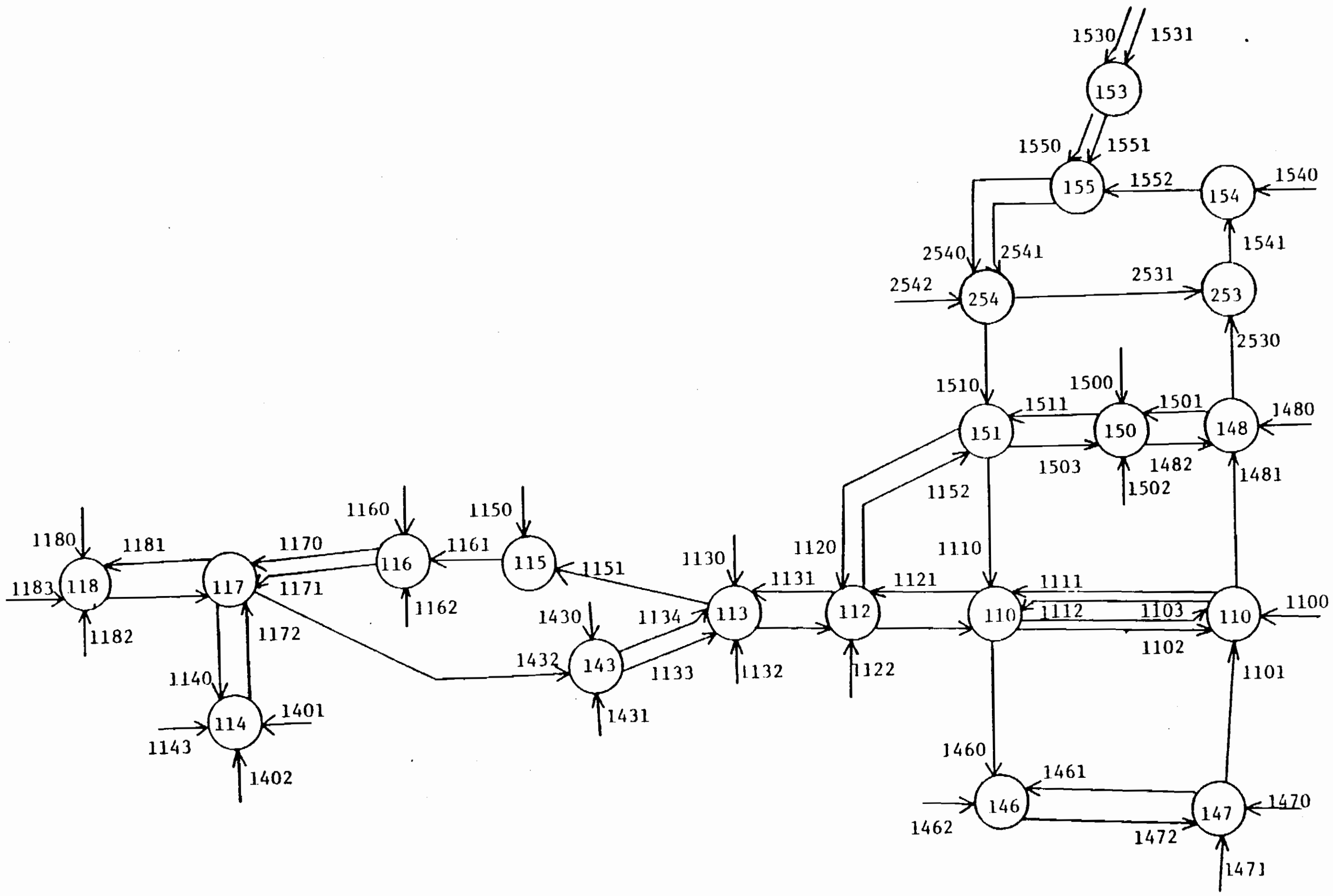

FIGURE 4.4 - TRANSYT Link-Node Diagram
(Arlington County)

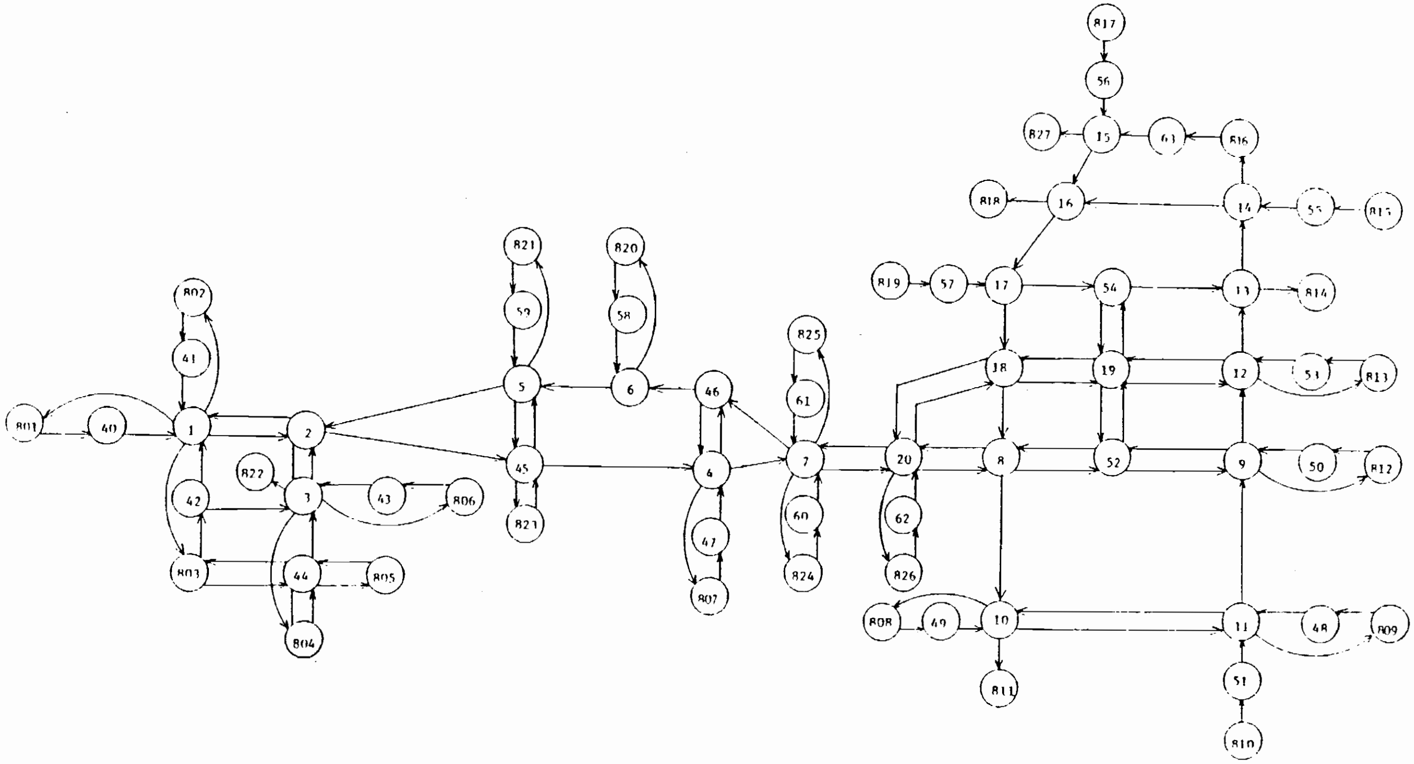

Figure 4.5 NETSIM Link-Node Diagram
(Arlington County)

saturated, requiring that the maximum-occupancy of the NETSIM program be increased from 1600 to 2500 vehicles. Nodes 1-20 are the signalized intersections of the network. Nodes 801-827 are entry and exit nodes. Nodes 45, 46, 52 and 54 are the four non-signalized intersections included in the study. Nodes 40-44, 47-51, 53, and 55-63 are "dummy" nodes. Since there exists an underpass beneath node 8 (Wilson Blvd. & Ft. Myer Dr.) a sink node on link 18, 8 and source node on link 8, 10 were implemented to model the traffic using the underpass.

CHAPTER 5

ANALYSIS

This chapter presents the results obtained from the TRANSYT 7 and NETSIM computer runs. The analysis period for both networks is the A.M. peak hour. The analysis is divided into two parts; part one, the Prices Fork Road network; and part two, the Arlington County network.

5.1 Prices Fork Road

For the Prices Fork Road network, 72 combinations of cycle length and stop penalty were entered into the TRANSYT 7 program. The entry flow rates corresponding to the NETSIM link-node diagram (Figure 4.3) are given in Table 5.1. The values of delay, stops, speed and performance index generated by TRANSYT 7 are shown in Tables A.1 - A.8 for cycle lengths of 60 to 120 seconds. According to the TRANSYT documentation [8], a stop penalty of zero will minimize delay, and as the stop penalty increases, stops will decrease and delay will increase. This was not always the case as can be seen in the data presented in Tables A.1 - A.8. With the exception of the 70 second cycle, the values of delay predicted by TRANSYT were inconsistent with its logic for all cycle lengths tested. Delay was not always minimized with a stop penalty of zero, and delay did not always increase with the stop penalty. For the 70, 75, 90 and 120 second cycle lengths the stops predicted by TRANSYT 7 failed to follow its logic. For all these cycle lengths there were incidents where predicted stops increased with a larger stop penalty.

TABLE 5.1 - Entry Link Flow Rates (Prices Fork Road)

Link	Flow Rate (Veh/Hr)	Lanes
801, 1	856	2
802, 3	500	2
803, 5	8	1
804, 6	136	2
805, 8	936	2
806, 9	88	1
807, 11	708	2
808, 12	400	2

The performance index is the measure of effectiveness produced by TRANSYT normally used to compare different timing plans. Plots of performance index versus cycle length for different stop penalties are presented in Figures A.1 - A.9. For most of the stop penalties tested (Figures A.1 - A.7) there is a smooth relationship between performance index and cycle length. The performance index decreases to a minimum and then increases as cycle length increases. For the larger stop penalties of 100, and 1000 there is an irregular relationship between the performance index and cycle length. For the stop penalty equal to 100 (Figure A.8), a local minimum occurred at 90 seconds. For a stop penalty of 1000 (Figure A.9) local minima occurred at 80 and 100 seconds and the global minimum at a 140 second cycle length.

Once the TRANSYT runs had been completed, the resulting timing plans were entered into NETSIM. A simulation time of one hour was used for each NETSIM run. A single NETSIM run was executed for each TRANSYT timing plan and the seed for the random number generator was constant for all NETSIM runs. Fuel consumption, stops and delay are estimated by NETSIM through microscopic simulation. The values of fuel consumption efficiency (FCE) in MPG for the Prices Fork Road network are given in Table 5.2. These values are plotted against cycle length for the nine stop penalties in Figures A.10 - A.18. The graphs of performance index versus cycle length indicate an optimal cycle length in the 70 to 90 second range for all stop penalties except 1000. The plots of FCE show a similar trend, with the optimal cycle length in the 70 to 80 second range. Both sets of graphs show that as cycle length falls

TABLE 5.2 - NETSIM Fuel Consumption Efficiency Prices Fork Road

TRANSYT Stop Penalty	Cycle Length = 60 Sec. (MPG)	Cycle Length = 70 Sec. (MPG)	Cycle Length = 75 Sec. (MPG)	Cycle Length = 80 Sec. (MPG)
0	7.24	9.31	10.13	10.13
6	6.74	9.50	9.90	9.65
10	7.02	10.50	9.90	10.22
20	7.02	10.08	10.42	9.82
40	6.79	9.53	10.26	9.82
60	6.82	9.53	8.66	10.33
80	6.83	9.63	10.08	10.30
100	7.34	9.74	10.08	10.32
1000	6.42	9.58	8.11	8.82

TRANSYT Stop Penalty	Cycle Length = 90 Sec. (MPG)	Cycle Length = 100 Sec. (MPG)	Cycle Length = 120 Sec. (MPG)	Cycle Length = 140 Sec. (MPG)
0	8.93	8.76	7.91	7.99
6	9.58	8.63	8.25	7.99
10	9.47	7.82	8.35	8.27
20	9.25	8.20	6.79	8.14
40	9.05	8.29	5.95	5.64
60	8.31	7.82	6.41	6.17
80	8.29	8.16	6.58	5.98
100	8.44	8.10	7.01	5.50
1000	9.03	7.79	6.57	4.59

below 70 seconds, the lower limit of the optimum range, fuel consumption efficiency and performance index both drastically worsen.

For most of the stop penalties tested, there was little difference in fuel consumption efficiency in the 70 to 80 second range. For the worst case, the stop penalty equal to 60, the difference was still only 16%. Webster [15] has shown that average delay per vehicle at an isolated intersection is fairly insensitive to changes in the cycle length for the range 0.75 C_o to 1.5 C_o, where C_o is the minimum delay cycle length. For the Prices Fork Road network, fuel consumption efficiency is much more sensitive to changes in cycle length in a similar range around the optimum fuel consumption cycle length.

Besides fuel consumption values, NETSIM also produces estimates of delay and stops. These values of average delay/vehicle, total delay, average stops/vehicle, and total stops are given in Tables A.9 - A.16. Also presented in Tables A.9 - A.16 are the corresponding values of total delay and stops predicted by TRANSYT. For all cases tested, the TRANSYT delay and stop values are much lower than those predicted by NETSIM. For many cases, the NETSIM estimates of total delay are two to almost three times greater than the TRANSYT values. Part of this difference can be attributed to the fact that TRANSYT calculates only stopped time delay and NETSIM calculates total delay.

Since one of the objectives of this thesis is to determine whether or not there is a particular stop penalty which will minimize fuel consumption, NETSIM FCE was plotted versus stop penalty for each cycle length. These graphs are shown in Figures A.19 - A.26. From these plots it is not possible to determine an optimal stop penalty. The only stop penalty to produce optimum fuel consumption efficiency for more than one cycle length was a value of ten. Stop penalties of 0, 6, 20, 60 and 100 also produced optimum FCE.

The performance index of TRANSYT, the normal measure of effectiveness used to evaluate alternate timing strategies, was tested for its ability to predict minimum fuel consumption. Plots of NETSIM predicted total fuel consumption (in gallons per hour) versus performance index are given in Figures A.27 - A.35. For only one case, the stop penalty equal to six, did the minimum performance index give minimum fuel consumption. For the stop penalty equal to 1000, there is an almost inverse relationship, with fuel consumption decreasing as performance index increases. For the other stop penalties tested (0, 10, 20, 40, 60, 80, 100), fuel consumption is very sensitive to small changes in the performance index in the vicinity of the optimal performance index.

Because the performance index of TRANSYT was unable to show any consistent relationship with fuel consumption, the TRANSYT values of total delay and stops/second were plotted against NETSIM FCE. FCE versus total TRANSYT delay (vehicle-hours/hour) is shown in Figure 5.1. Nothing definite can be determined from this graph. Although the general trend of the data might indicate that minimum delay maximizes FCE, the data is too dispersed to state this conclusively. NETSIM FCE versus TRANSYT generated stops/second is shown in Figure 5.2. As was the case with NETSIM FCE versus TRANSYT delay, no relationship can be

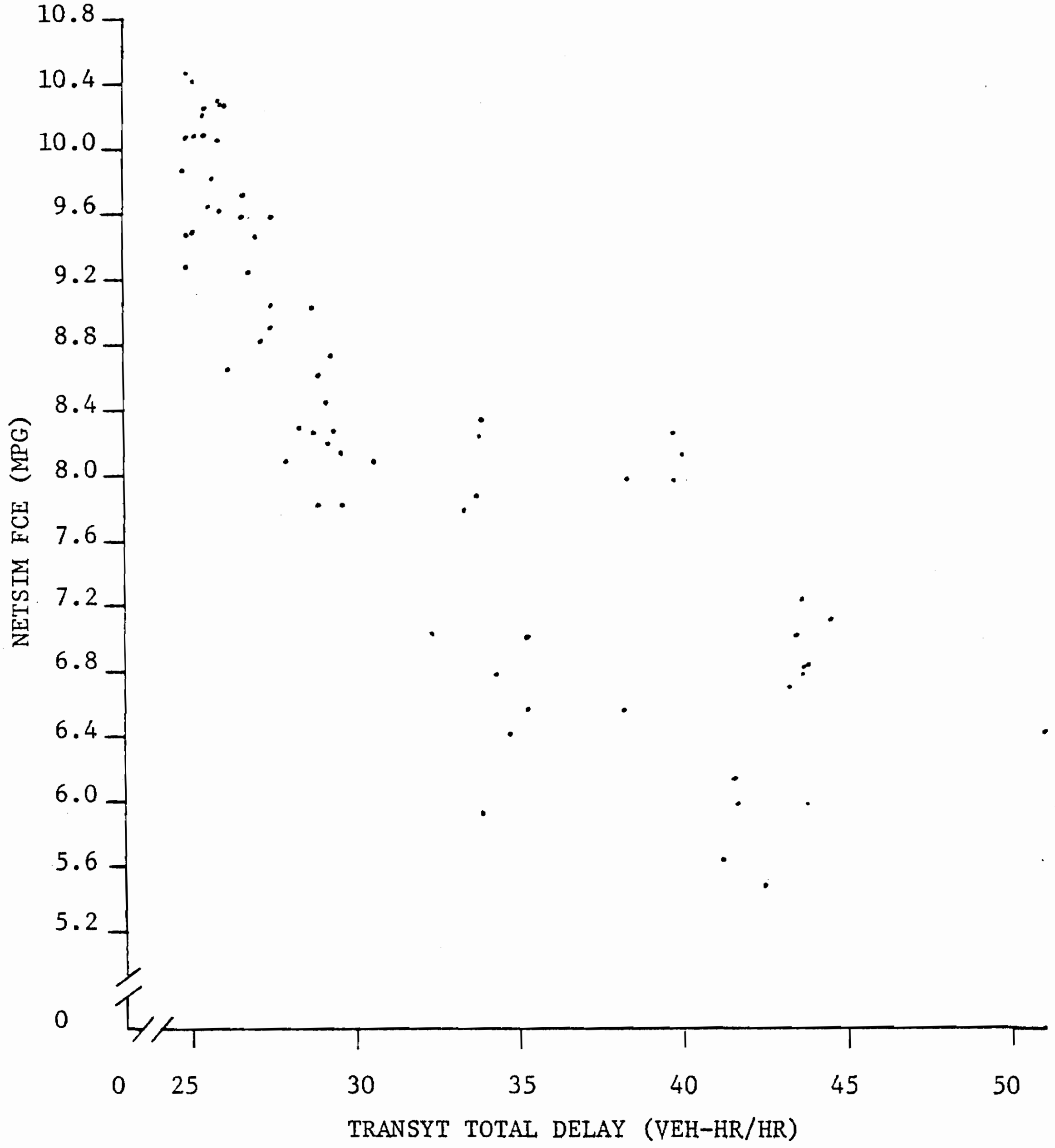

FIGURE 5.1 - NETSIM FCE vs. TRANSYT TOTAL DELAY
(Prices Fork Road)

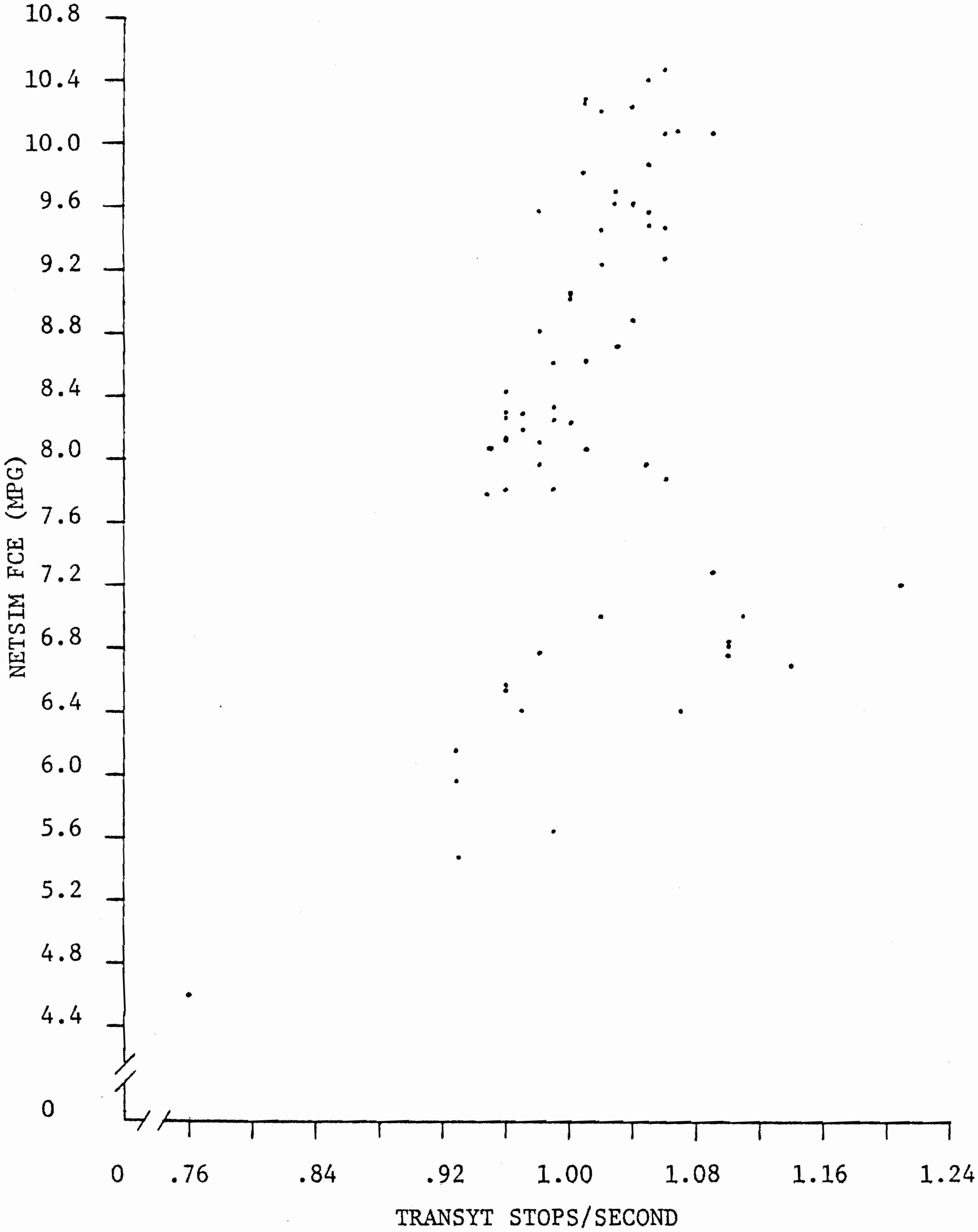

FIGURE 5.2 - <u>NETSIM FCE vs. TRANSYT Stops/Second</u>
(Prices Fork Road)

determined from the plot of NETSIM FCE versus TRANSYT stops/second.

Once it was determined for the Prices Fork Road network that TRANSYT could not be used as a direct means for minimizing fuel consumption, the NETSIM values of delay and stops were analyzed. Figure 5.3 shows that the plot of NETSIM FCE versus NETSIM average delay/vehicle. The figure shows a very smooth relationship between FCE and average delay/vehicle. When average delay is at a minimum FCE is at a maximum and conversely, when average delay is greatest, FCE is lowest. The same relationship is true for FCE versus average stopped time delay/vehicle, shown in Figure 5.4. The timing plan which produces both minimum delay and maximum FCE was generated using a 70 second cycle length and stop penalty equal to 10.

One of the objectives of this thesis is to examine the effect of vehicle stops on network fuel consumption. Figure 5.5 shows the plot of NETSIM FCE versus NETSIM values of average stops/vehicle. Again there is no clear relationship to be found. Another objective of this research is to analyze the relationship between vehicle stops and vehicle delay. Figure 5.6 gives a plot of NETSIM average delay/vehicle against NETSIM average stops/vehicle. Nothing conclusive can be drawn from neither this plot nor the graph of NETSIM average stopped time delay/vehicle versus NETSIM average stops/vehicle (Figure 5.7). The only definite point from either graph is that the timing plan which produced the minimum stops (cycle length = 140 seconds) also produced the maximum delay.

The final piece of data from the NETSIM analysis is the number

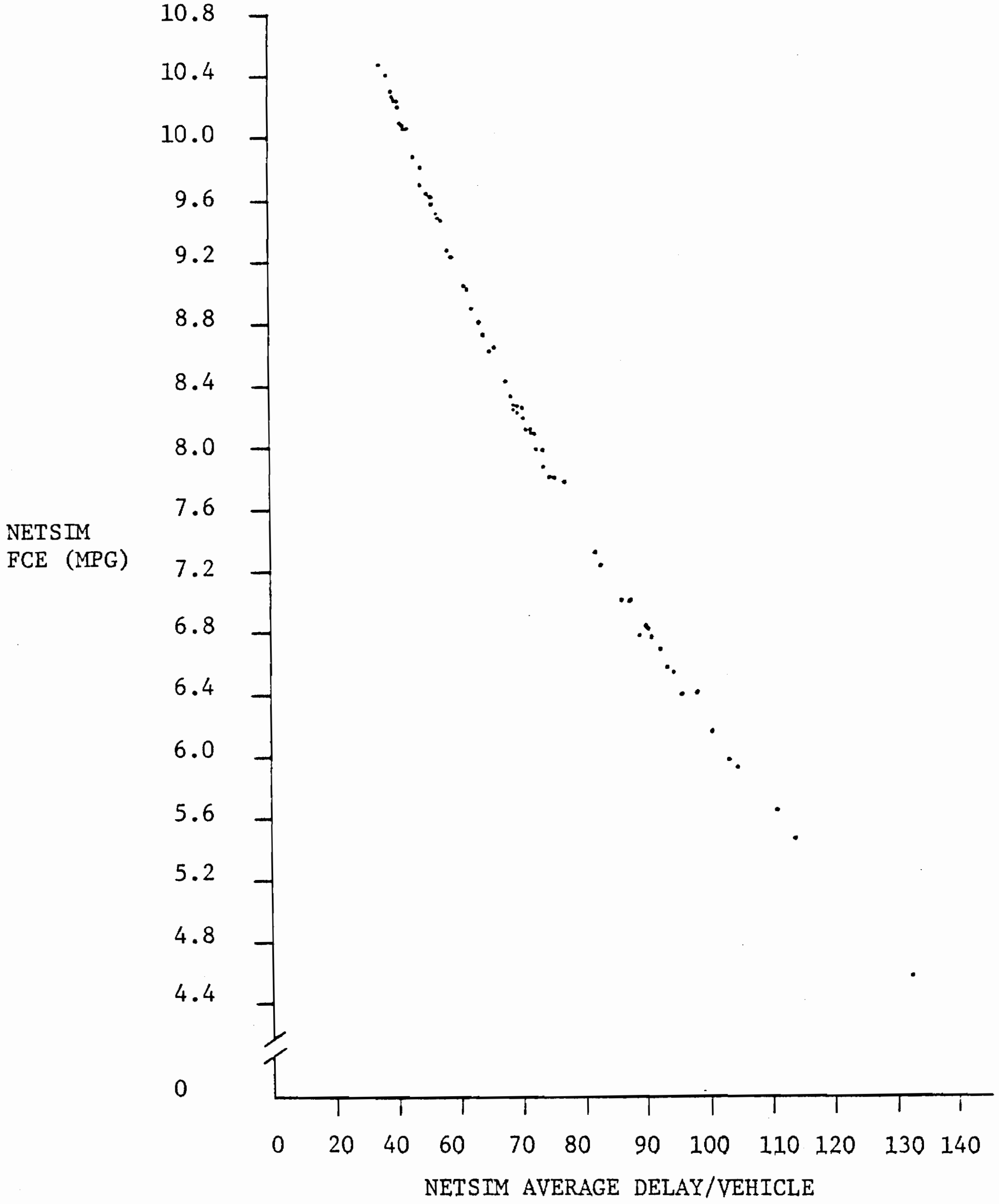

FIGURE 5.3 - NETSIM FCE vs. NETSIM Average Delay/Vehicle (Prices Fork Road)

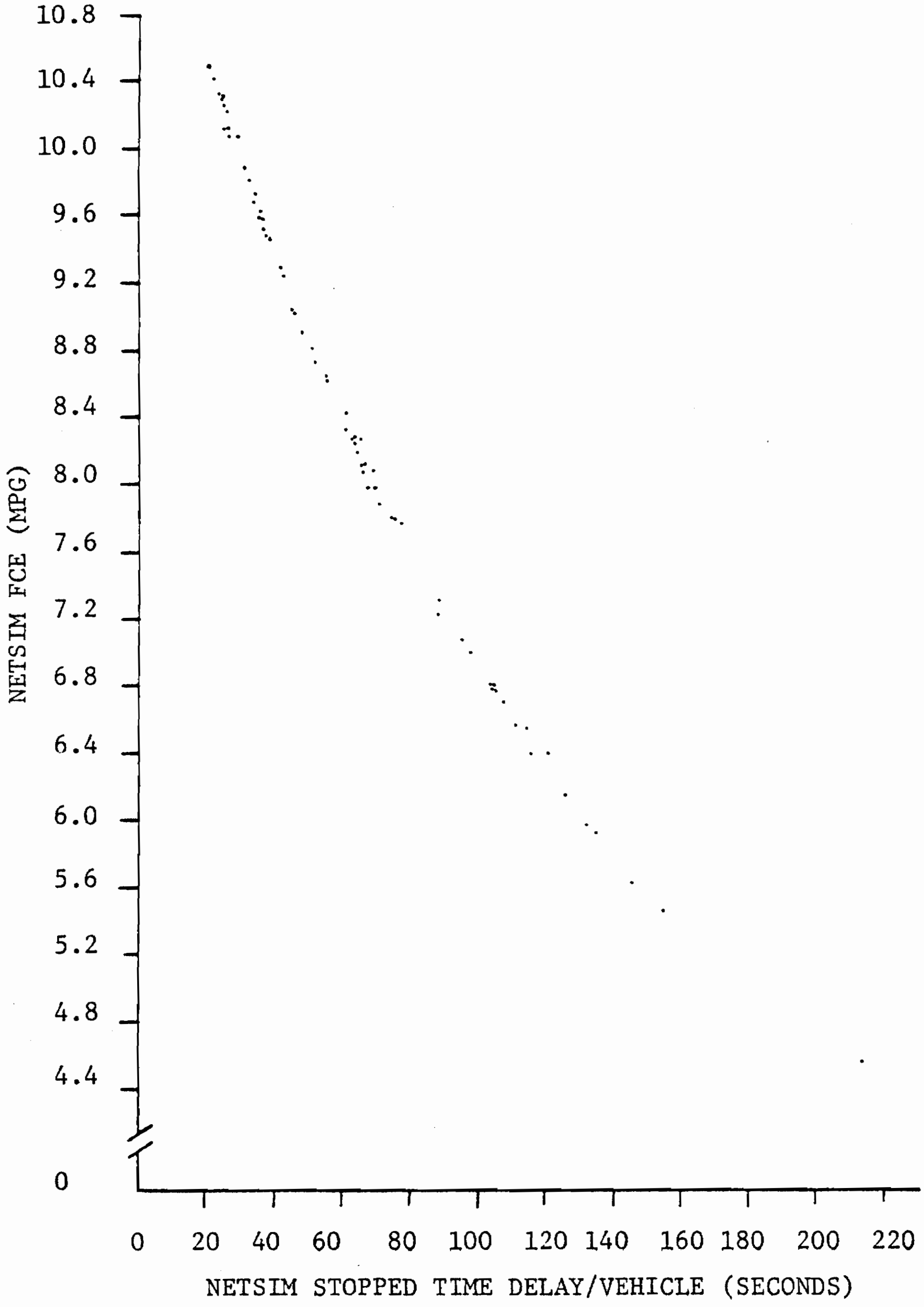

FIGURE 5.4 - NETSIM FCE vs. NETSIM Stopped Time Delay/Vehicle (Prices Fork Road)

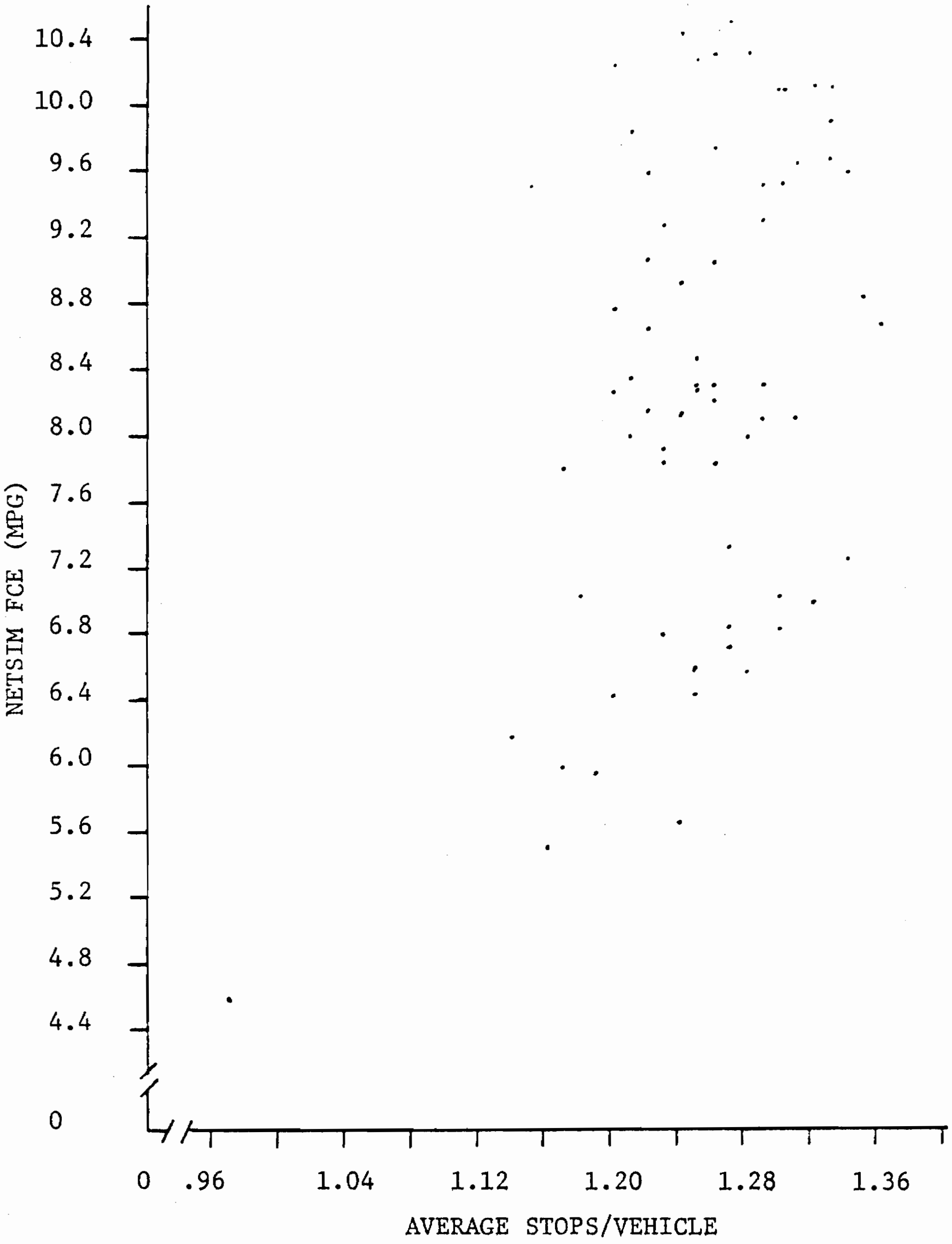

FIGURE 5.5 - NETSIM FCE vs. NETSIM Stops/Vehicle (Prices Fork Road)

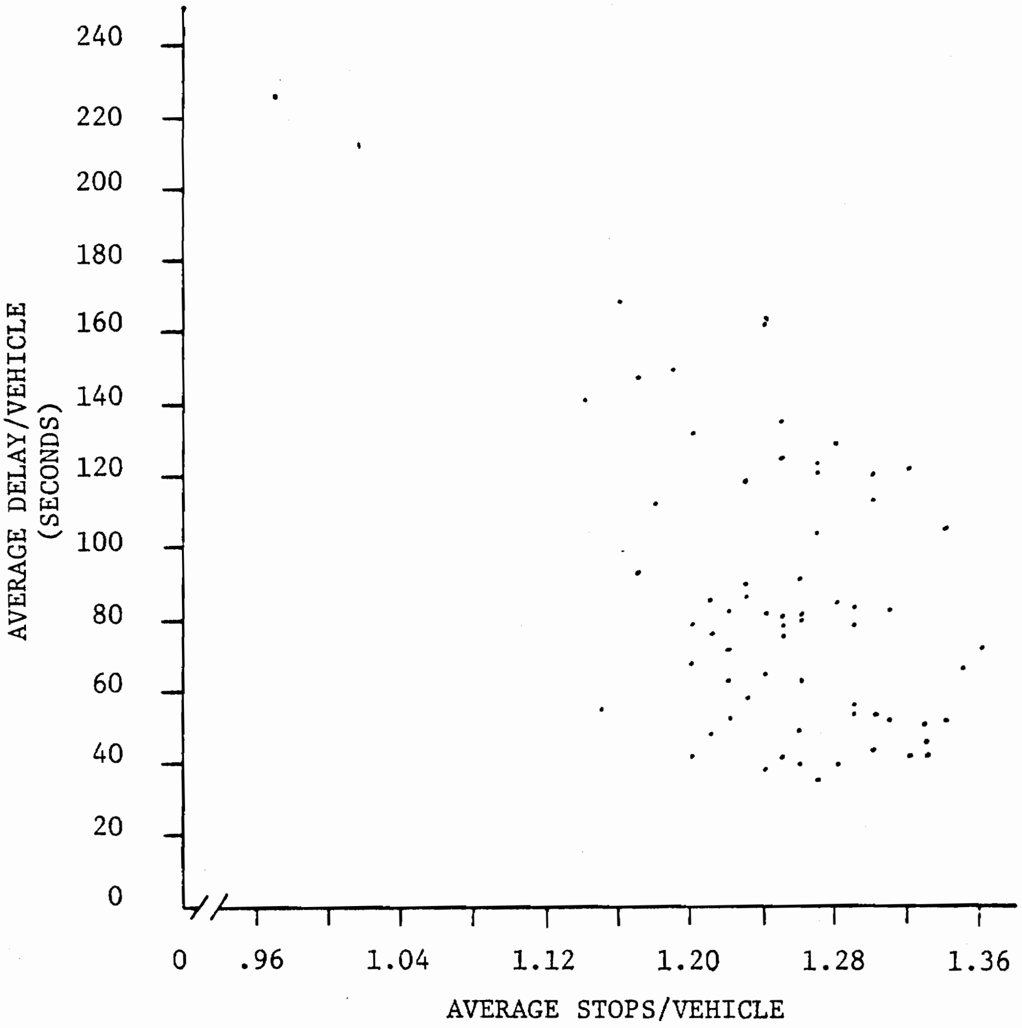

FIGURE 5.6 - NETSIM Delay/Vehicle vs. NETSIM Stops/Vehicle
(Prices Fork Road)

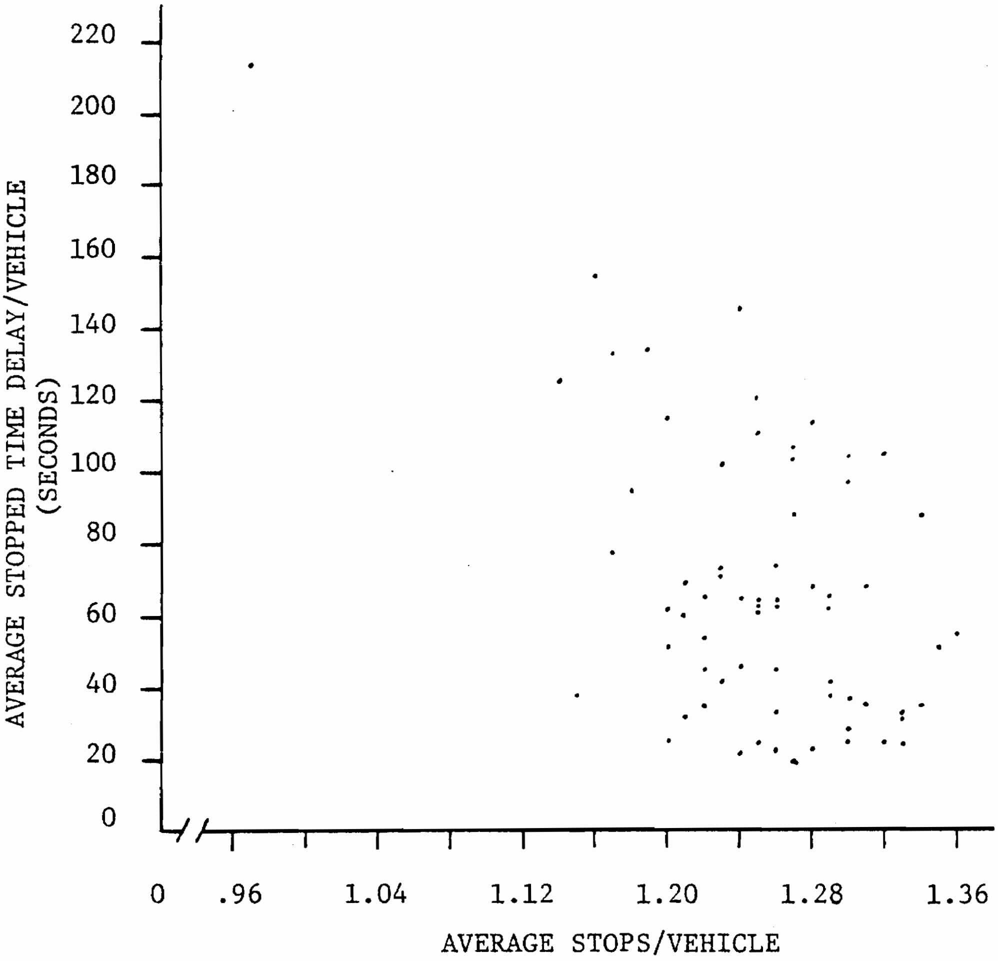

FIGURE 5.7 - <u>NETSIM Stopped Time Delay/Vehicle vs. NETSIM Stops/Vehicle</u>
(Prices Fork Road)

of vehicles that each signal timing plan was able to carry. The number of vehicle trips for each cycle length and stop penalty are given in Table 5.3.

5.2 Arlington County

A similar analysis of the TRANSYT 7 and NETSIM computer turns was made for the Arlington County network. 132 different combinations of cycle length and stop penalty were run with the TRANSYT 7 computer program for the Arlington County network. The entry link flow rates corresponding to the NETSIM link-node diagram (Figure 4.5) are given in Table 5.4. The cumulative network totals of delay, stops per second, and network performance index obtained from TRANSYT are given in Tables A.17 - A.28. As was the case for the Prices Fork Road network, the TRANSYT 7 estimates of delay and stops did not follow the logic of the program. For every cycle length tested there are inconsistent values of delay and stops.

The plots of performance index versus cycle length are shown in Figures A.36 - A.45. For most of the stop penalties evaluated there appears to be a smooth relationship between performance index and cycle length. The exception being the higher stop penalties 100, 200, and 1000, as happened with the Prices Fork Road network. For the timing plan utilizing a zero stop penalty, the performance index increased drastically for cycle lengths less than the optimal 70 second cycle. For stop penalties from 6 to 100 the performance index is much less sensitive to cycle lengths less than the optimum. The optimal cycle length for the ten different stop penalties range from 70 seconds to

TABLE 5.3 - NETSIM Estimated Vehicle Trips Per Hour Prices Fork Road

TRANSYT Stop Penalty	Cycle Length = 60 Sec.	Cycle Length = 70 Sec.	Cycle Length = 75 Sec.	Cycle Length = 80 Sec.
0	3571	3629	3640	3641
6	3561	3635	3638	3631
10	3574	3643	3638	3635
20	3574	3638	3640	3629
40	3566	3627	3640	3629
60	3568	3627	3597	3639
80	3562	3628	3640	3641
100	3581	3635	3640	3637
1000	3550	3634	3427	3603

TRANSYT Stop Penalty	Cycle Length = 90 Sec.	Cycle Length = 100 Sec.	Cycle Length = 120 Sec.	Cycle Length = 140 Sec.
0	3619	3612	3585	3608
6	3625	3611	3596	3603
10	3624	3591	3599	3613
20	3625	3599	3533	3611
40	3615	3608	3508	3495
60	3610	3590	3504	3510
80	3558	3609	3520	3508
100	3551	3604	3546	3489
1000	3623	3473	3512	3494

TABLE 5.4 - Entry Link Flow Rates (Arlington County)

Link	Flow Rate (Veh/Hr)	Lanes
801, 40	1745	2
802, 42	250	2
803, 42	110	1
803, 44	180	1
804, 44	278	1
805, 44	58	1
806, 43	74	1
807, 47	160	1
808, 49	312	2
809, 48	114	2
810, 51	1292	3
812, 50	434	2
813, 53	168	1
815, 55	550	2
816, 63	440	2
817, 56	1834	3
819, 57	1272	2
820, 58	40	1
821, 59	206	2
823, 45	152	2
824, 60	150	2
825, 61	120	2
826, 62	36	1

80 seconds. Also, as the stop penalty increased so did the optimal cycle length.

Of the 132 TRANSYT 7 runs, 90 of the timing plans were entered into NETSIM for fuel consumption evaluation. As in the Prices Fork Road analysis, a single one hour simulation NETSIM run was executed for each TRANSYT generated timing plan. Again, the seed for the random number generator in NETSIM was the same for all runs so as to predict accurate trends. The TRANSYT 7 timing plans evaluated were; cycle lengths of 60, 65, 70, 75, 80, 85, 90, 95 and 100 seconds with stop penalties of 0, 6, 10, 20, 40, 60, 80, 100 and 200; 60, 65, 70 and 75 second cycles with a stop penalty of 1000; and cycle length of 110, 120 and 140 seconds with stop penalties of 10 and 20. The values of FCE found from NETSIM are given in Table 5.5. These values are plotted against cycle length for the different stop penalties and shown in Figures A.46 - A.54. The range of optimal cycle lengths found for the different stop penalties is almost as wide as the range of cycle lengths. The optimal range is 60 to 100 seconds with optimal FCE cycle lengths occurring at 60, 75, 80, 85 and 100 seconds. For the Arlington County network, except when a stop penalty of zero is used, there is no dramatic decrease in FCE for cycle lengths less than the optimum.

The next relationship to be investigated is between the TRANSYT stop penalty and NETSIM FCE. The plots of this relationship for each cycle length are shown in Figures A.55 - A.63. Similar to the Prices Fork Road network, no particular stop penalty consistently produced maximum FCE. Stop penalties of 10 and 20 produced optimal FCE for

TABLE 5.5 - NETSIM Fuel Consumption Efficiency Arlington County, Virginia

TRANSYT Stop Penalty	Cycle Length = 60 Sec. (MPG)	Cycle Length = 65 Sec. (MPG)	Cycle Length = 70 Sec. (MPG)	Cycle Length = 75 Sec. (MPG)
0	4.89	5.98	6.62	7.56
6	5.43	6.02	5.66	5.77
10	4.98	5.06	6.86	5.65
20	6.06	4.69	5.12	5.61
40	5.31	4.60	4.86	5.96
60	6.39	4.14	4.95	5.65
80	6.03	4.59	4.95	6.88
100	6.11	4.47	4.87	6.71
200	7.26	6.90	5.42	6.38
1000	4.82	5.43	5.45	6.24

TRANSYT Stop Penalty	Cycle Length = 80 Sec. (MPG)	Cycle Length = 85 Sec. (MPG)	Cycle Length = 90 Sec. (MPG)	Cycle Length = 95 Sec. (MPG)
0	5.58	5.81	5.57	5.35
6	6.51	5.40	5.28	5.61
10	6.43	7.68	7.38	6.42
20	7.22	7.04	6.67	6.82
40	6.23	6.86	6.06	6.09
60	5.84	5.72	6.19	6.38
80	6.05	5.87	6.02	6.03
100	5.99	5.87	6.02	6.13
200	6.58	5.26	5.97	6.07

TRANSYT Stop Penalty	Cycle Length = 100 Sec. (MPG)	Cycle Length = 110 Sec. (MPG)	Cycle Length = 120 Sec. (MPG)	Cycle Length = 140 Sec. (MPG)
0	5.10	--	--	--
6	6.00	--	--	--
10	7.00	5.98	5.58	3.61
20	5.87	6.70	5.18	--
40	5.92	--	--	--
60	6.39	--	--	--
80	6.03	--	--	--
100	6.19	--	--	--
200	5.62	--	--	--

three cycle lengths each, 200 twice, and a zero stop penalty once.

The performance index was again of no help in finding a way to analyze TRANSYT results which would give maximum FCE. The plots of NETSIM FCE versus performance index are shown in Figures A.64 - A.72. From the graphs it can be seen that there is no consistent relationship between NETSIM FCE and TRANSYT performance index. In a couple of cases, the highest FCE was obtained from a signal timing plan with the worst performance index (stop penalties equal to 60 and 200).

Since the performance index was unable to help define optimal FCE for the Arlington County network, NETSIM FCE was plotted against TRANSYT total delay, and TRANSYT stops/second as was done for the Prices Fork Road network. Neither the delay (Figure 5.8) or stops (Figure 5.9) predicted by TRANSYT show any kind of relationship to NETSIM FCE.

As happened with the Prices Fork Road network, no useful relationship could be obtained between the TRANSYT 7 results and the NETSIM values of FCE. Therefore, the NETSIM values of stops and delay were analyzed for the Arlington County network as well. The values of average delay/vehicle, total delay, average stops/vehicle, and total stops obtained from NETSIM are given in Tables A.29 - A.40 and compared to the TRANSYT values for the same cycle length and stop penalties. The figures in these tables show a tremendous difference in the values obtained from the two programs. The NETSIM values of delay for almost every case are five to ten times greater than the TRANSYT values of delay. The NETSIM values of total stops are generally about twice as

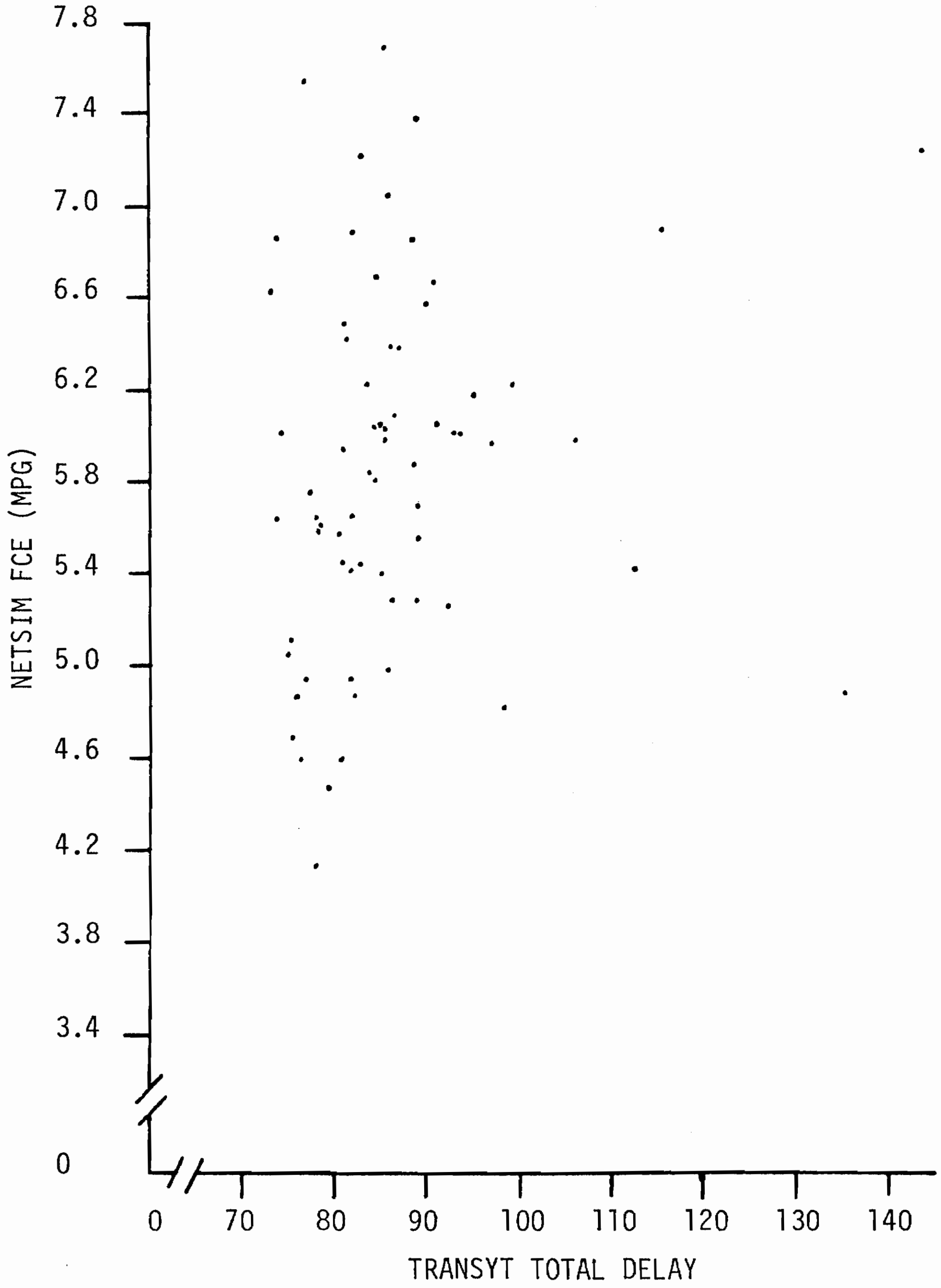

FIGURE 5.8 - NETSIM FCE vs. TRANSYT Total Delay (Arlington County)

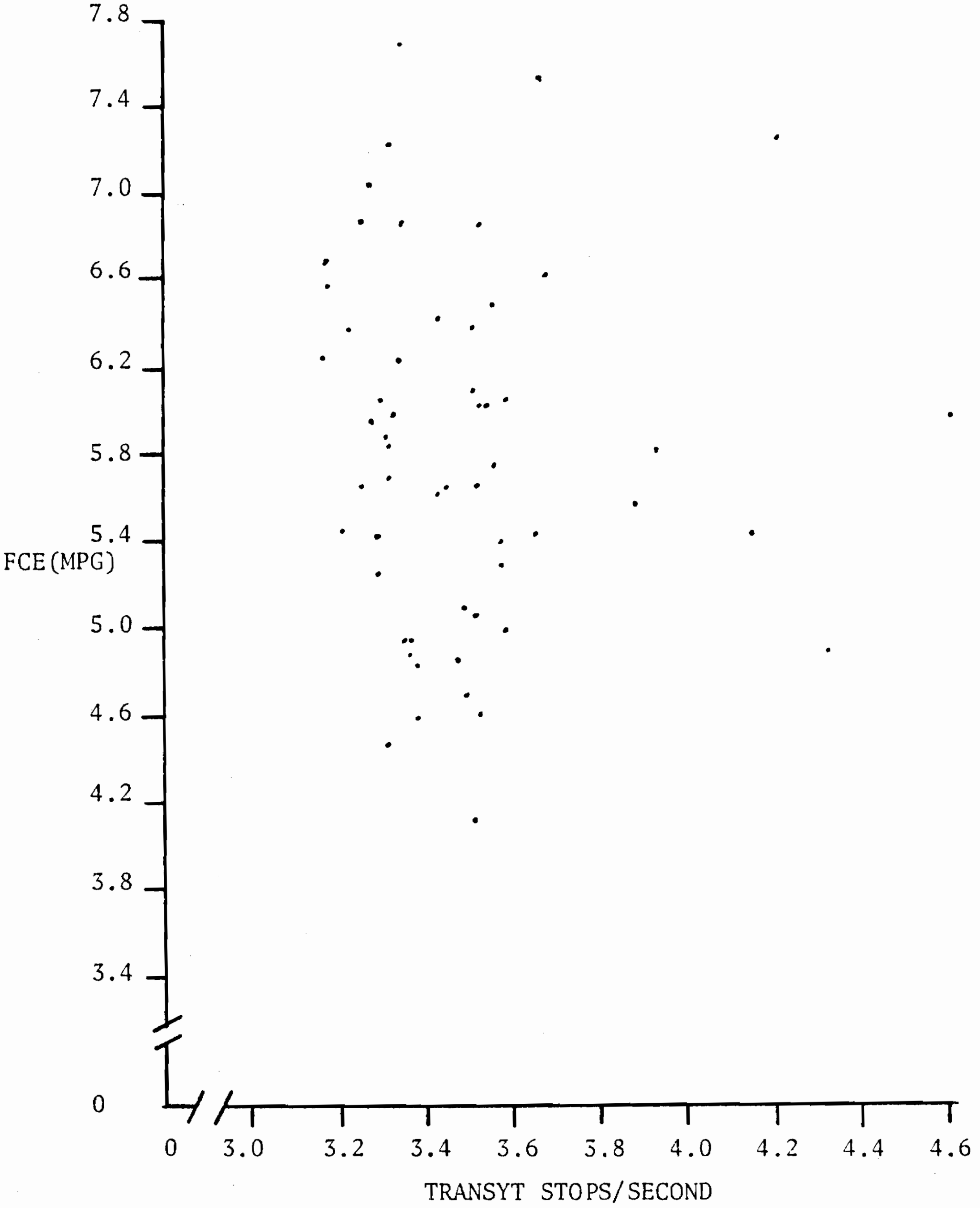

FIGURE 5.9 - FCE vs. TRANSYT Stops/Second
(Arlington County)

many as the number of TRANSYT stops.

NETSIM FCE was plotted versus NETSIM average delay/vehicle and average stopped delay/vehicle. Both graphs (Figures 5.10 and 5.11) show a very definite relationship between delay and FCE. As with the Prices Fork Road network, when delay is minimized (either average or stopped time delay/vehicle) FCE is maximized.

To further analyze the relationship between stops and fuel consumption, Figure 5.12 shows the plot of FCE versus NETSIM values for average stops/vehicle. Like the Prices Fork Road network, the NETSIM values for the Arlington County network show no definite relationship between FCE and stops/vehicle. The lack of a definite relationship also occurred when the NETSIM values of average delay/vehicle were plotted against the average stops/vehicle predicted by NETSIM (Figure 5.13).

The number of vehicles that NETSIM estimated the Arlington County network could carry for each signal timing plan are given in Table 5.6. It is generally believed that longer cycle lengths have greater capacity than shorter cycle lengths since the amount of lost time is reduced and therefore usable green time is increased. For this network the capacity is greatest for cycle lengths in the 85 to 100 second range. As the cycle length is increased over 100 seconds, the few data points available indicate that the capacity of the Arlington County network decreases. Two additional NETSIM runs were attempted for a 140 second cycle with a stop penalty of 20 and a 300 second cycle with a stop penalty of 10. The 300 second cycle was attempted so the theory

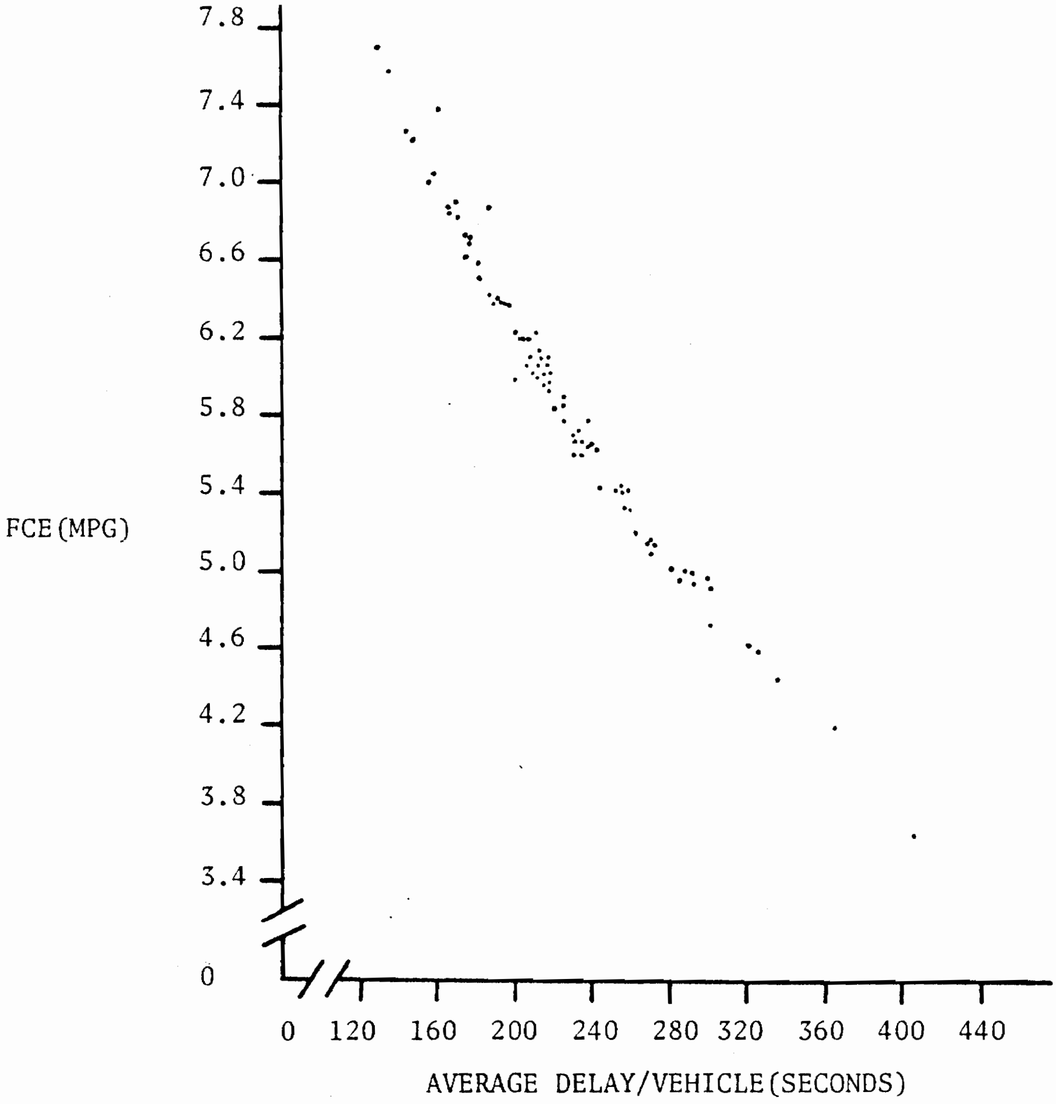

FIGURE 5.10 - FCE vs. Average Delay/Vehicle
(Arlington County)

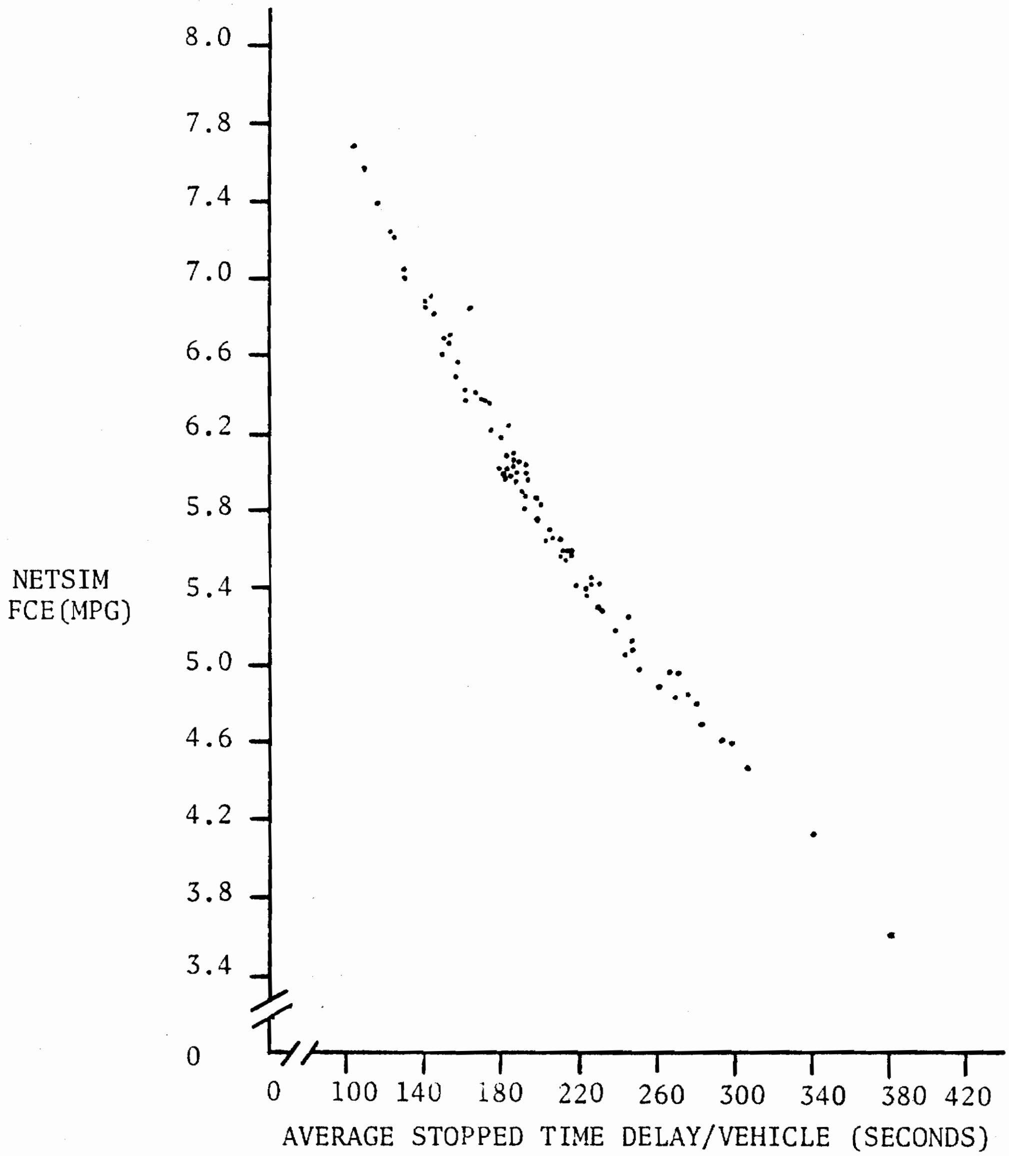

FIGURE 5.11 - FCE vs. Average Stopped Time Delay/Vehicle (Arlington County)

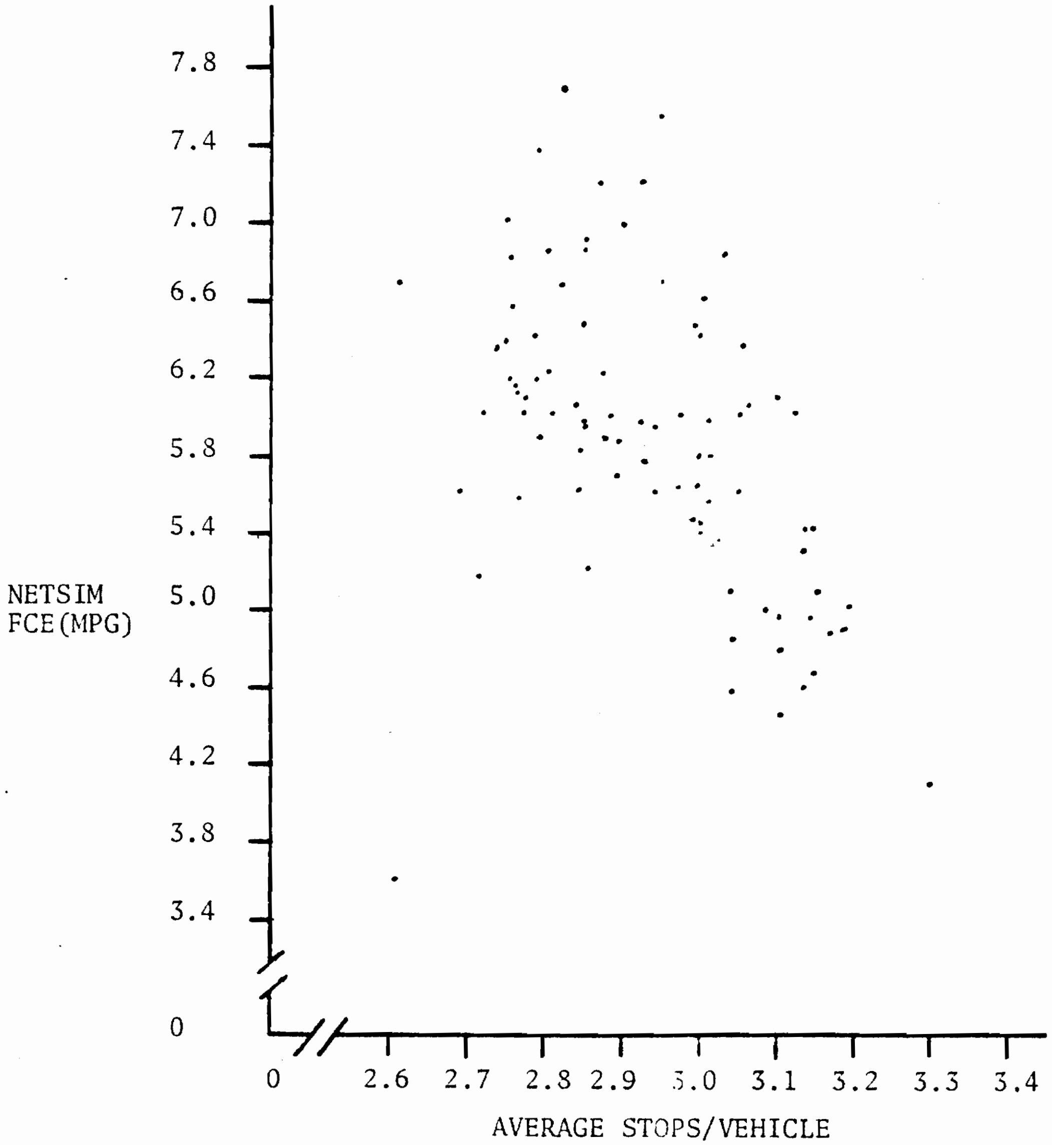

FIGURE 5.12 - FCE vs. Average Stops/Vehicle (Arlington County)

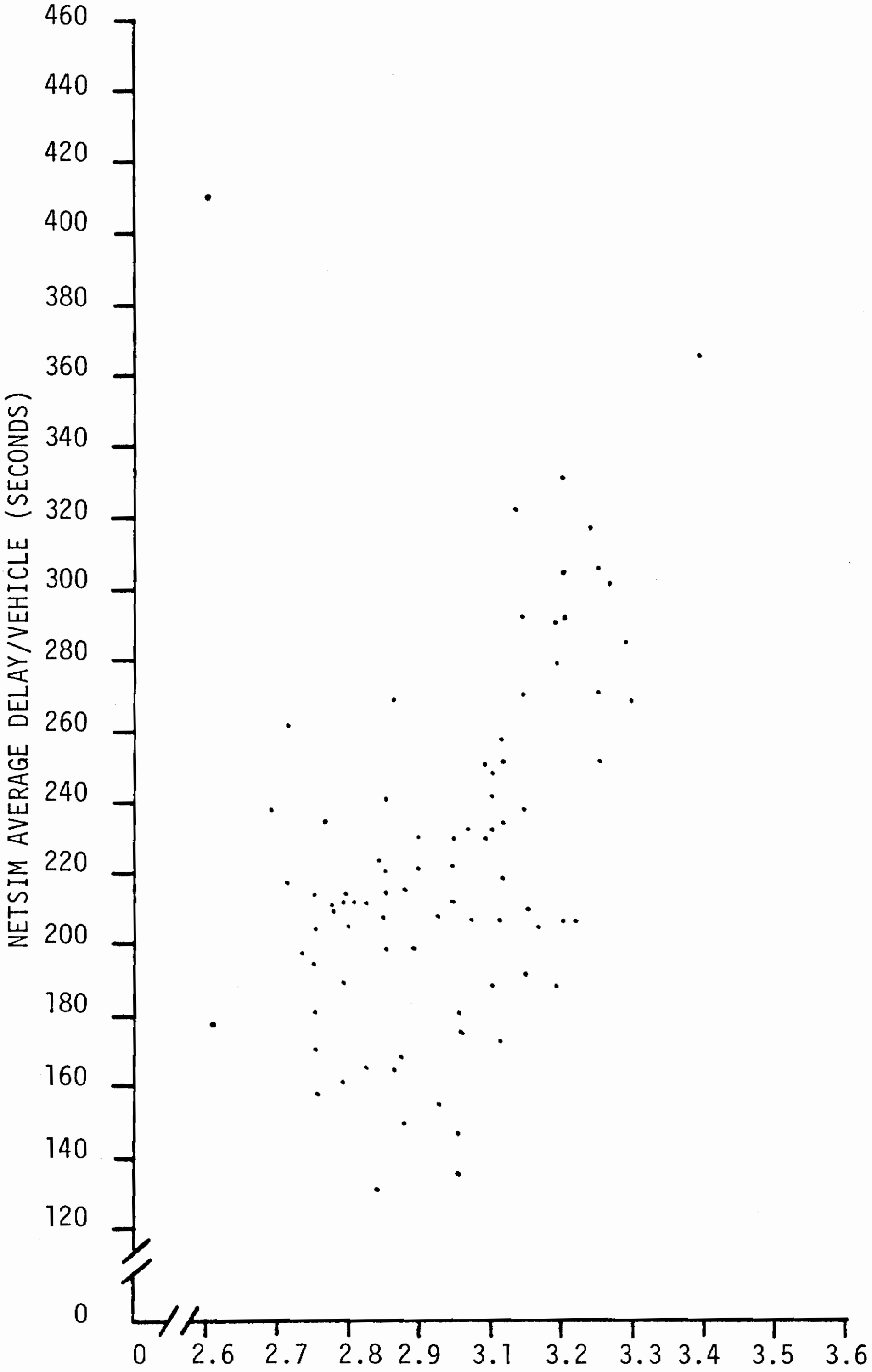

FIGURE 5.13 - NETSIM Average Delay/Vehicle vs. NETSIM Average Stops/Vehicle (Arlington County)

TABLE 5.6 - NETSIM Estimated Vehicle Trips Per Hour Arlington County, Virginia

TRANSYT Stop Penalty	Cycle Length = 60 Sec.	Cycle Length = 65 Sec.	Cycle Length = 70 Sec.	Cycle Length = 75 Sec.	Cycle Length = 80 Sec.	Cycle Length = 85 Sec.
0	8721	8988	9273	9302	9211	9247
6	8756	9019	8963	8999	9141	9121
10	8689	8862	9024	8966	8995	9347
20	8924	8696	8856	8946	9214	9329
40	8466	8557	8724	9206	9192	9377
60	8898	8565	8835	9096	8972	9189
80	8922	8435	8719	9185	8914	9247
100	8658	8449	8668	9306	8997	9247
200	8847	8936	8718	8844	9220	8669
1000	8111	8668	8856	8361	--	--

TRANSYT Stop Penalty	Cycle Length = 90 Sec.	Cycle Length = 95 Sec.	Cycle Length = 100 Sec.	Cycle Length = 110 Sec.	Cycle Length = 120 Sec.	Cycle Length = 140 Sec.
0	9103	9145	9050	--	--	--
6	9014	8951	9274	--	--	--
10	9507	9320	9576	9236	9169	8447
20	9268	9179	9283	9139	8980	--
40	9272	9114	9259	--	--	--
60	9142	9115	9219	--	--	--
80	9294	9066	9190	--	--	--
100	9294	9005	9173	--	--	--
200	9308	9224	9030	--	--	--

that capacity increases with cycle length could be tested. Unfortunately, the NETSIM program was unable to handle either of these timing plans due to its maximum-occupancy limit being reached.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This final chapter presents the conclusions drawn from the analysis of the data presented in Chapter 5. The NETSIM results are the basis from which most conclusions are made. The conclusions given attempt to answer the questions raised in Chapter 2, Goals and Objectives. Recommendations for further research are also presented.

6.1 Consistency of TRANSYT 7

One of the first questions raised when this thesis began was: How does TRANSYT perform and is it consistent with its logic? From the data presented in Chapter 5, it is concluded that TRANSYT does not perform in a truly consistent manner. There were many cases where delay decreased and stops increased when the TRANSYT logic dictates otherwise. This inconsistency could be caused by the hill-climbing procedure in TRANSYT. Since it is only an approximating optimization method, it could lead to some inconsistent results.

6.2 TRANSYT 7 As a Means to Minimize Fuel Consumption

A second goal of this thesis was to determine if TRANSYT 7 could be used so as to minimize fuel consumption in signalized networks. Based on the output from the TRANSYT 7 and NETSIM computer runs it is not possible to determine from TRANSYT 7 alone whether the signal timing plan it has developed will minimize fuel consumption or not. Of the three principle measures of effectiveness produced from TRANSYT (delay, stops and performance index) none showed any definite relationship with fuel consumption efficiency. Attempts to find a stop penalty which consistently minimizes fuel consumption also failed. No one stop penalty was found that would accomplish this. Although stop penalties of 10 and 20 minimized fuel consumption for several cycle lengths, there was no evidence to support the TRANSYT documentation's claim that "values up to 20 tend to minimize fuel consumption". Several stop penalties other than 10 and 20 also minimized fuel consumption for different cycle lengths.

6.3 Accuracy of TRANSYT 7

Webster's delay equation [15] was used to estimate average delay per vehicle on several links entering the two study networks. Since these links were on the border of the networks their flow characteristics would be similar to an isolated intersection. For most all of the links evaluated the values of delay obtained from Webster's equation were very similar to the values predicted by NETSIM. The TRANSYT 7 values were significantly less than those of Webster's and NETSIM. The cases where Webster's and NETSIM were greatly different occured when NETSIM indicated a saturated link downstream thereby causing increased delay on the upstream link. The major weakness in TRANSYT's traffic model appears to be its inability to accurately model saturated conditions. This is a situation where TRANSYT could be most beneficial, but instead it is its weakest point.

6.4 Fuel Consumption vs. Cycle Length

From the previous work regarding fuel consumption and cycle length, there were some conflicting views on this subject. Bauer and Courage were proclaiming longer cycle lengths would minimize fuel consumption. While on the other hand, Hurley and Ball, and Cohen and Euler were claiming that the minimum delay cycle would also produce minimum fuel consumption. The analysis performed for this thesis showed that FCE in the two networks is maximized when average delay/vehicle is minimized. This is perhaps the most significant finding of this thesis. Delay, the measure of effectiveness normally used for evaluating traffic signal settings may also be used to evaluate fuel consumption in networks.

6.5 Fuel Consumption vs. Vehicle Stops

From Claffey's data, it was reasonable to assume that if one could minimize or lower the number of stops, without increasing delay significantly, fuel consumption could be minimized. After analyzing the plots of FCE versus stops/vehicle and FCE vs. delay/vehicle, it was concluded that stops have much less influence on FCE than was previously believed. From the analysis it was found that delay is the critical element in traffic flow and not stops. It was also found that no relationship could be determined between stops and delay.

6.6 Final Conclusions

When this research first began, there were hopes that TRANSYT would be found to be a reliable, accurate tool that the traffic engineer could use with confidence. Now, that hope of confidence has changed to a warning of caution. One should beware of placing trust in the TRANSYT traffic model under high volume conditions. Perhaps under light flow conditions TRANSYT may be more reliable. If TRANSYT signal timings are implemented, it is recommended that field studies of delay be made before and after the signal strategy is implemented. The field data can be used to evaluate the effect of the TRANSYT signal timing strategy and be compared with the values predicted by TRANSYT. Unfortunately, such data collection would be both time consuming and expensive, and would be contrary to the basic purpose of a model.

Although TRANSYT was not found to be the reliable tool as hoped, a significant finding was made. For the two networks analyzed, fuel consumption appears to be totally dependent upon delay. No other variable tested showed any relationship with fuel consumption. Although they may not have known it, traffic engineers who have been timing their traffic signals to minimize delay have also been minimizing the fuel consumption at their signals. The question is, have they been doing this accurately?

6.7 Recommendations

As was stated in Chapter 2, the intersection is the "location where most accidents occur, where the greatest delay occurs, where the most fuel is wasted, where congestion is the greatest, and where land use tends to be in greatest conflict with the highway" [7]. With this many problems associated with one element of our transportation network, there is much research that could be performed to study ways of improving our intersections.

Due to the time and cost factors involved with executing the NETSIM program, the network analysis was limited to only two networks and one level of demand for each. Greater confidence in the data trends shown in this thesis could be gained by either examining these same networks for the off-peak and P.M. peak periods or different networks with different demands.

Another area of possible study could involve testing TRANSYT in a light volume network. Both of the networks analyzed for this thesis had saturated links. It would be worthwhile to test TRANSYT's accuracy in networks free of saturated links.

Prices Fork Road has very high cross-street volumes, therefore another arterial with only minor cross-street flows would be worth analyzing. Perhaps in this situation, stops would be found to have more of a relationship with fuel consumption than was found in this research.

This thesis examined only TRANSYT 7's ability to minimize fuel consumption in networks. Another possibility would be to perform a similar analysis using SIGOP to generate the signal timing plans.

Since TRANSYT was found to have some severe shortcomings, research could be concentrated on improving its accuracy, particularly in its delay model. One possibility could be to include an estimate of deceleration and acceleration delay in the TRANSYT model. Presently TRANSYT estimates only stopped time delay. Average deceleration delay/vehicle was added to the TRANSYT delay values for several entry links of the two networks analyzed and then compared to the NETSIM values of average delay/vehicle. The values of deceleration delay were calculated by multiplying the probability of stopping, obtained from Webster's equation [15], times the deceleration delay time given by Winfrey [29]. The values of TRANSYT delay, the added deceleration delay, the adjusted TRANSYT delay, and the NETSIM delay are given in Table 6.1. The adjusted values of TRANSYT delay are much closer to the NETSIM delay values. Because these were entry links, only deceleration delay was added. For internal links, TRANSYT could be altered so that it would estimate acceleration delay to vehicles leaving the upstream node and then add this to the deceleration delay at the downstream node.

Although TRANSYT has its weaknesses, it is still perhaps the best available program. The final comment on TRANSYT is, if it is to be used, it should be used with caution and with field monitoring.

TABLE 6.1 - Comparison of TRANSYT Adjusted Delay With NETSIM Delay

TRANSYT Delay (Sec/Veh)	Deceleration Delay (Sec/Veh)	Adjusted TRANSYT Delay (Sec/Veh)	NETSIM Delay (Sec/Veh)
10.881	4.558	15.439	18.2
10.149	5.023	15.172	16.2
10.149	5.023	15.172	16.7
5.815	4.047	9.862	11.9
1.249	1.669	2.918	4.6
7.307	3.190	10.497	11.0
6.918	2.978	9.896	10.6
7.386	2.861	10.247	10.3
17.968	4.358	22.326	19.0
8.087	3.084	11.171	11.7
10.490	3.221	13.711	15.0

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APPENDIX A

TRANSYT and NETSIM Computer Results

TABLE A.1 - TRANSYT 7 Output
Prices Fork Road
Cycle Length = 60 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)	Speed (Km/Hr)
0	44.62	24.826	19.799	44.625	1.21	18.00
6	51.04	24.961	19.242	44.203	1.14	18.12
10	55.49	25.106	19.270	44.376	1.11	18.07
20	66.62	25.106	19.292	44.398	1.11	18.06
40	88.75	25.413	19.187	44.600	1.10	18.01
60	110.68	25.413	19.198	44.611	1.10	18.00
80	132.51	25.413	19.315	44.728	1.10	17.97
100	154.22	26.289	19.251	45.540	1.09	17.74
1000	1124.25	31.524	19.538	51.062	1.07	16.34

TABLE A.2 - TRANSYT 7 Output
Prices Fork Road
Cycle Length = 70 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)	Speed (Km/Hr)
0	25.91	5.215	20.691	25.906	1.06	25.57
6	32.26	5.338	20.577	25.915	1.06	25.57
10	36.49	5.338	20.584	25.922	1.06	25.56
20	47.05	5.338	20.583	25.921	1.06	25.56
40	68.02	5.569	20.500	26.069	1.05	25.48
60	89.00	5.569	20.500	26.069	1.05	25.48
80	110.09	6.564	20.343	26.907	1.04	25.01
100	130.31	7.083	20.521	27.604	1.03	24.63
1000	1079.18	6.066	21.513	27.579	1.05	24.65

TABLE A.3 - TRANSYT 7 Output
Prices Fork Road
Cycle Length = 75 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)	Speed (Km/Hr)
0	26.24	4.092	22.152	26.244	1.09	25.38
6	32.15	4.298	21.552	25.850	1.05	25.60
10	36.34	4.298	21.552	25.850	1.05	25.60
20	47.06	4.193	21.957	26.150	1.05	25.43
40	67.86	4.665	21.739	26.404	1.04	25.29
60	87.98	4.310	22.846	27.156	1.01	24.87
80	109.57	4.543	22.263	26.806	1.03	25.07
100	130.25	4.543	22.263	26.806	1.03	25.07
1000	1036.98	4.969	23.880	28.849	1.01	23.99

TABLE A.4 - TRANSYT 7 Output
Prices Fork Road
Cycle Length = 80 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)	Speed (Km/Hr)
0	26.45	3.395	23.050	26.445	1.07	25.27
6	32.75	3.437	23.104	26.541	1.03	25.21
10	36.68	3.967	22.516	26.483	1.02	25.25
20	46.91	4.158	22.510	26.668	1.01	25.14
40	67.15	4.158	22.510	26.668	1.01	25.14
60	87.73	3.984	22.931	26.915	1.01	25.01
80	108.03	3.942	23.069	27.011	1.01	24.95
100	128.34	3.942	22.993	26.935	1.01	24.99
1000	1009.67	4.160	23.971	28.131	.98	24.35

TABLE A.5 - TRANSYT 7 Output
Prices Fork Road
Cycle Length = 90 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)	Speed (Km/Hr)
0	28.32	3.117	25.208	28.325	1.04	24.25
6	34.48	3.180	25.392	28.572	.98	24.13
10	38.15	3.346	24.653	27.999	1.02	24.42
20	48.11	3.147	24.648	27.795	1.02	24.53
40	68.60	3.780	24.662	28.442	1.00	24.19
60	87.06	3.518	25.786	29.304	.96	23.76
80	106.64	3.669	26.047	29.716	.96	23.56
100	125.82	4.120	26.052	30.172	.96	23.34
1000	1024.87	4.232	25.511	29.743	1.00	23.54

TABLE A.6 - TRANSYT 7 Output
Prices Fork Road
Cycle Length = 100 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)	Speed (Km/Hr)
0	30.21	3.182	27.032	30.214	1.03	23.32
6	35.82	3.001	26.890	29.891	.99	23.47
10	39.78	3.001	26.898	29.899	.99	23.47
20	49.54	3.296	26.872	30.168	.97	23.34
40	69.04	3.314	27.055	30.369	.97	23.24
60	88.13	3.555	26.996	30.551	.96	23.16
80	107.32	3.555	27.024	30.579	.96	23.14
100	126.88	3.955	27.626	31.581	.95	22.68
1000	989.00	5.750	28.520	34.270	.95	21.53

TABLE A.7 - TRANSYT 7 Output
Prices Fork Road
Cycle Length = 120 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)	Speed (Km/Hr)
0	34.81	2.914	31.899	34.813	1.06	21.31
6	40.87	3.241	31.616	34.857	1.00	21.29
10	44.85	3.241	31.680	34.921	.99	21.26
20	54.73	3.511	31.696	35.207	.98	21.15
40	75.76	3.656	31.139	34.795	1.02	21.31
60	93.81	3.556	32.109	35.665	.97	20.97
80	113.30	3.784	32.384	36.168	.96	20.78
100	137.70	4.016	32.113	36.149	1.02	20.79
1000	1003.18	5.186	33.909	39.095	.96	19.73

TABLE A.8 - TRANSYT 7 Output
Prices Fork Road
Cycle Length = 140 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)	Speed (Km/Hr)
0	40.81	3.061	37.747	40.808	1.05	19.16
6	45.21	3.325	35.988	39.313	.98	19.65
10	50.75	3.235	37.607	40.842	.99	19.15
20	60.56	3.280	37.765	41.045	.98	19.08
40	81.85	4.284	37.917	42.201	.99	18.72
60	98.62	5.153	37.407	42.560	.93	18.61
80	117.23	5.153	37.647	42.800	.93	18.53
100	136.31	6.295	37.251	43.546	.93	18.31
1000	927.37	127.048	42.821	169.869	.76	6.04

TABLE A.9 - TRANSYT and NETSIM Values of Delay and Stops
Prices Fork Road
Cycle Length = 60 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	44.625	4356	105.34	104.492	1.34	4785
6	44.203	4104	123.24	121.907	1.27	4522
10	44.376	3996	113.71	112.892	1.30	4646
20	44.398	3996	113.71	112.892	1.30	4646
40	44.600	3960	121.24	120.098	1.32	4707
60	44.611	3960	120.37	119.300	1.30	4638
80	44.728	3960	120.03	118.767	1.27	4524
100	45.540	3924	104.07	103.525	1.27	4548
1000	51.062	3852	135.46	133.583	1.25	4438

TABLE A.10 - TRANSYT and NETSIM Values of Delay and Stops
Prices Fork Road
Cycle Length = 70 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	25.906	3816	56.88	57.338	1.29	4681
6	25.915	3816	53.77	54.293	1.29	4689
10	25.922	3816	36.87	37.306	1.27	4627
20	25.921	3816	43.62	44.085	1.30	4729
40	26.069	3780	53.29	53.687	1.30	4715
60	26.069	3780	53.29	53.687	1.30	4715
80	26.907	3744	51.56	51.965	1.31	4753
100	27.604	3708	48.88	49.355	1.26	4580
1000	27.579	3780	51.51	51.998	1.34	4870

TABLE A.11 - TRANSYT and NETSIM Values of Delay and Stops
Prices Fork Road
Cycle Length = 75 Seconds

Stop Penalty	TRANSYT		NETSIM			
	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	26.244	3924	42.29	42.758	1.32	4804.8
6	25.850	3780	46.68	47.167	1.33	4838
10	25.850	3780	46.68	47.167	1.33	4838
20	26.150	3780	38.42	38.843	1.24	4514
40	26.404	3744	40.96	41.417	1.25	4550
60	27.156	3636	71.22	71.158	1.36	4892
80	26.806	3708	43.05	43.532	1.30	4732
100	26.806	3708	43.05	43.532	1.30	4732
1000	28.849	3636	82.80	78.825	1.31	4489

TABLE A.12 - TRANSYT and NETSIM Values of Delay and Stops
Prices Fork Road
Cycle Length = 80 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	26.445	3852	41.90	42.373	1.33	4842
6	26.541	3708	50.05	50.487	1.33	4829
10	26.483	3672	41.93	42.342	1.20	4362
20	26.668	3636	48.32	48.710	1.21	4391
40	26.668	3636	48.32	48.710	1.21	4391
60	26.915	3636	39.37	39.802	1.26	4585
80	27.011	3626	39.74	40.188	1.26	4588
100	26.935	3636	39.65	40.060	1.28	4656
1000	28.131	3528	67.44	67.502	1.35	4864

TABLE A.13 - TRANSYT and NETSIM Values of Delay and Stops
Prices Fork Road
Cycle Length = 90 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	28.325	3744	64.37	64.710	1.24	4488
6	28.572	3528	51.99	52.355	1.22	4422
10	27.999	3672	54.75	55.110	1.15	4223
20	27.795	3672	58.39	58.800	1.23	4518
40	28.442	3600	62.36	62.617	1.22	4410
60	29.304	3456	78.33	78.547	1.29	4657
80	29.716	3456	80.21	79.278	1.25	4447
100	30.172	3456	76.46	75.420	1.25	4439
1000	29.743	3600	62.38	62.778	1.26	4565

TABLE A.14 - TRANSYT and NETSIM Values of Delay and Stops
Prices Fork Road
Cycle Length = 100 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	30.214	3708	68.10	68.328	1.20	4334
6	29.891	3564	70.70	70.918	1.22	4405
10	29.899	3564	89.88	89.657	1.23	4417
20	30.168	3492	80.62	80.600	1.26	4535
40	30.369	3492	79.47	79.643	1.26	4546
60	30.551	3456	90.49	90.240	1.26	4523
80	30.579	3456	82.90	83.108	1.22	4403
100	31.581	3420	83.09	83.182	1.29	4649
1000	34.270	3420	93.01	89.727	1.17	4063

TABLE A.15 - TRANSYT and NETSIM Values of Delay and Stops
Prices Fork Road
Cycle Length = 120 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	34.813	3816	87.38	87.017	1.23	4410
6	34.857	3600	78.91	78.825	1.20	4315
10	34.921	3564	76.68	76.662	1.21	4355
20	35.207	3528	118.60	116.397	1.23	4346
40	34.795	3672	149.68	145.85	1.19	4174
60	35.665	3492	131.16	127.665	1.20	4205
80	36.168	3456	126.39	123.58	1.25	4400
100	36.149	3672	111.40	109.73	1.18	4184
1000	39.095	3456	128.97	125.82	1.28	4495

TABLE A.16 - TRANSYT and NETSIM Values of Delay and Stops
Prices Fork Road
Cycle Length = 140 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	40.808	3780	84.90	85.090	1.28	4618
6	39.313	3528	86.11	86.178	1.21	4360
10	40.842	3564	78.40	78.678	1.25	4516
20	41.045	3528	81.61	81.858	1.24	4478
40	42.201	3564	161.65	156.938	1.24	4334
60	42.560	3348	140.68	137.158	1.14	4001
80	42.800	3348	147.55	143.775	1.17	4104
100	43.546	3348	168.67	163.470	1.16	4047
1000	169.869	2736	226.93	220.252	.97	3389

TABLE A.17 - TRANSYT 7 Output
Arlington County, Va.
Cycle Length = 60 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	135.62	63.857	71.761	135.618	4.33
6	105.03	23.439	59.629	83.068	3.66
10	119.65	23.530	60.278	85.808	3.58
20	156.97	23.661	61.418	85.079	3.59
40	229.25	23.857	62.085	85.942	3.58
60	296.93	24.030	62.061	86.091	3.51
80	368.57	23.704	61.975	85.679	3.54
100	437.83	24.068	62.754	86.822	3.51
200	986.75	67.305	76.480	143.785	4.21
1000	3477.67	32.297	66.387	98.684	3.38
10000	35627.21	875.888	101.001	976.889	3.47

TABLE A.18 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 65 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	106.72	31.378	75.345	106.723	4.61
6	95.34	10.487	63.692	74.179	3.53
10	109.89	10.515	64.290	74.805	3.51
20	145.44	10.642	64.946	75.588	3.49
40	217.22	10.764	65.674	76.438	3.52
60	289.03	10.956	67.324	78.280	3.51
80	351.04	12.073	68.644	80.717	3.38
100	410.14	12.046	67.203	79.249	3.31
200	944.21	34.529	80.613	115.142	4.15
1000	3385.86	41.896	70.421	112.317	3.27
10000	32127.31	906.945	106.738	1013.683	3.11

TABLE A.19 TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 70 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	73.27	6.476	66.797	73.273	3.68
6	95.15	6.642	67.366	74.008	3.52
10	109.76	6.819	67.687	74.506	3.53
20	145.05	6.756	68.511	75.267	3.49
40	214.94	6.845	69.118	75.963	3.47
60	278.12	7.372	69.715	77.087	3.35
80	350.84	7.962	74.075	82.037	3.36
100	418.82	7.962	74.463	82.425	3.36
200	739.80	8,170	74.071	82.241	3.29
1000	3293.77	8.578	72.357	80.935	3.21
10000	37483.09	338.432	91.252	429.684	3.71

TABLE A.20 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 75 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	76.75	5.780	70.973	76.753	3.67
6	98.89	6.054	71.502	77.556	3.56
10	112.42	6.079	71.819	77.898	3.45
20	147.18	6.199	72.325	78.524	3.43
40	212.65	7.205	74.121	81.326	3.28
60	277.63	7.266	75.047	82.313	3.26
80	343.09	7.301	74.771	82.072	3.26
100	402.89	9.461	75.390	84.851	3.18
200	732.28	10.001	76.718	86.719	3.23
1000	3265.34	21.309	77.254	98.563	3.17
10000	36972.54	372.047	99.040	471.087	3.65

TABLE A.21 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 80 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	80.72	5.241	75.478	80.719	3.88
6	102.74	5.533	75.870	81.403	3.56
10	115.86	5.712	75.803	81.515	3.43
20	148.71	6.030	76.360	83.390	3.32
40	217.39	6.331	77.441	83.772	3.34
60	283.47	6.419	77.709	84.128	3.32
80	349.03	6.911	77.989	84.900	3.30
100	418.20	6.832	78.726	85.558	3.33
200	726.17	9.759	80.305	90.064	3.18
1000	3159.09	62.035	83.104	145.139	3.01
10000	35975.88	427.614	107.073	534.687	3.54

TABLE A.22 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 85 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	84.50	5.136	79.362	84.498	3.93
6	106.54	5.383	79.686	85.069	3.58
10	119.09	5.735	79.767	85.502	3.36
20	151.49	5.980	79.983	85.963	3.28
40	221.98	6.107	81.993	88.100	3.35
60	288.19	6.608	82.970	89.578	3.31
80	353.90	6.648	82.322	88.970	3.31
100	420.13	6.648	82.322	88.970	3.31
200	749.40	8.706	83.530	92.236	3.29
1000	3166.06	69.809	87.926	157.735	3.01
10000	37470.88	124.645	97.930	222.575	3.72

TABLE A.23 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 90 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	88.49	5.079	83.416	88.495	3.87
6	109.90	5.239	83.514	88.753	3.52
10	121.88	5.545	83.358	88.903	3.30
20	157.91	5.726	85.063	90.789	3.36
40	220.74	5.686	85.073	90.759	3.25
60	288.69	6.457	86.039	92.496	3.27
80	357.12	6.512	87.168	93.680	3.29
100	423.07	6.514	87.233	93.747	3.29
200	753.33	8.114	88.867	96.981	3.28
1000	3361.34	73.618	90.236	163.854	3.20
10000	36162.56	152.877	101.774	254.651	3.59

TABLE A.24 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 95 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	92.71	5.072	87.635	92.707	3.91
6	115.11	5.291	89.242	94.533	3.43
10	127.47	5.410	88.806	94.216	3.33
20	159.94	5.964	88.347	94.311	3.28
40	226.01	6.413	89.195	95.608	3.26
60	291.40	6.603	90.079	96.682	3.25
80	357.47	7.218	90.902	98.120	3.24
100	422.14	7.601	90.953	98.554	3.24
200	748.76	7.229	91.097	98.326	3.25
1000	3296.53	85.550	94.369	179.919	3.12
10000	36026.32	165.528	108.465	273.993	3.58

TABLE A.25 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 100 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	97.05	4.934	92.118	97.052	3.91
6	120.65	5.053	93.345	98.398	3.71
10	136.47	5.108	95.026	100.134	3.63
20	165.44	5.485	93.869	99.354	3.30
40	231.57	5.940	94.470	100.410	3.28
60	296.07	6.797	94.195	100.992	3.25
80	361.98	7.151	94.571	101.722	3.25
100	426.40	7.415	94.926	102.341	3.24
200	744.45	8.496	95.567	104.063	3.20
1000	3317.40	9.557	96.310	105.867	3.21
10000	35615.93	187.807	113.452	301.259	3.53

TABLE A.26 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 110 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	106.18	5.122	101.056	106.178	3.88
6	129.31	5.264	102.296	107.560	3.63
10	144.81	5.370	103.125	108.495	3.63
20	173.16	5.868	101.847	107.715	3.27
40	239.25	6.804	103.049	109.853	3.23
60	303.69	7.203	103.101	110.304	3.22
80	377.15	7.497	105.933	113.43	3.30
100	440.22	9.876	107.050	116.926	3.23
200	753.34	11.072	107.179	118.251	3.18
1000	3303.98	18.185	109.450	127.635	3.18
10000	36163.54	95.199	120.756	215.955	3.59

TABLE A.27 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 120 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	111.25	5.300	105.945	111.245	3.63
6	134.78	5.500	107.677	113.177	3.60
10	149.28	5.547	108.834	114.381	3.49
20	201.71	8.474	121.291	129.765	3.60
40	273.28	8.375	123.296	131.671	3.54
60	343.52	9.404	125.428	134.832	3.48
80	417.90	9.819	128.994	138.813	3.49
100	480.69	8.702	123.769	132.471	3.48
200	820.72	9.406	127.183	136.589	3.42
1000	3633.32	65.255	136.121	201.376	3.43
10000	36932.08	112.921	131.438	244.359	3.67

TABLE A.28 - TRANSYT 7 Output
Arlington County, Virginia
Cycle Length = 140 Seconds

Stop Penalty	Performance Index	Random Delay (Veh-Hrs/Hr)	Uniform Delay (Veh-Hrs/Hr)	Total Delay (Veh-Hrs/Hr)	Stops (Veh/Sec)
0	142.25	6.324	135.921	142.245	4.30
6	164.84	7.483	134.900	142.383	3.74
10	180.83	8.011	135.263	143.274	3.76
20	220.18	7.984	138.912	146.896	3.66
40	289.90	10.170	137.888	148.058	3.55
60	369.82	9.100	142.429	151.529	3.64
80	447.79	11.303	142.016	153.319	3.68
100	518.51	10.933	140.826	151.759	3.67
200	899.57	23.252	150.256	173.508	3.63
1000	3742.80	93.431	150.535	243.966	3.50
10000	28744.22	906.207	201.816	1108.023	2.76

TABLE A.29 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 60 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	135.618	15588	284.52	689.247	3.18	27732.78
6	83.068	13176	243.43	592.075	3.00	26268.00
10	85.808	12888	279.13	673.707	3.08	26762.12
20	85.079	12924	204.95	508.060	3.06	27307.44
40	85.942	12888	255.78	601.498	3.13	26498.58
60	86.091	12636	188.42	465.707	3.06	27227.88
80	85.679	12744	207.19	513.487	3.12	27836.64
100	86.822	12636	207.43	498.865	3.10	26839.80
200	143.785	15156	148.44	364.790	2.92	25833.24
1000	98.684	12168	305.39	688.055	3.10	25144.10

TABLE A.30 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 65 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	106.723	16956	208.12	519.602	3.01	27054.00
6	74.179	12708	210.14	526.450	3.05	27507.95
10	74.805	12636	269.92	664.448	3.19	28269.78
20	75.588	12564	306.19	739.630	3.15	27392.00
40	76.438	12672	316.40	752.073	3.13	26783.00
60	78.280	12636	366.60	872.207	3.29	28179.00
80	80.717	12168	322.16	754.838	3.03	25558.00
100	79.249	11916	332.94	781.390	3.10	26192.00
200	115.142	14940	168.48	418.198	2.86	25557.00
1000	112.317	11772	253.30	609.900	3.14	27217.00

TABLE A.31 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 70 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	73.273	13248	174.97	450.695	3.01	27912
6	74.008	12672	231.79	577.098	2.99	26799
10	74.506	12708	190.97	478.687	3.03	27343
20	75.267	12564	272.08	669.317	3.15	27896
40	75.963	12492	293.91	712.240	3.03	26434
60	77.087	12060	291.90	716.375	3.14	27742
80	82.037	12096	293.38	710.542	3.10	27029
100	82.425	12096	301.76	726.570	3.17	27478
200	82.241	11844	256.97	622.295	3.13	27287
1000	80.935	11556	252.38	620.848	2.99	26479

TABLE A.32 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 75 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	76.753	13212	136.00	351.410	2.95	27441
6	77.556	12816	223.43	558.523	2.93	26367
10	77.898	12420	231.67	576.982	2.94	26360
20	78.524	12348	238.13	591.742	3.04	27196
40	81.326	11808	212.72	543.968	2.94	27066
60	82.313	11736	234.76	593.158	2.96	26924
80	82.072	11736	166.97	426.005	2.86	26269
100	84.851	11448	177.66	459.250	2.95	27453
200	86.719	11628	198.98	488.835	2.85	25205
1000	98.563	11412	212.10	492.602	2.81	23494

TABLE A.33 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 80 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	80.719	13968	233.50	597.445	3.00	27633
6	81.403	12816	182.68	463.845	2.99	27332
10	81.515	12348	188.22	470.290	3.00	26985
20	83.390	11952	151.65	388.145	2.87	26444
40	83.772	12024	199.77	510.068	2.88	26473
60	84.128	11952	224.50	559.503	2.84	25480
80	84.900	11880	216.23	535.403	2.87	25583
100	85.558	11988	220.66	551.462	2.85	25641
200	90.064	11448	182.19	446.617	2.76	25447

TABLE A.34 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 85 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	84.498	14148	218.74	561.853	3.02	27926
6	85.069	12888	249.22	631.427	3.00	27363
10	85.502	12096	131.55	341.563	2.83	26452
20	85.963	11808	158.84	411.613	2.76	25748
40	88.100	12060	166.82	434.518	2.81	26349
60	89.578	11916	232.47	593.382	2.89	26556
80	88.970	11916	223.88	575.062	2.89	26724
100	88.970	11916	223.88	575.062	2.89	26724
200	92.236	11844	269.74	649.553	2.86	24793

TABLE A.35 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 90 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	88.495	13932	235.29	594.968	3.01	27400
6	88.753	12672	258.65	647.620	3.01	27132
10	88.903	11880	162.08	428.027	2.79	26524
20	90.789	12096	176.55	454.517	2.83	26228
40	90.759	11700	208.32	536.527	2.84	26332
60	92.496	11772	205.25	521.217	2.79	25506
80	93.680	11844	212.06	547.467	2.82	26209
100	93.747	11844	212.06	547.467	2.82	26209
200	96.981	11808	216.81	560.570	2.85	26528

TABLE A.36 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 95 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	92.707	14076	252.93	642.515	3.02	27618
6	94.533	12348	241.69	600.943	2.84	25421
10	94.216	11988	189.81	491.387	2.78	25910
20	94.311	11808	171.76	437.935	2.76	25334
40	95.608	11736	210.18	532.093	2.77	25246
60	96.682	11700	197.29	499.517	2.73	24884
80	98.120	11664	217.74	548.340	2.72	24660
100	98.553	11664	210.01	525.325	2.77	24944
200	98.326	11700	212.97	545.670	2.78	25643

TABLE A.37 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 100 Seconds

Stop Penalty	TRANSYT		NETSIM			
	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
0	97.052	14076	271.46	682.433	3.03	27422
6	98.398	13356	207.76	535.205	2.97	27544
10	100.134	13068	157.38	418.642	2.90	27770
20	99.354	11880	216.57	558.462	2.79	25900
40	100.410	11808	215.70	558.547	2.87	26754
60	100.992	11700	194.43	497.903	2.75	25352
80	101.722	11700	213.85	545.907	2.75	25272
100	102.341	11664	204.99	522.333	2.76	25317
200	104.063	11520	238.07	597.167	2.68	24200

TABLE A.38 - TRANSYT and NETSIM Values of Delay and Stops Arlington County Virginia Cycle Length = 110 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
10	108.495	13068	207.99	533.600	2.92	26969
20	107.715	11772	177.35	450.232	2.62	23944

TABLE A.39 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 120 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
10	114.381	12564	236.86	603.272	2.77	25398
20	129.765	12960	262.14	653.893	2.72	24426

TABLE A.40 - TRANSYT and NETSIM Values of Delay and Stops
Arlington County Virginia
Cycle Length = 140 Seconds

	TRANSYT		NETSIM			
Stop Penalty	Total Delay (Veh-Hrs/Hr)	Total Stops (Veh-Stops/Hr)	Delay Vehicle (Sec/Veh)	Total Delay (Veh-Hrs/Hr)	Average Stops (Stops/Veh)	Total Stops (Veh-Stops/Hr)
10	143.274	13536	411.34	965.165	2.61	22047

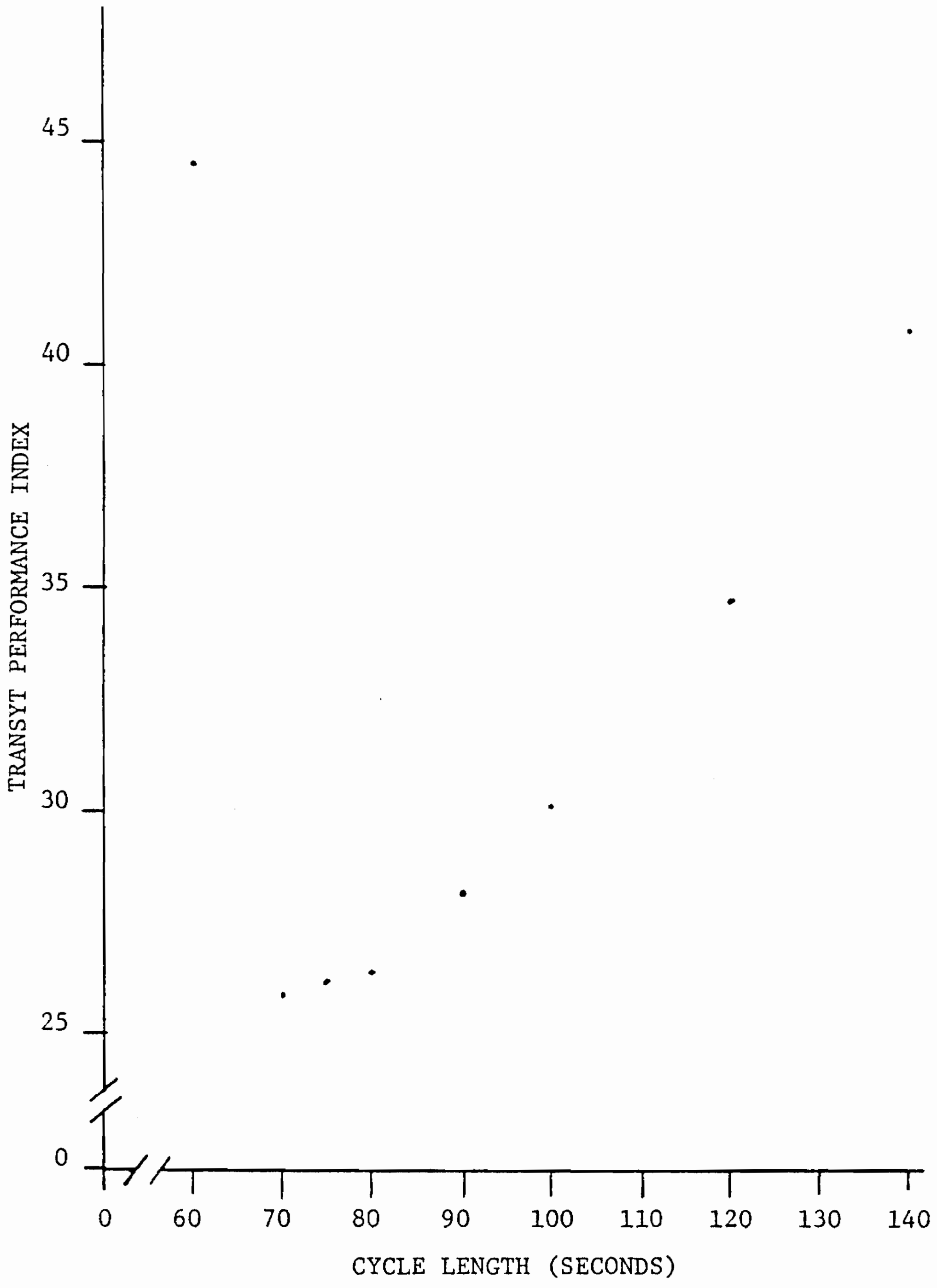

FIGURE A.1 - TRANSYT Performance Index vs. Cycle Length
(Stop Penalty = 0, Prices Fork Road)

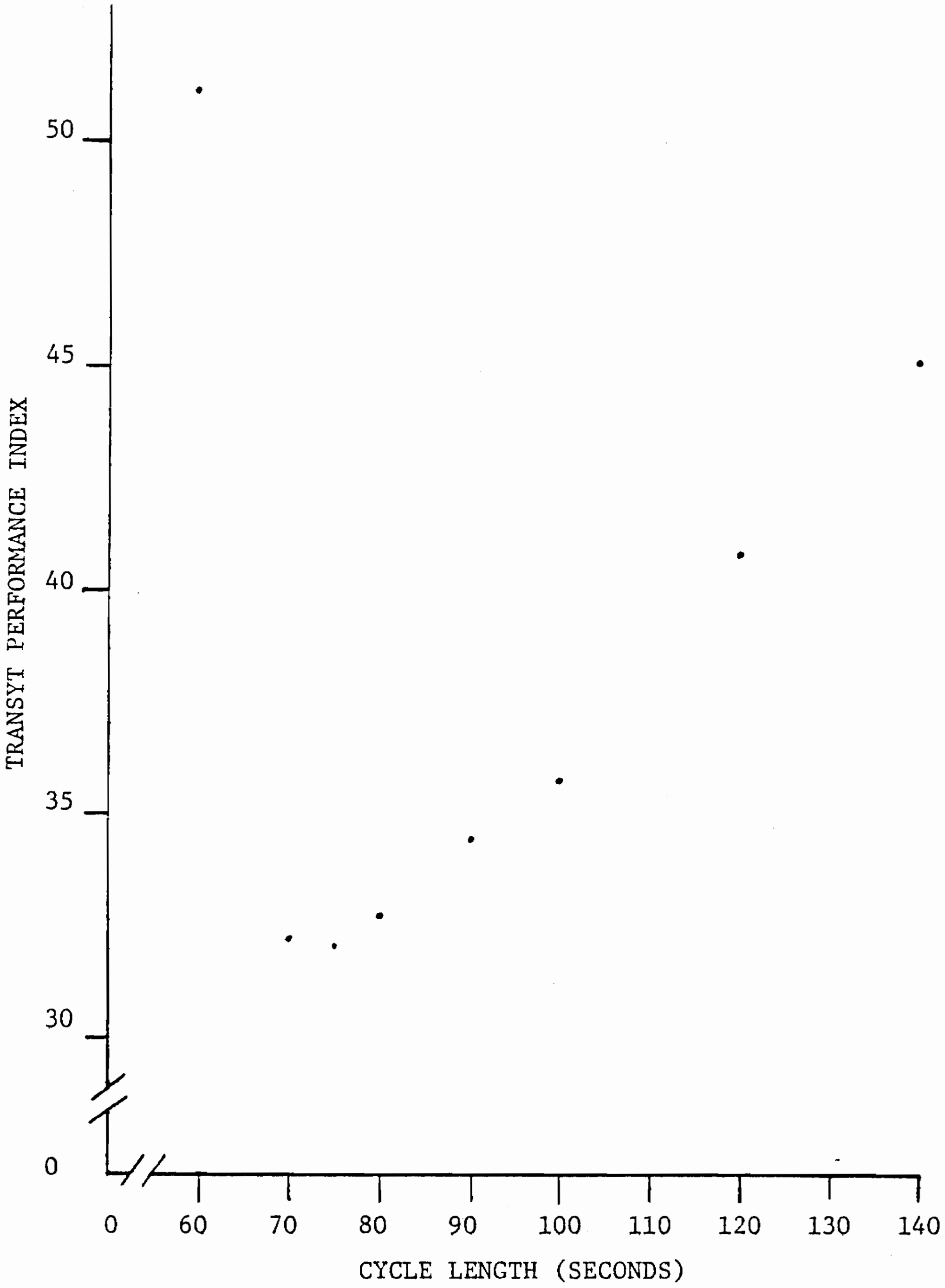

FIGURE A.2 - TRANSYT Performance Index vs. Cycle Length
(Stop Penalty = 6, Prices Fork Road)

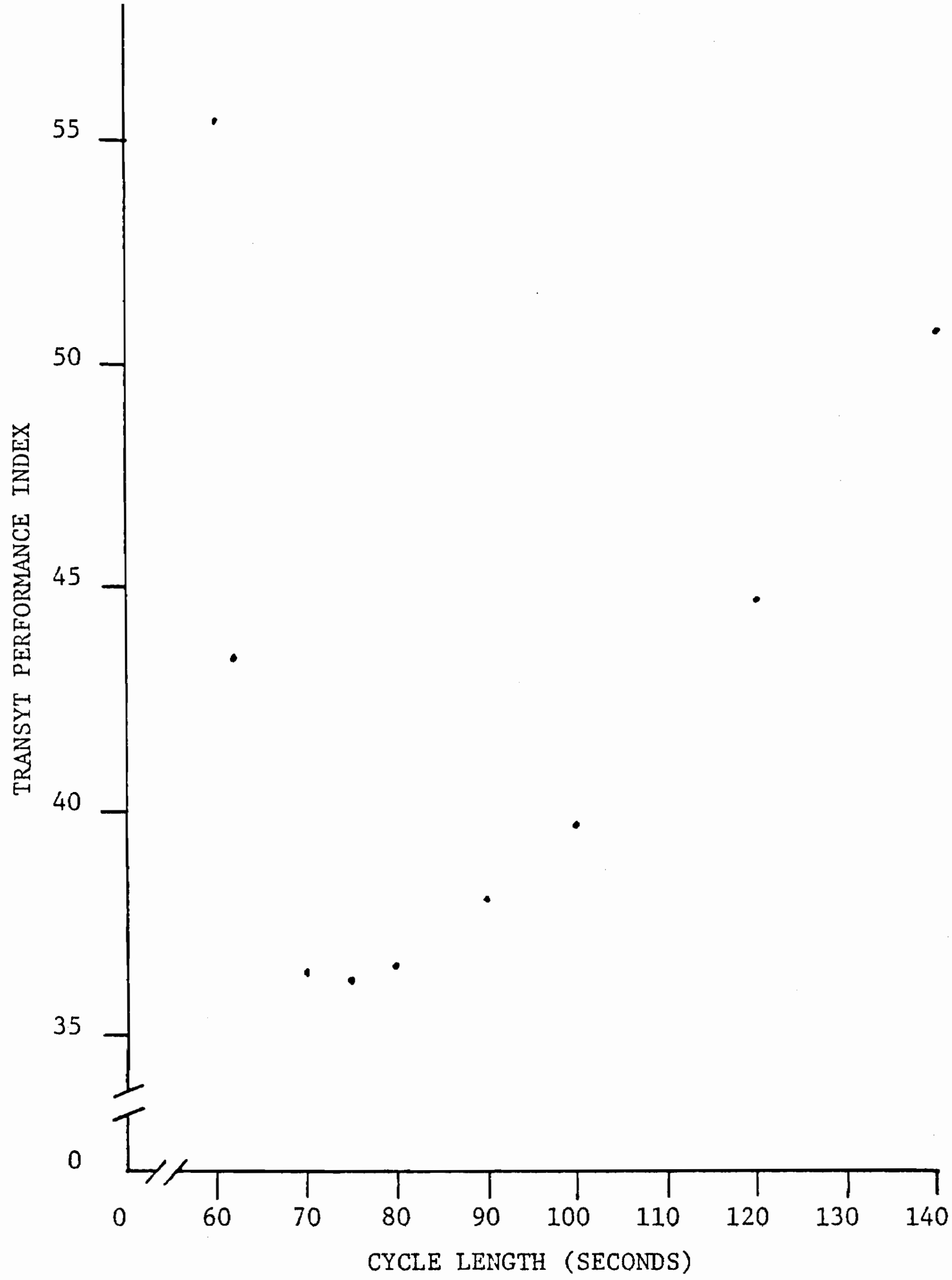

FIGURE A.3 - <u>TRANSYT Performance Index vs. Cycle Length</u>
(Stop Penalty = 10, Prices Fork Road)

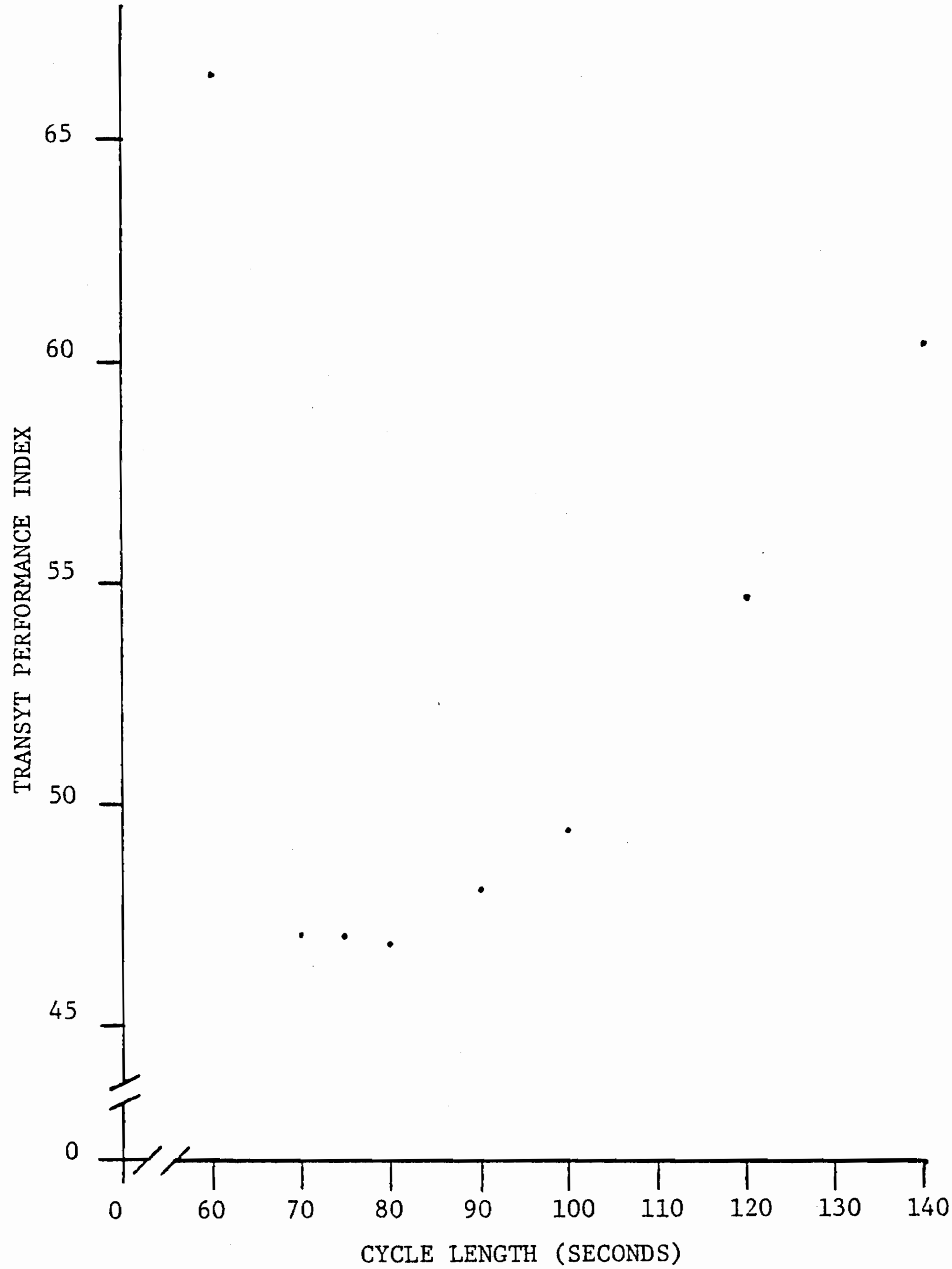

FIGURE A.4 - TRANSYT Performance Index vs. Cycle Length
(Stop Penalty = 20, Prices Fork Road)

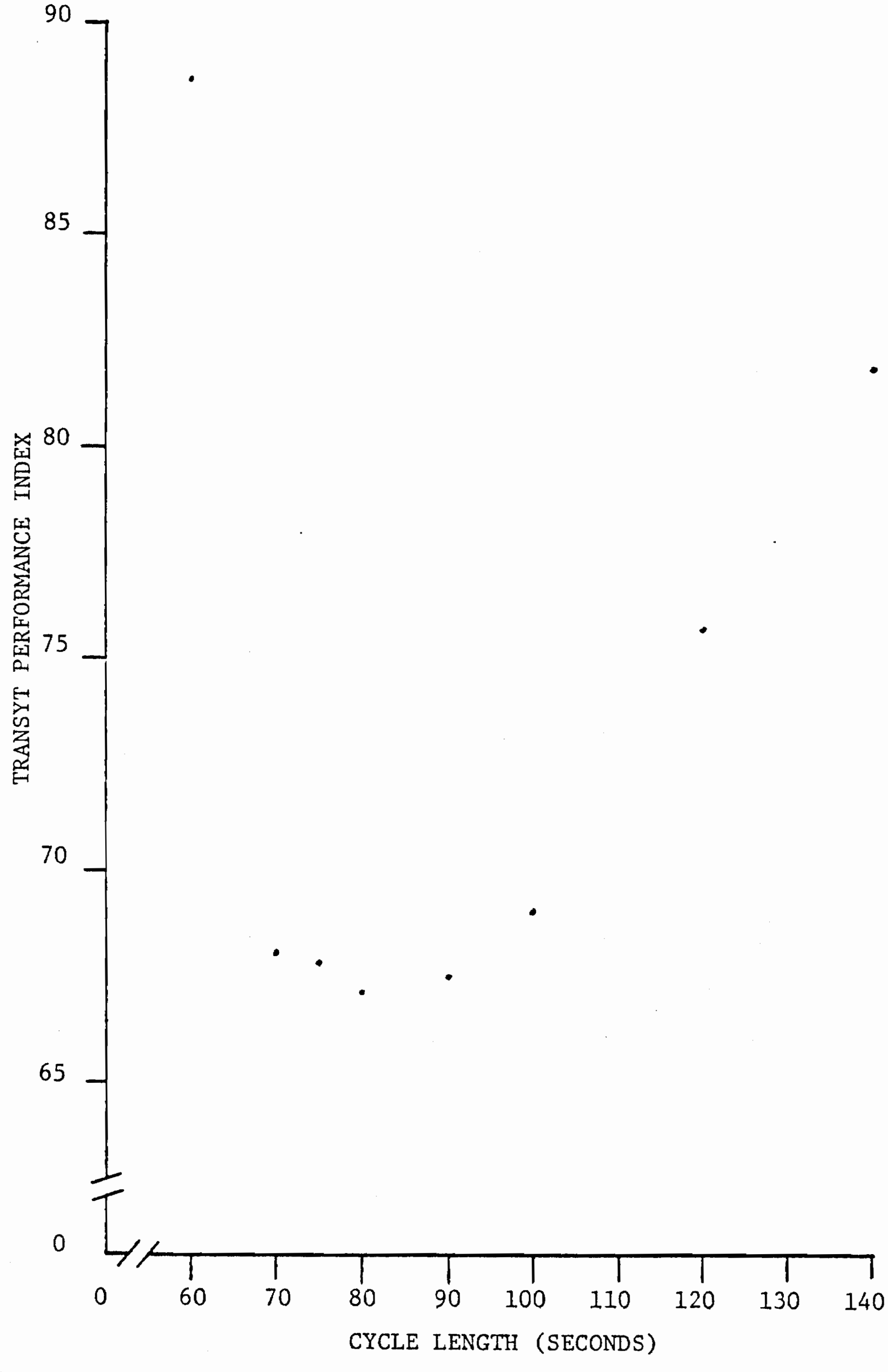

FIGURE A.5 - TRANSYT Performance Index vs. Cycle Length
(Stop Penalty = 40, Prices Fork Road)

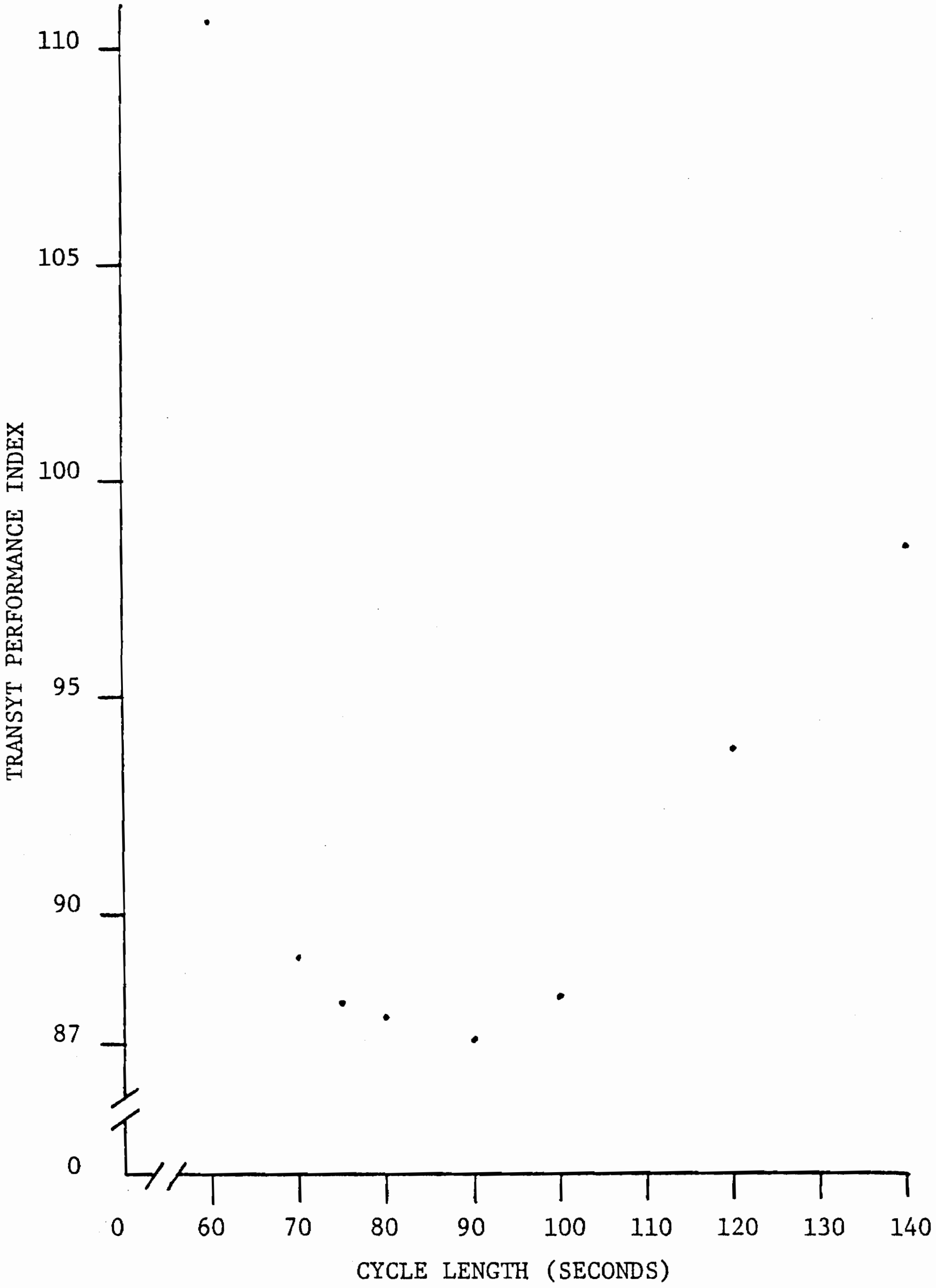

FIGURE A.6 - <u>TRANSYT Performance Index vs. Cycle Length</u>
(Stop Penalty = 60, Prices Fork Road)

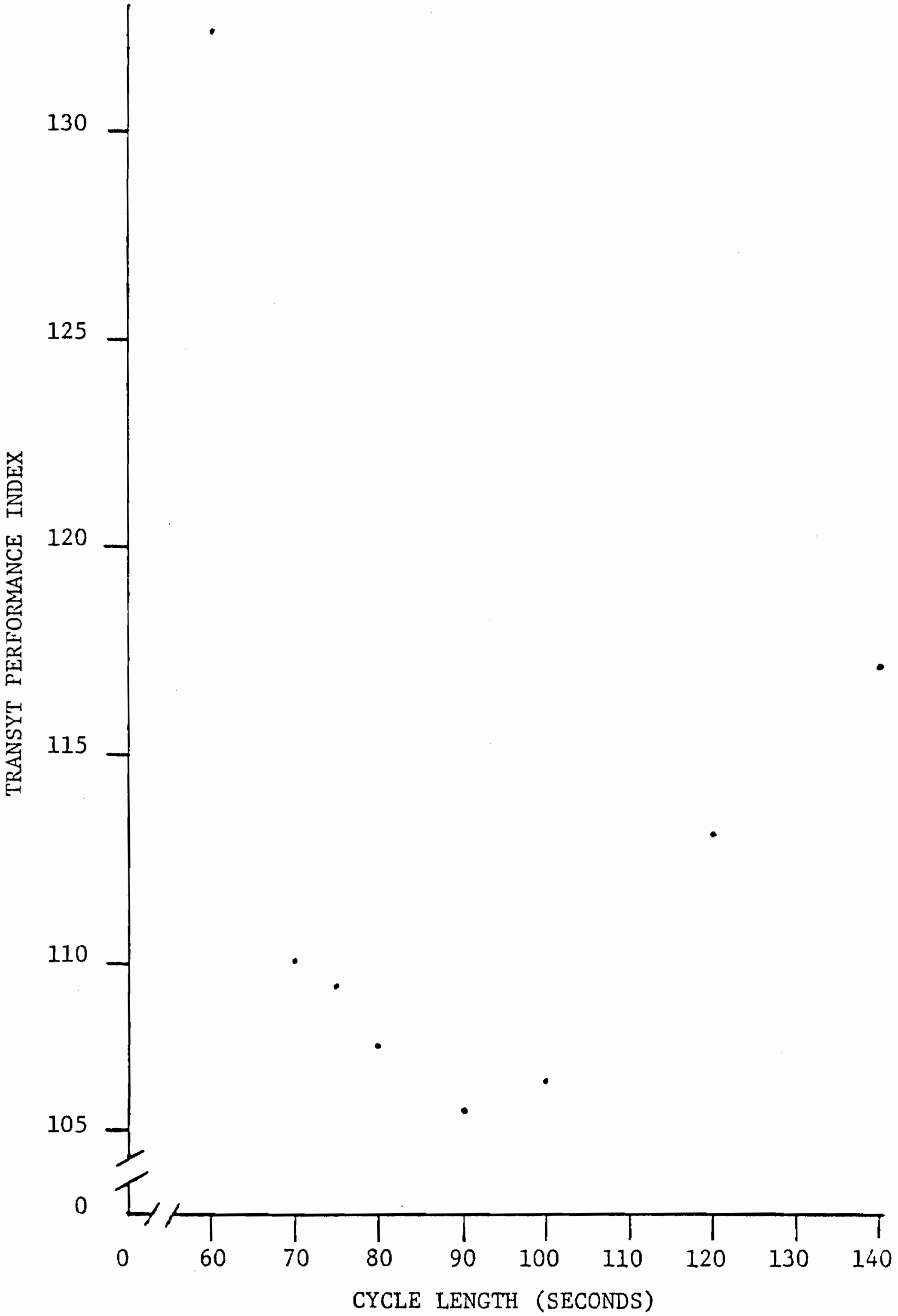

FIGURE A.7 - TRANSYT Performance Index vs. Cycle Length
(Stop Penalty = 80, Prices Fork Road)

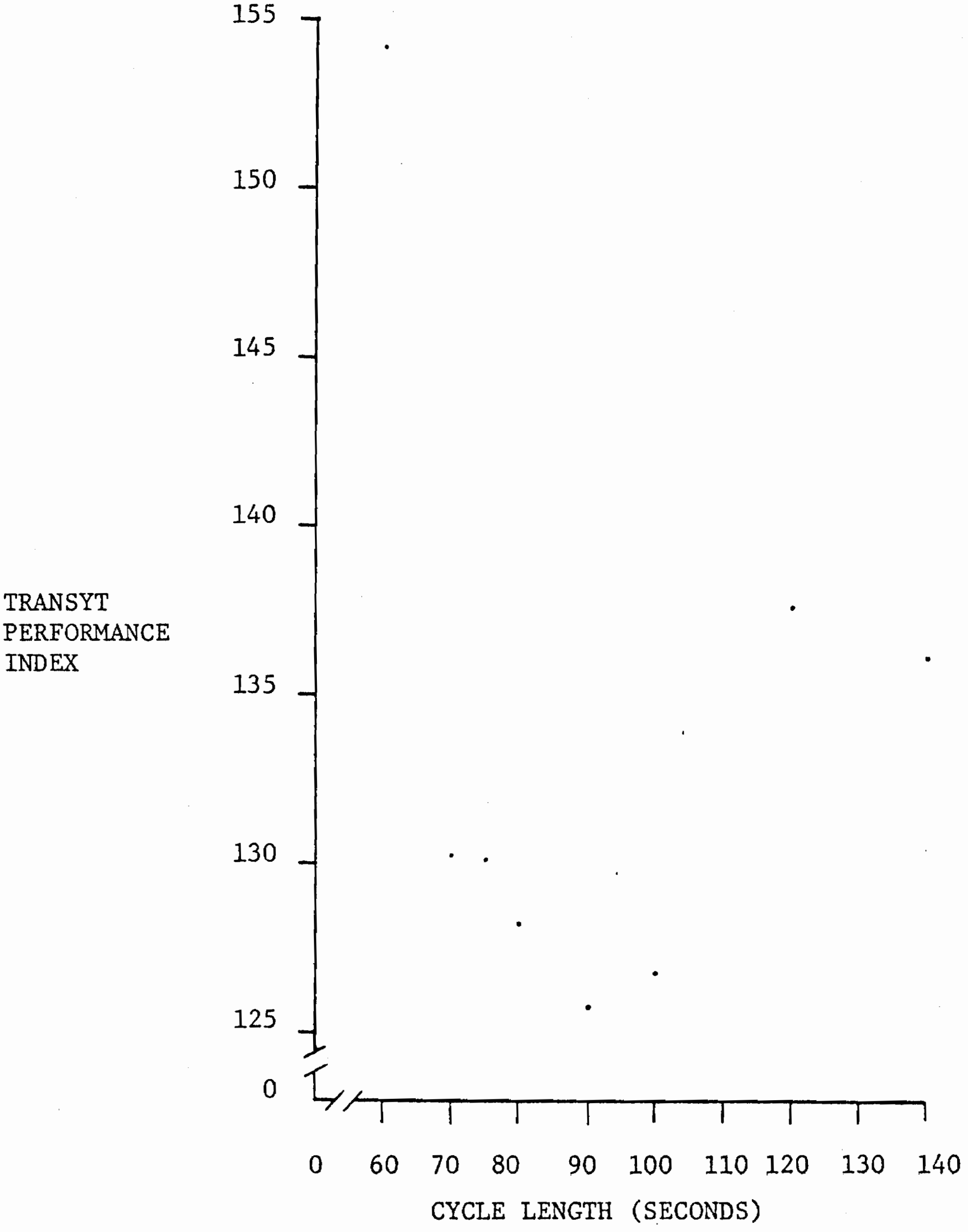

FIGURE A.8 - <u>TRANSYT Performance Index vs. Cycle Length</u>
(Stop Penalty = 1000, Prices Fork Road)

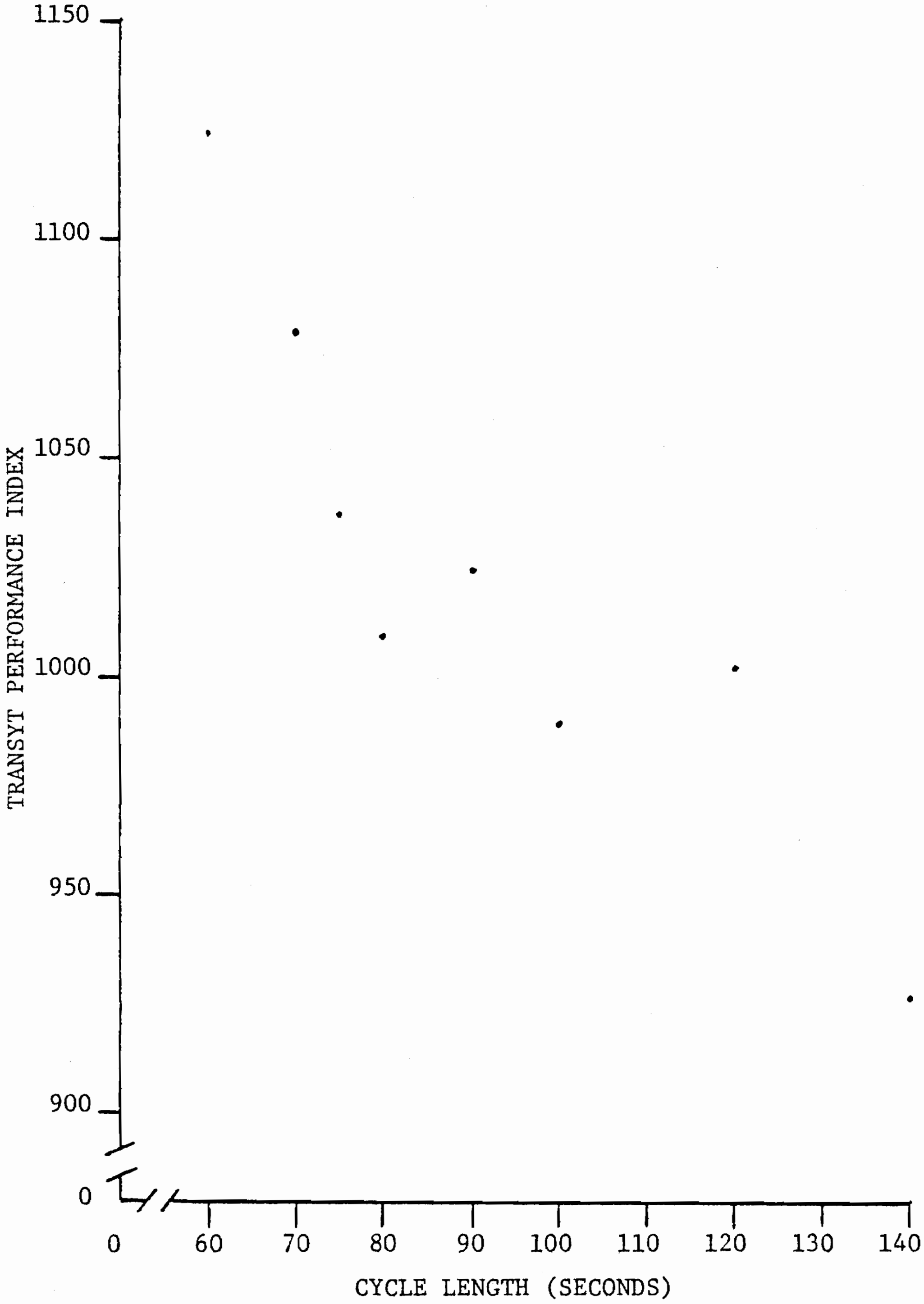

FIGURE A.9 - TRANSYT Performance Index vs. Cycle Length
(Stop Penalty = 1000, Prices Fork Road)

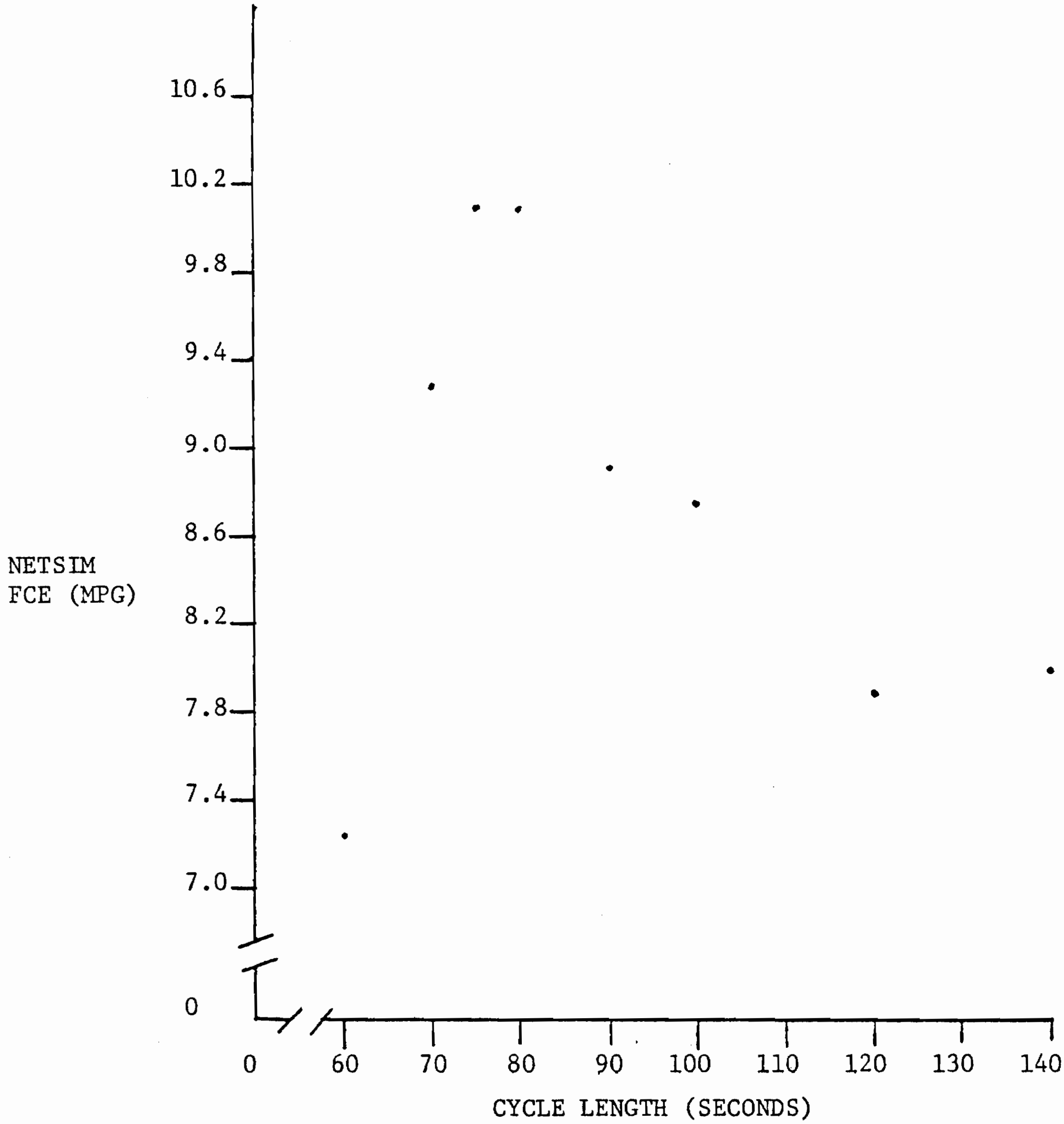

FIGURE A.10 - <u>NETSIM FCE vs. Cycle Length</u>
(Stop Penalty = 0,
Prices Fork Road)

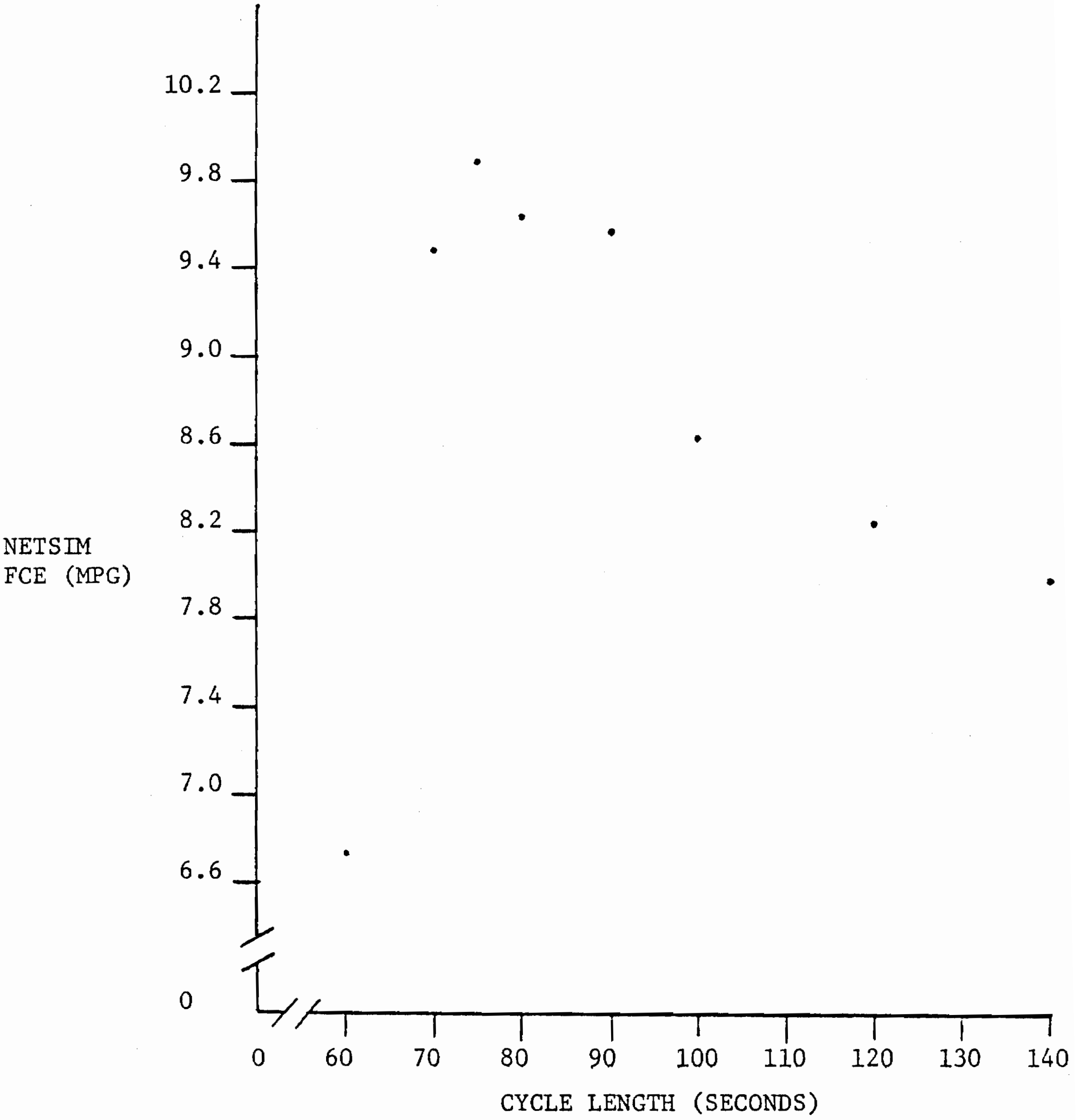

FIGURE A.11 - NETSIM FCE vs. Cycle Length (Stop Penalty = 6, Prices Fork Road)

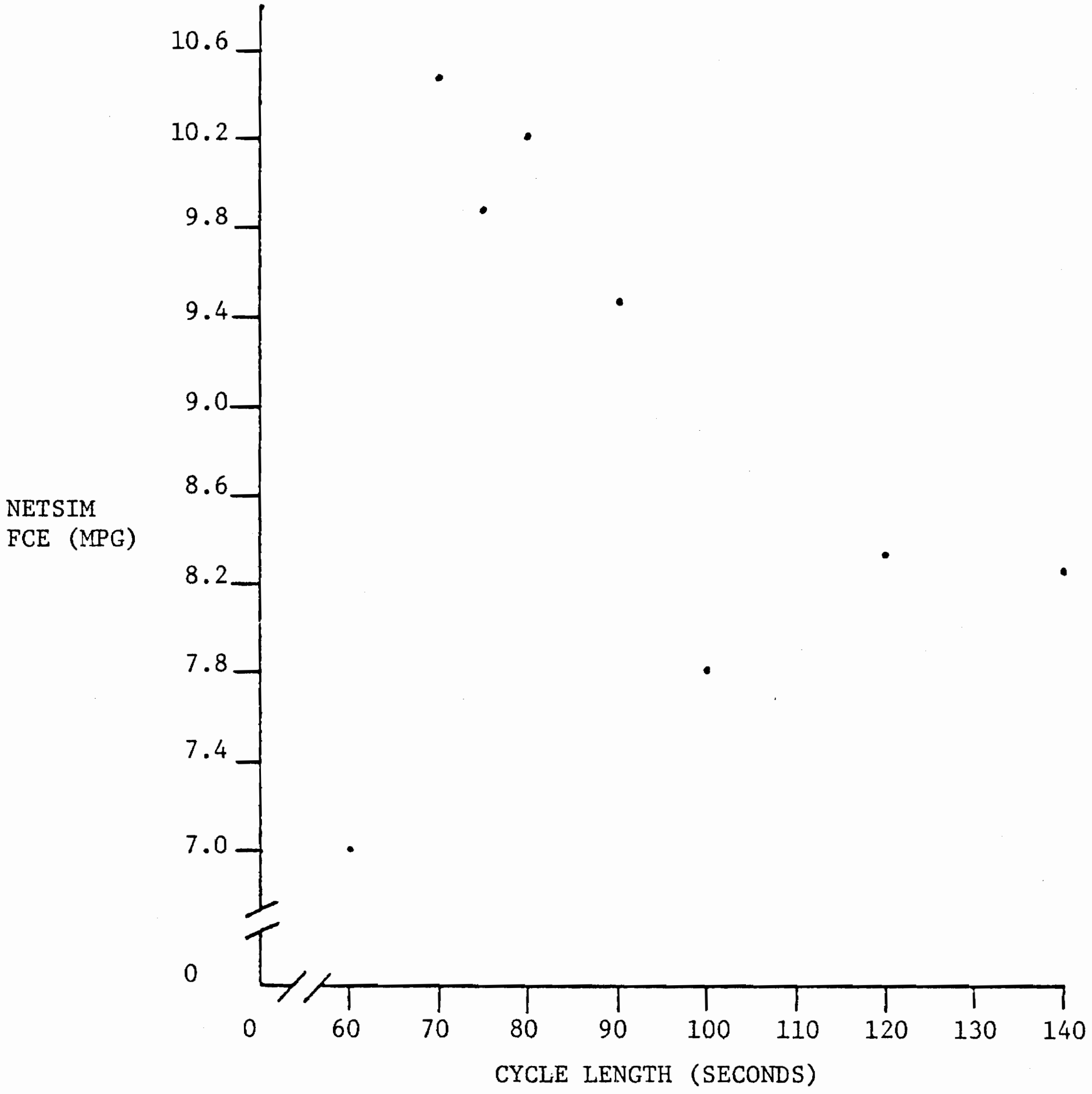

FIGURE A.12 - NETSIM FCE v. Cycle Length
(Stop Penalty = 10,
Prices Fork Road)

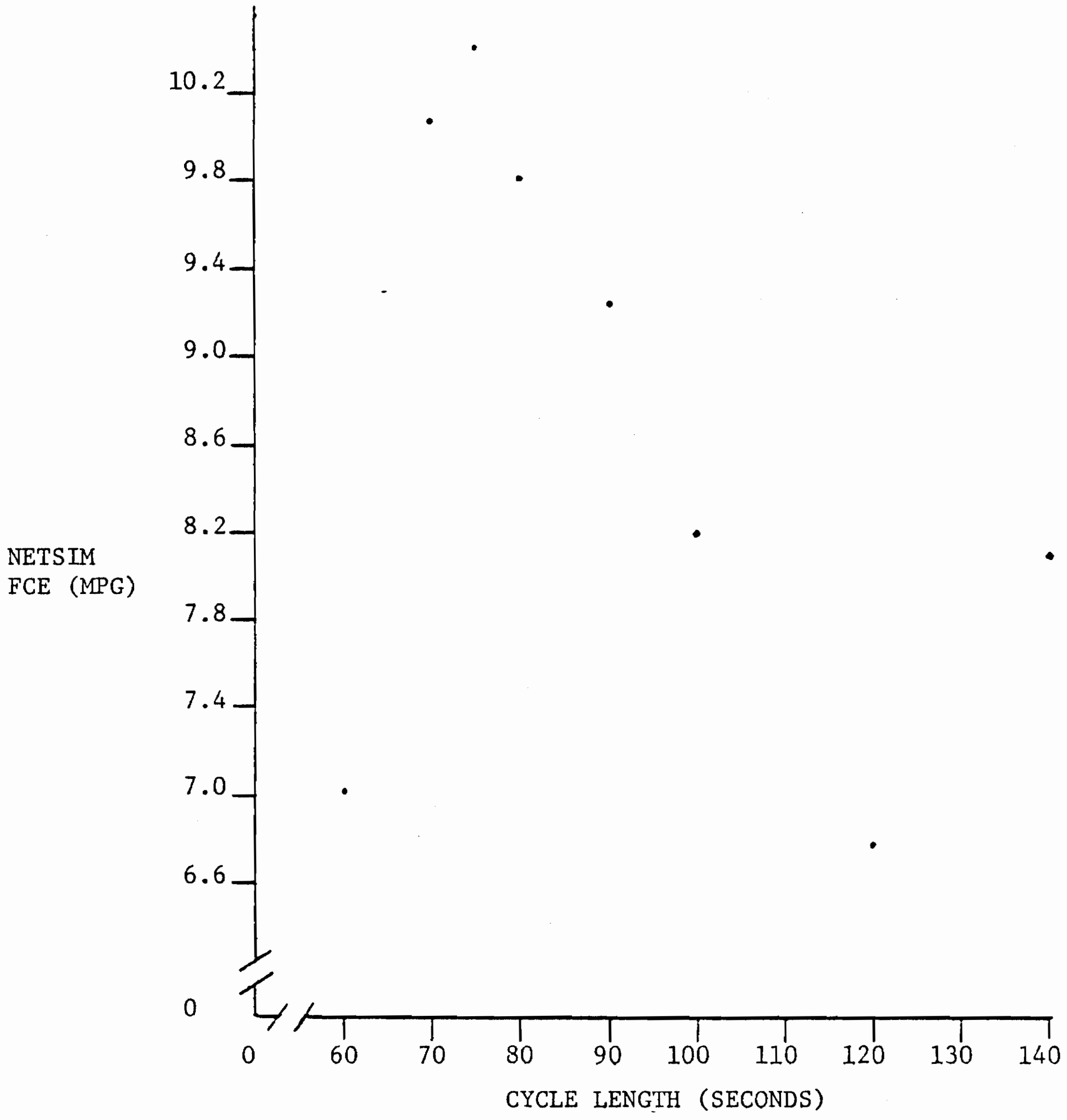

FIGURE A.13 - NETSIM FCE vs. Cycle Length (Stop Penalty = 20, Prices Fork Road)

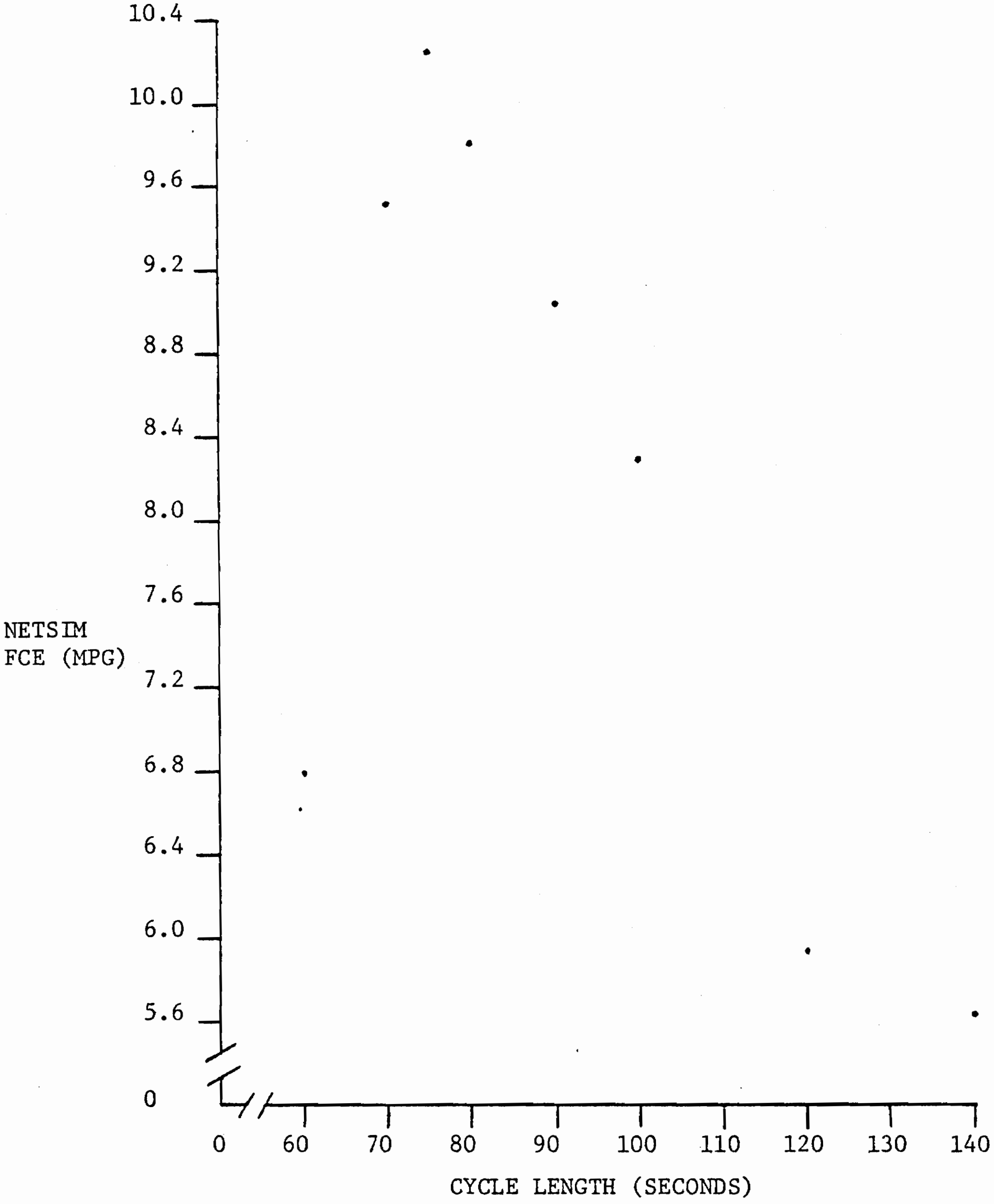

FIGURE A.14 - NETSIM FCE vs. Cycle Length
(Stop Penalty = 40,
Prices Fork Road)

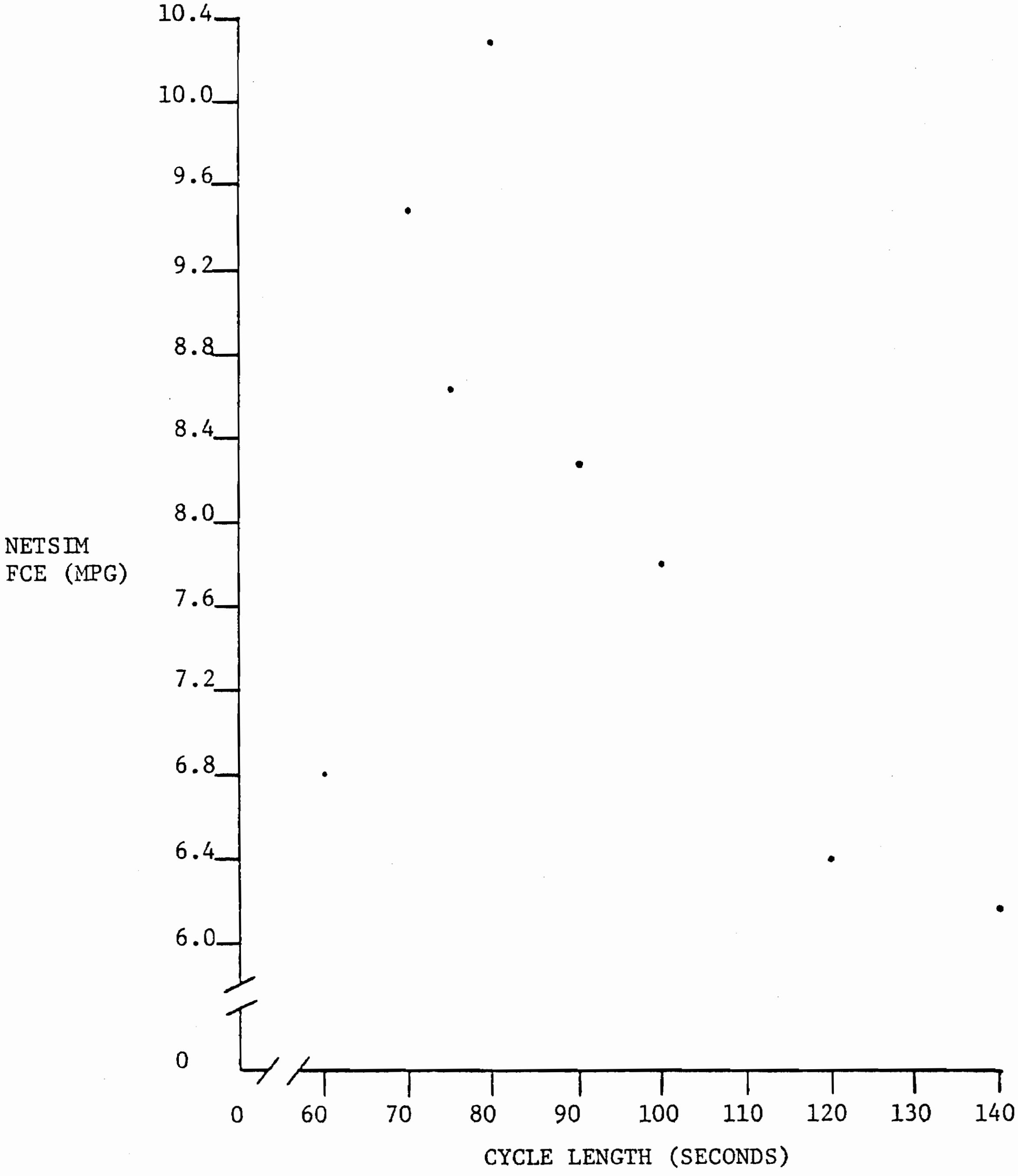

FIGURE A.15 - NETSIM FCE vs. Cycle Length
(Stop Penalty = 60,
Prices Fork Road)

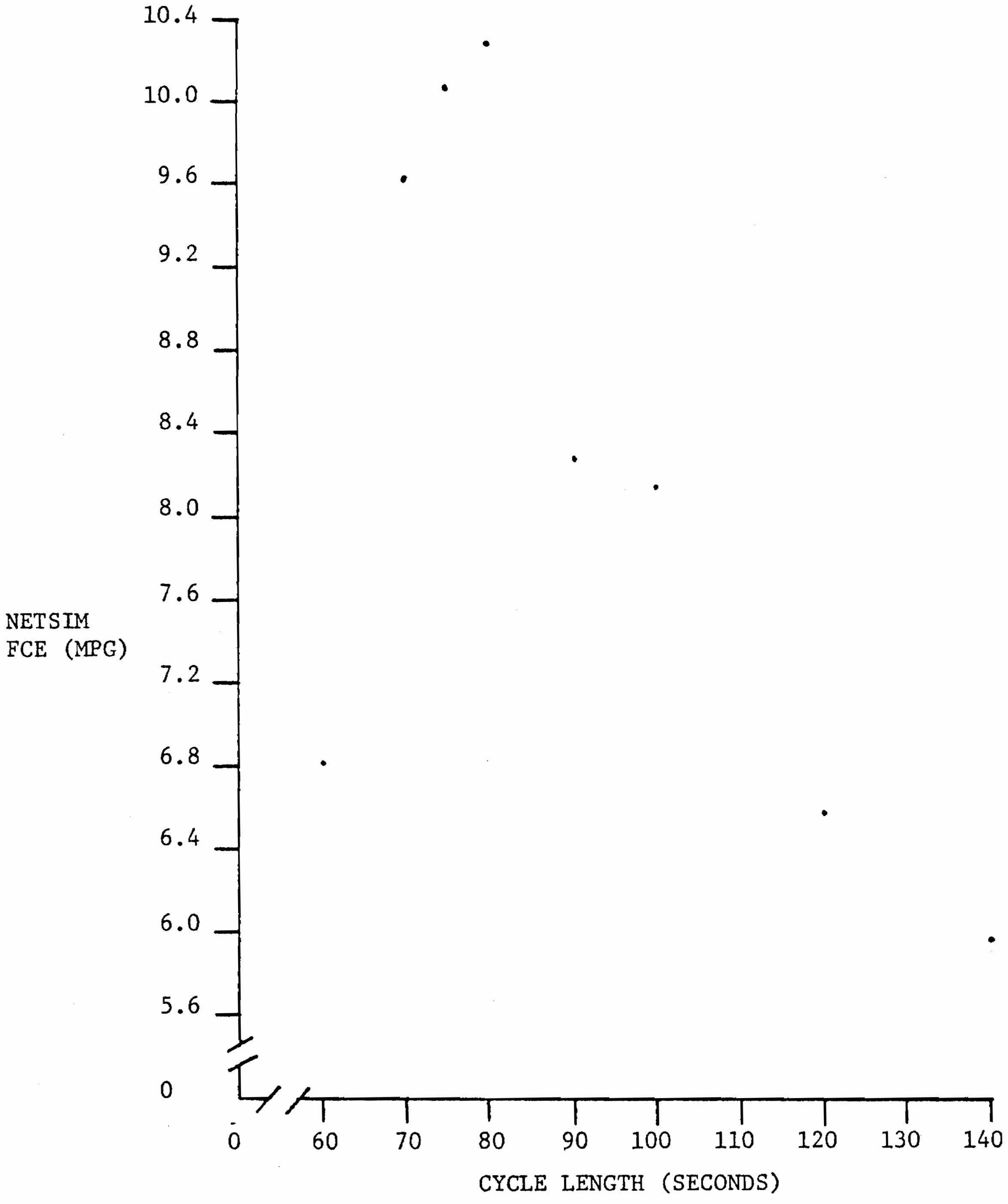

FIGURE A.16 - <u>NETSIM FCE vs. Cycle Length</u>
(Stop Penalty = 80,
Prices Fork Road)

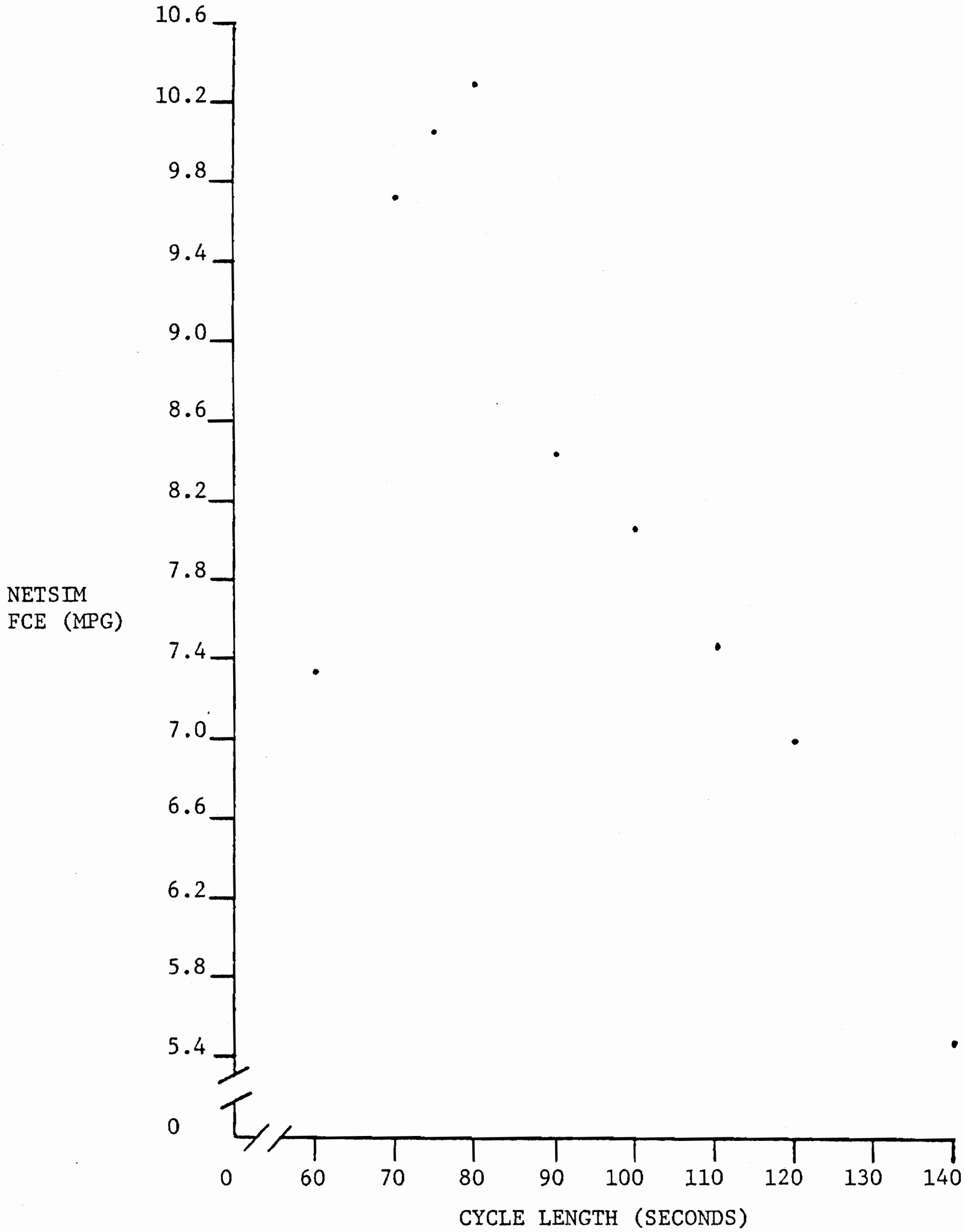

FIGURE A.17 - NETSIM FCE vs. Cycle Length
(Stop Penalty = 100,
Prices Fork Road)

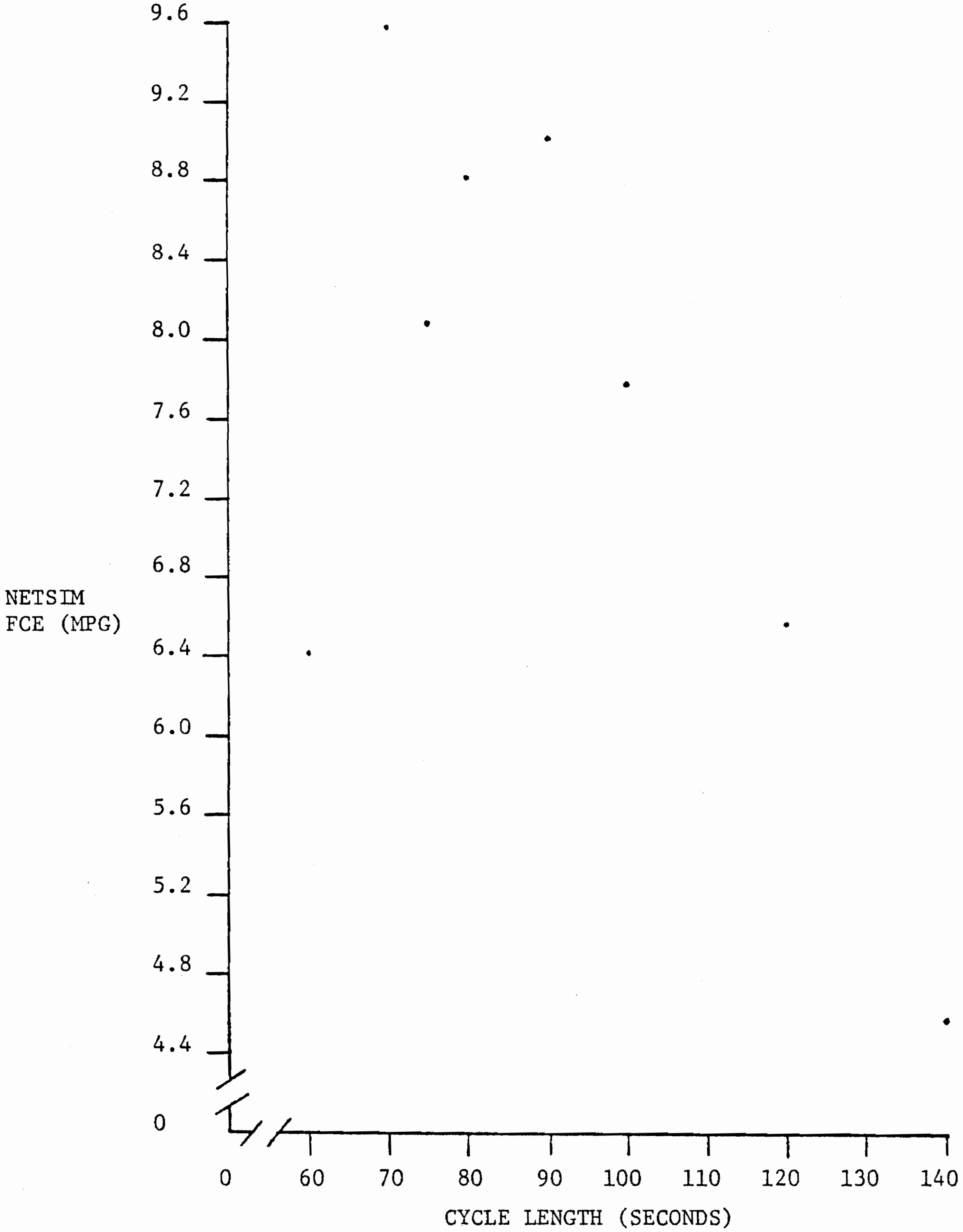

FIGURE A.18 - <u>NETSIM FCE vs. Cycle Length</u>
(Stop Penalty = 1000,
Prices Fork Road)

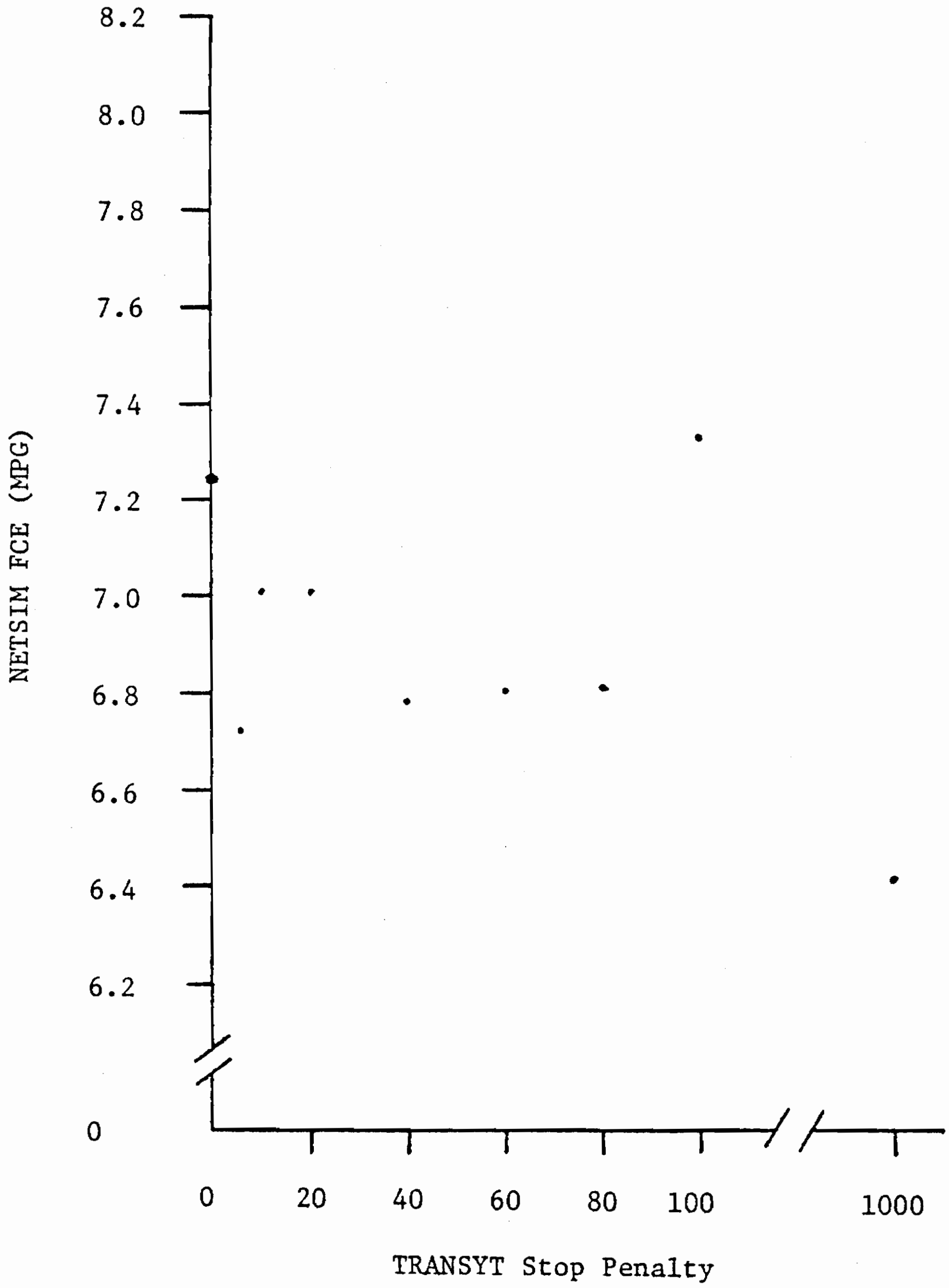

Figure A.19 - NETSIM FCE vs. TRANSYT Stop Penalty
(Cycle Length = 60 Seconds, Prices Fork)

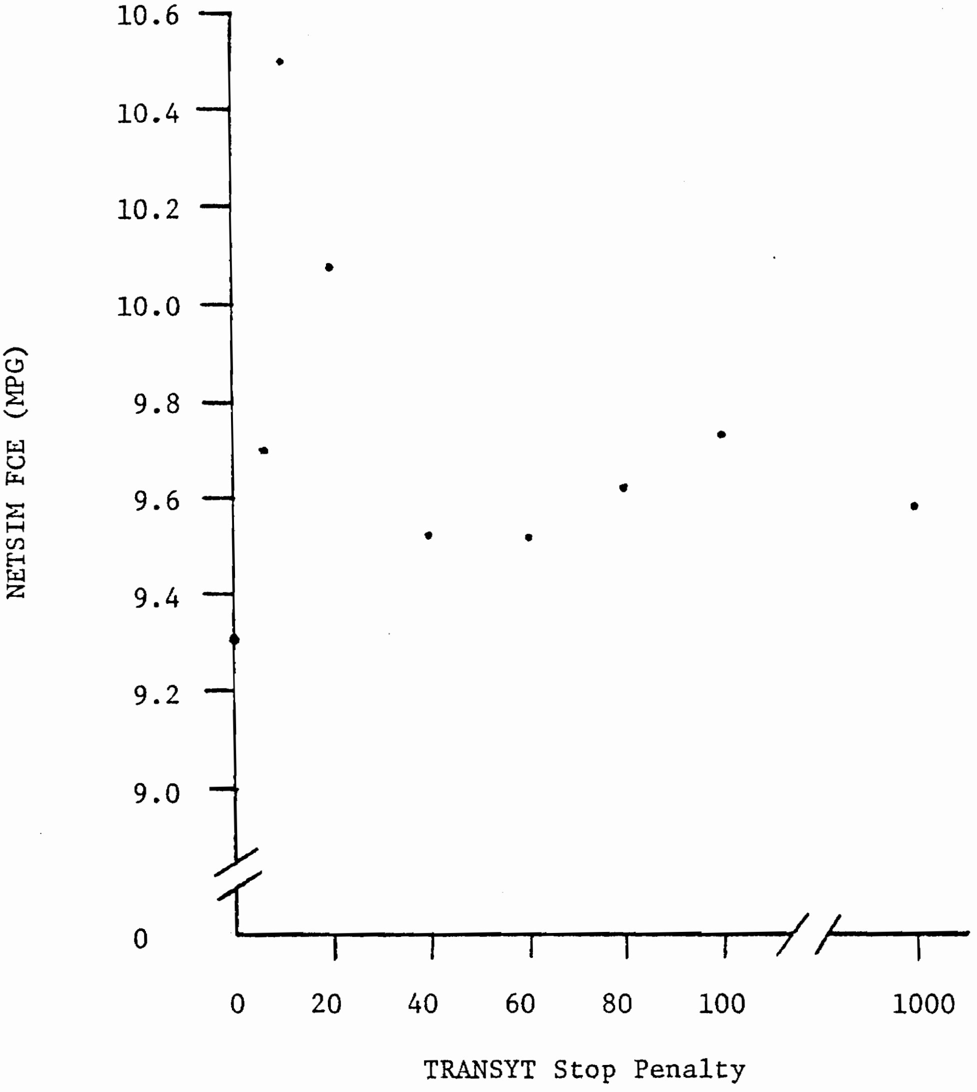

Figure A.20 - NETSIM FCE vs. TRANSYT Stop Penalty
(Cycle Length = 70 Seconds, Prices Fork)

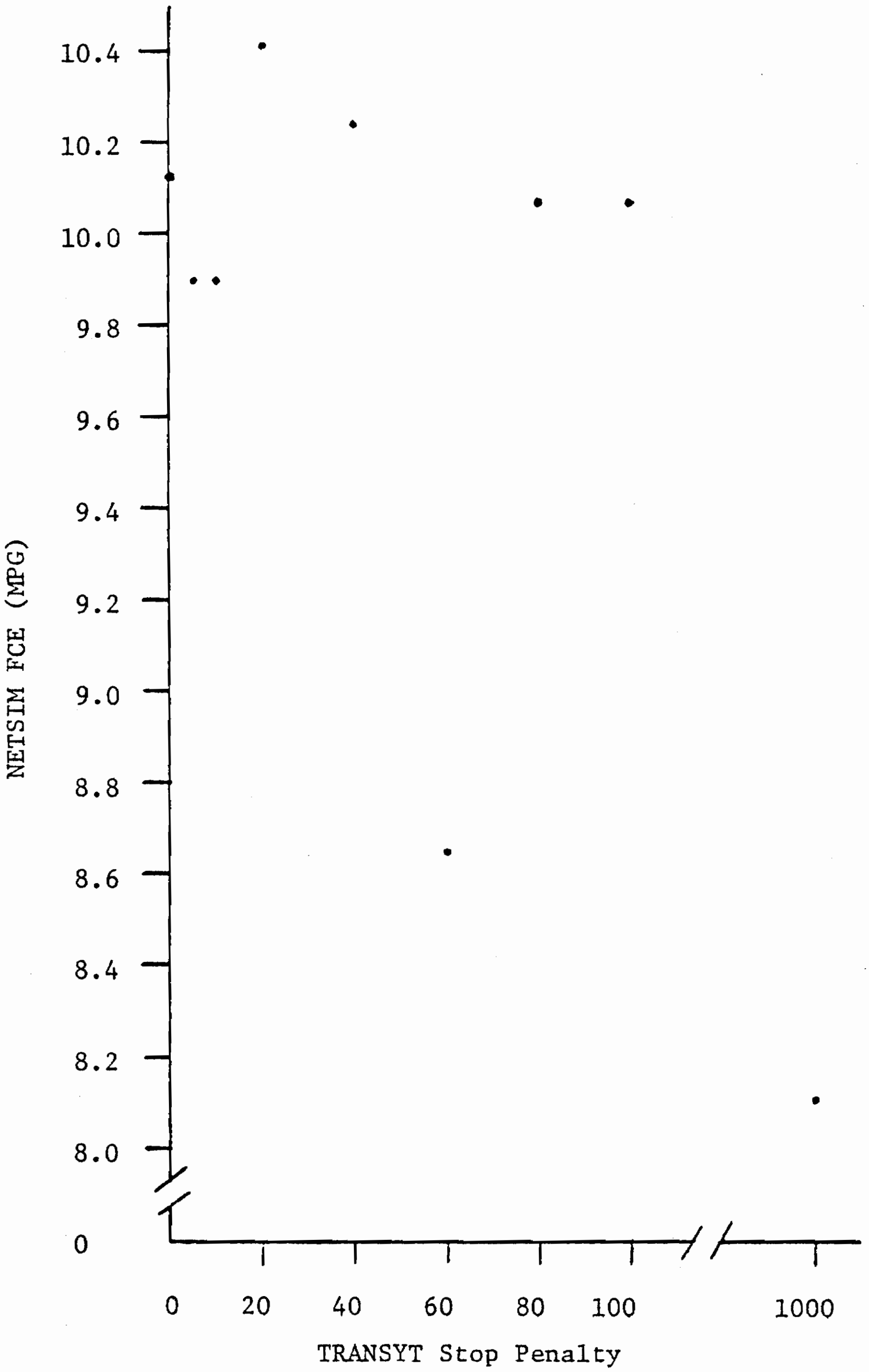

Figure A.21 - NETSIM FCE vs. TRANSTY Stop Penalty
(Cycle Length = 75 Seconds, Prices Fork)

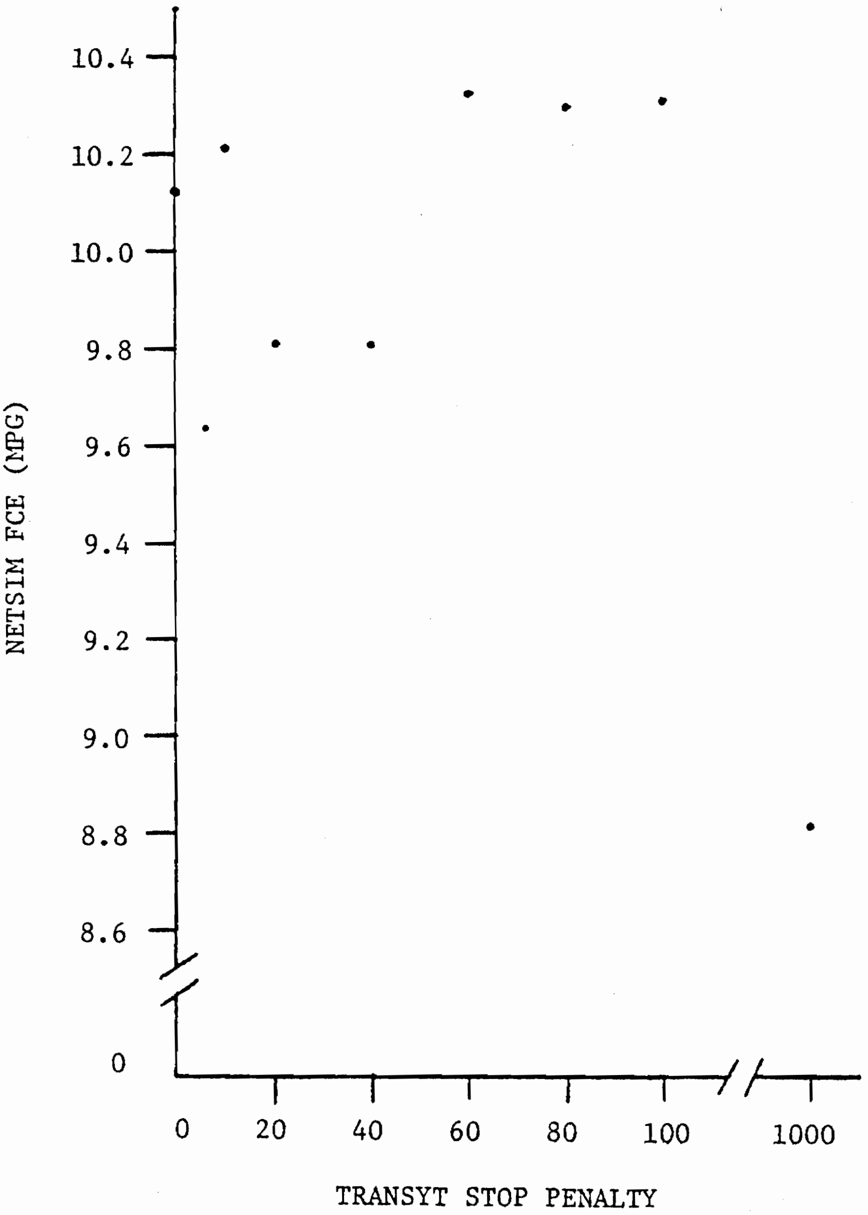

Figure A.22 - NETSIM FCE vs. TRANSYT Stop Penalty
(Cycle Length = 80 Seconds, Prices Fork)

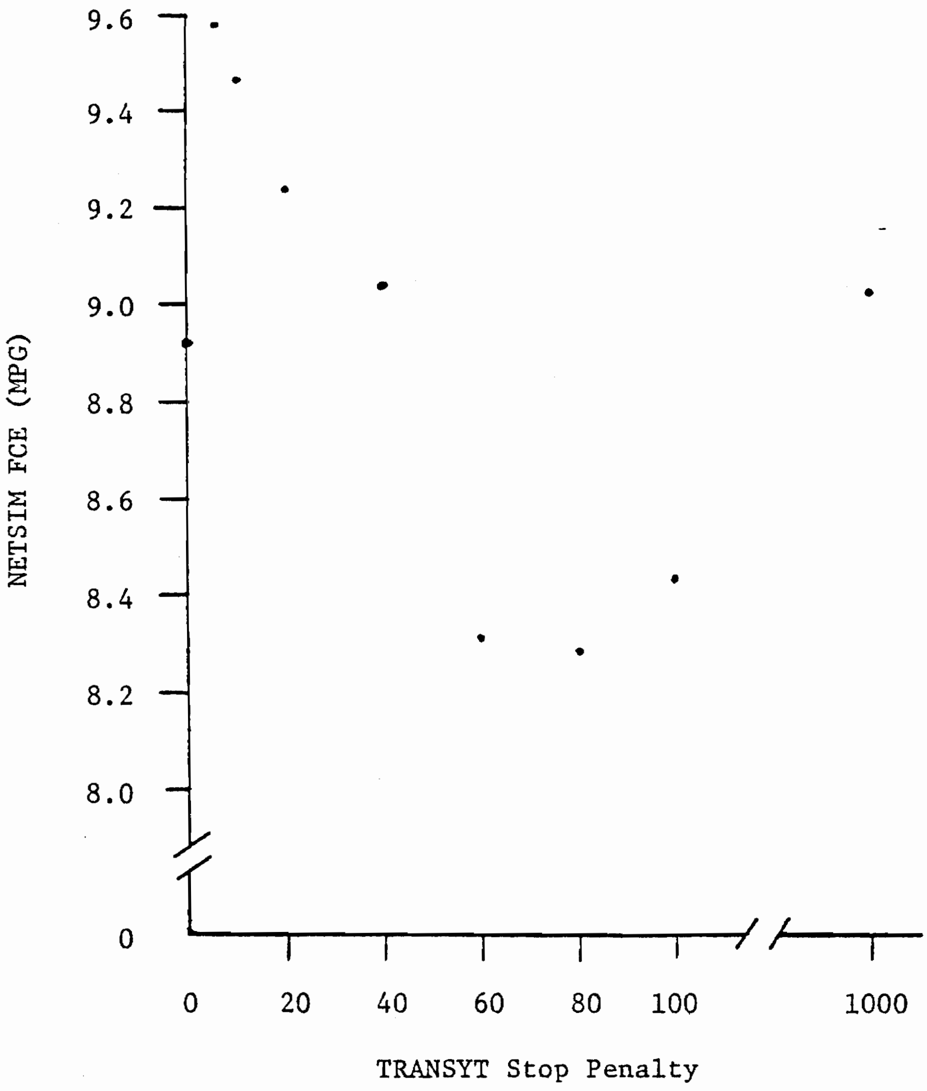

Figure A.23 - <u>NETSIM FCE vs. TRANSYT Stop Penalty</u>
(Cycle Length = 90 Seconds, Prices Fork)

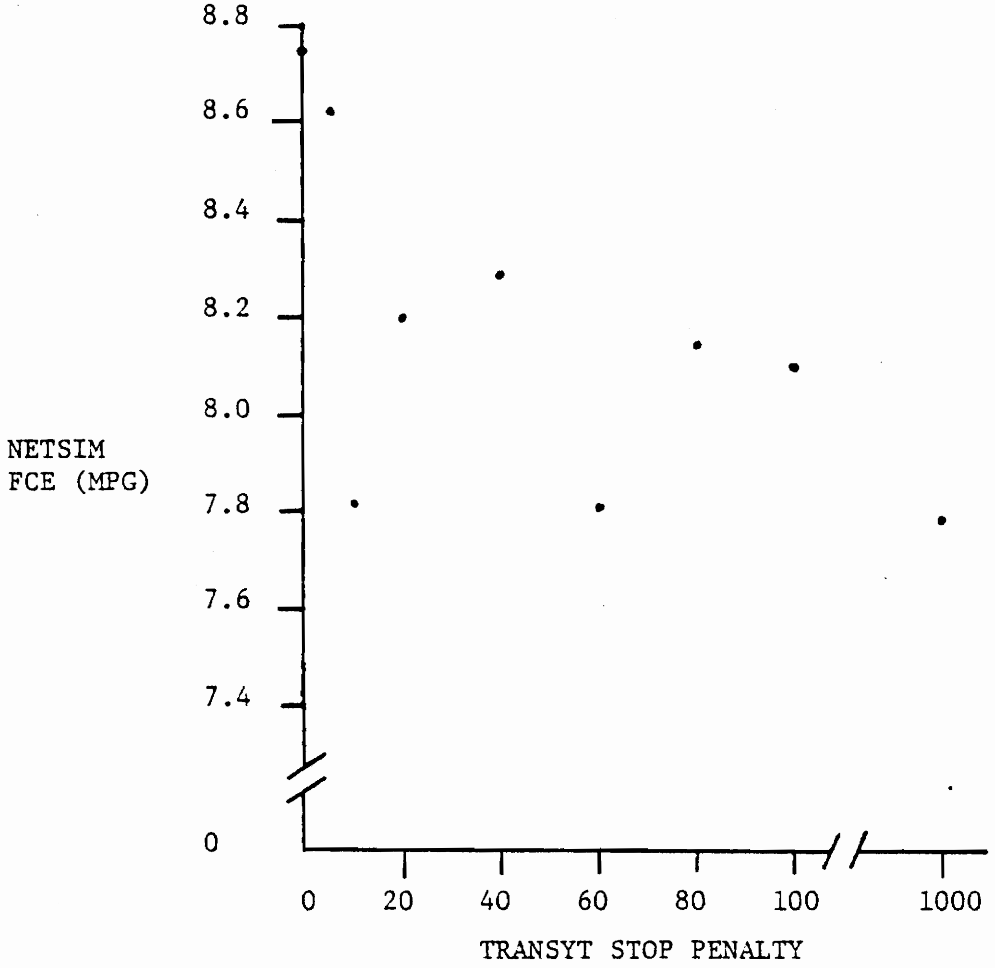

FIGURE A.24 - NETSIM FCE vs. TRANSYT Stop Penalty (Cycle Length = 100 Seconds, Prices Fork)

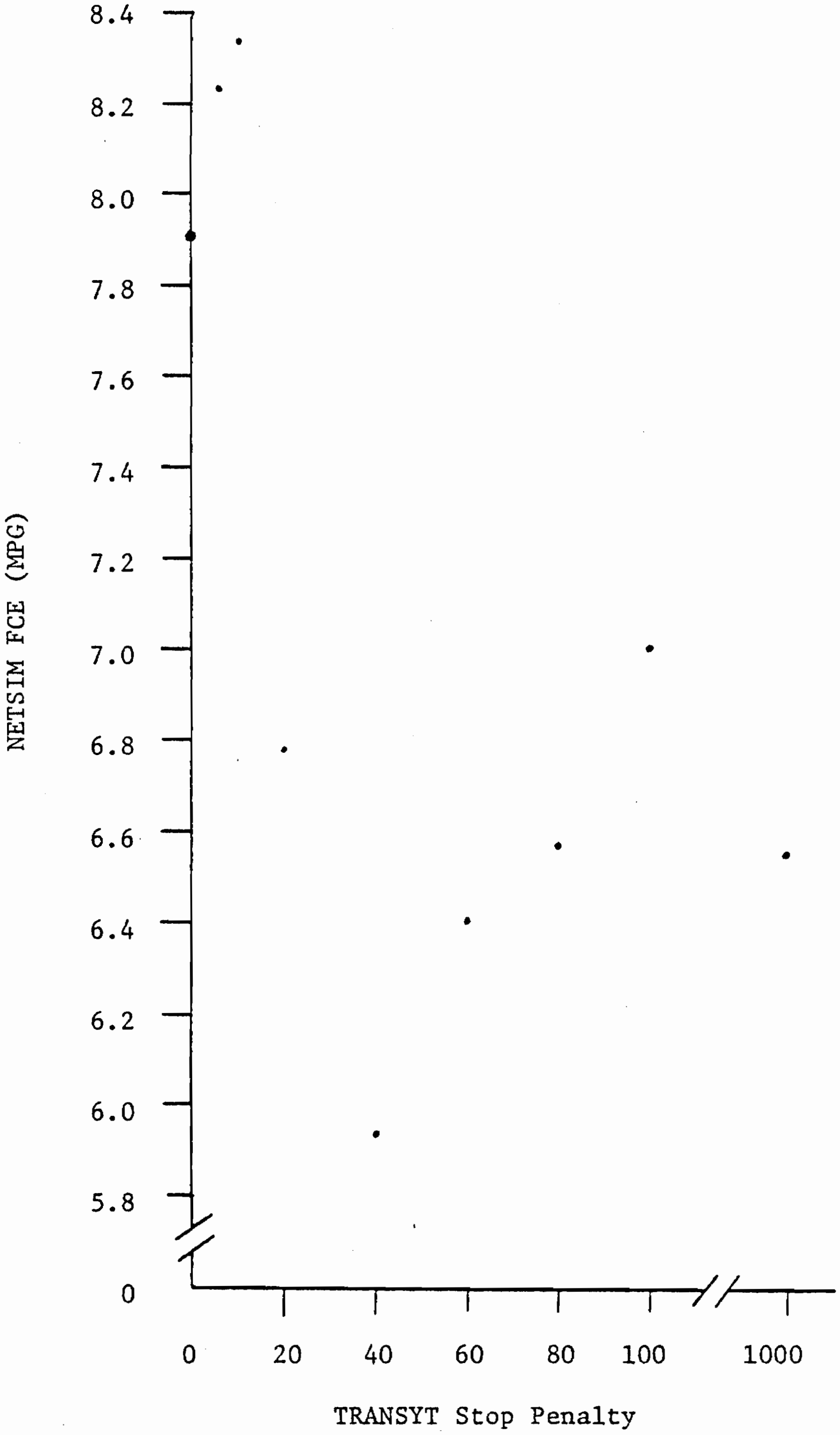

Figure A.25 - NETSIM FCE vs. TRANSYT Stop Penalty
(Cycle Length = 120 Seconds, Prices Fork)

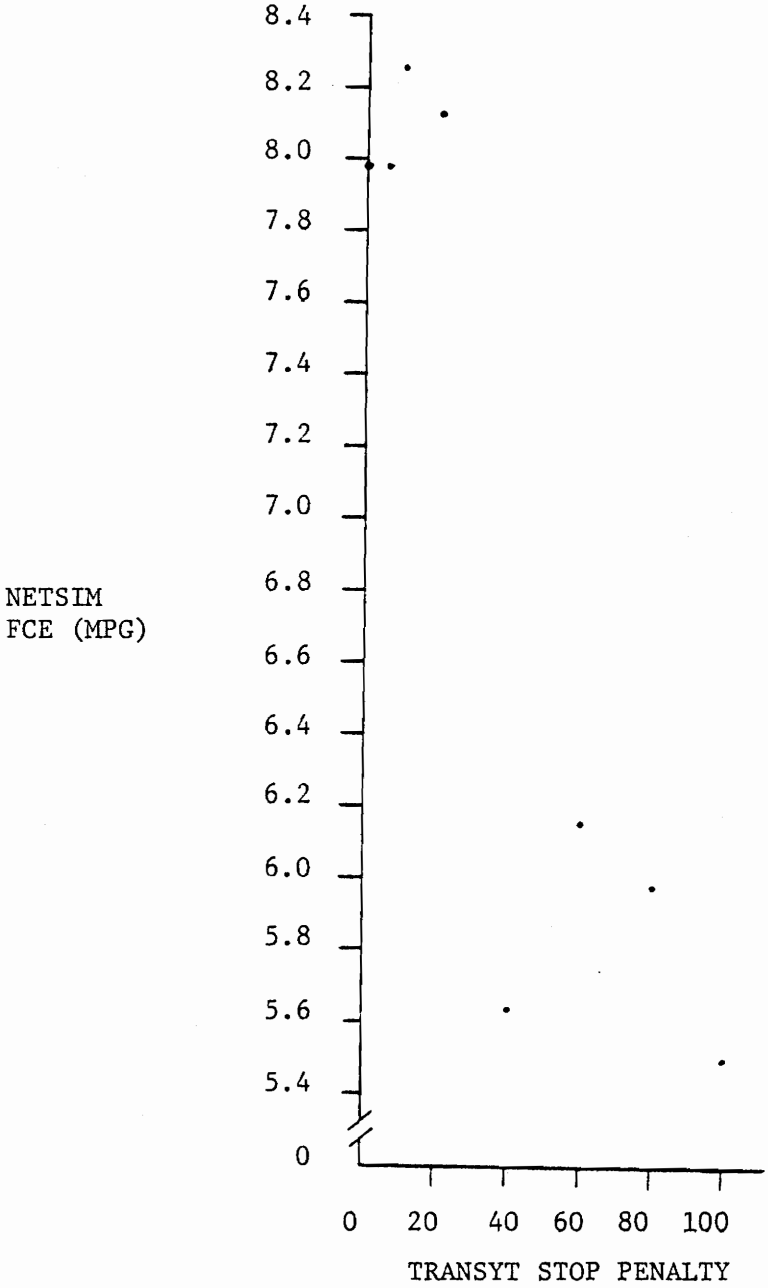

FIGURE A.26 - <u>NETSIM FCE vs. TRANSYT Stop Penalty</u>
(Cycle Length = 140 Seconds,
Prices Fork Road)

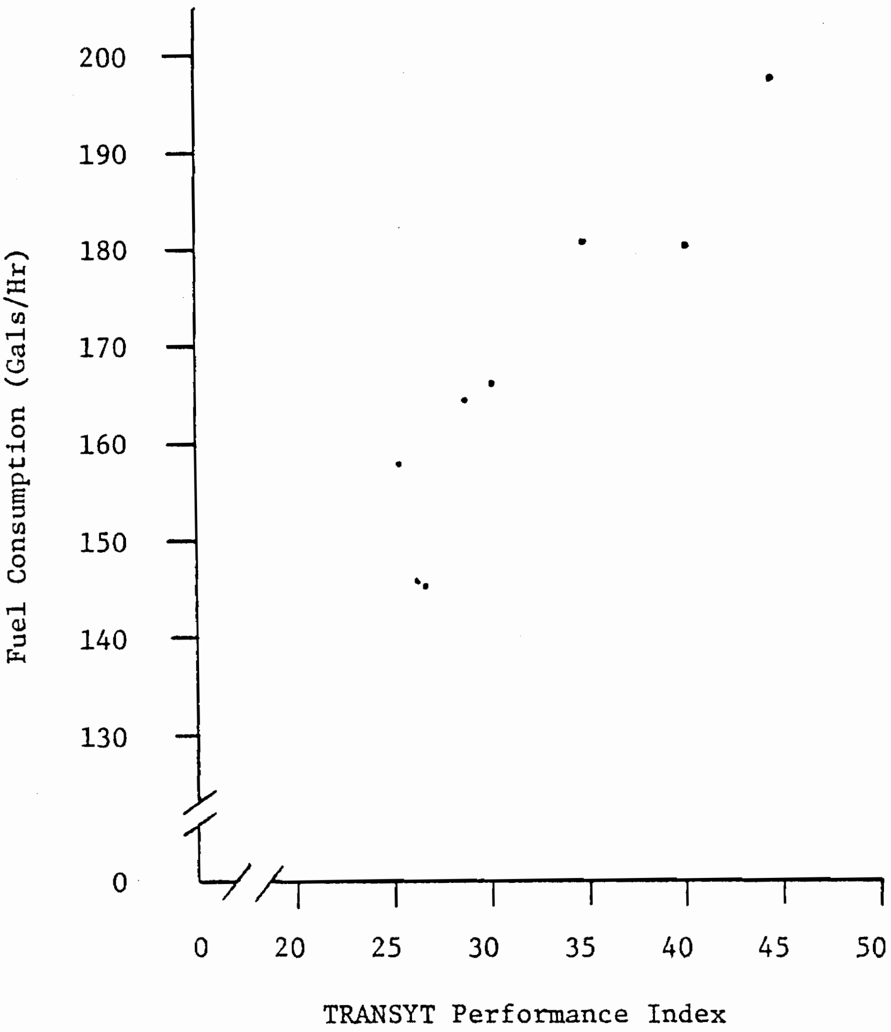

Figure A.27 - Fuel Consumption vs. TRANSYT Performance Index
(Stop Penalty = 0, Prices Fork Road)

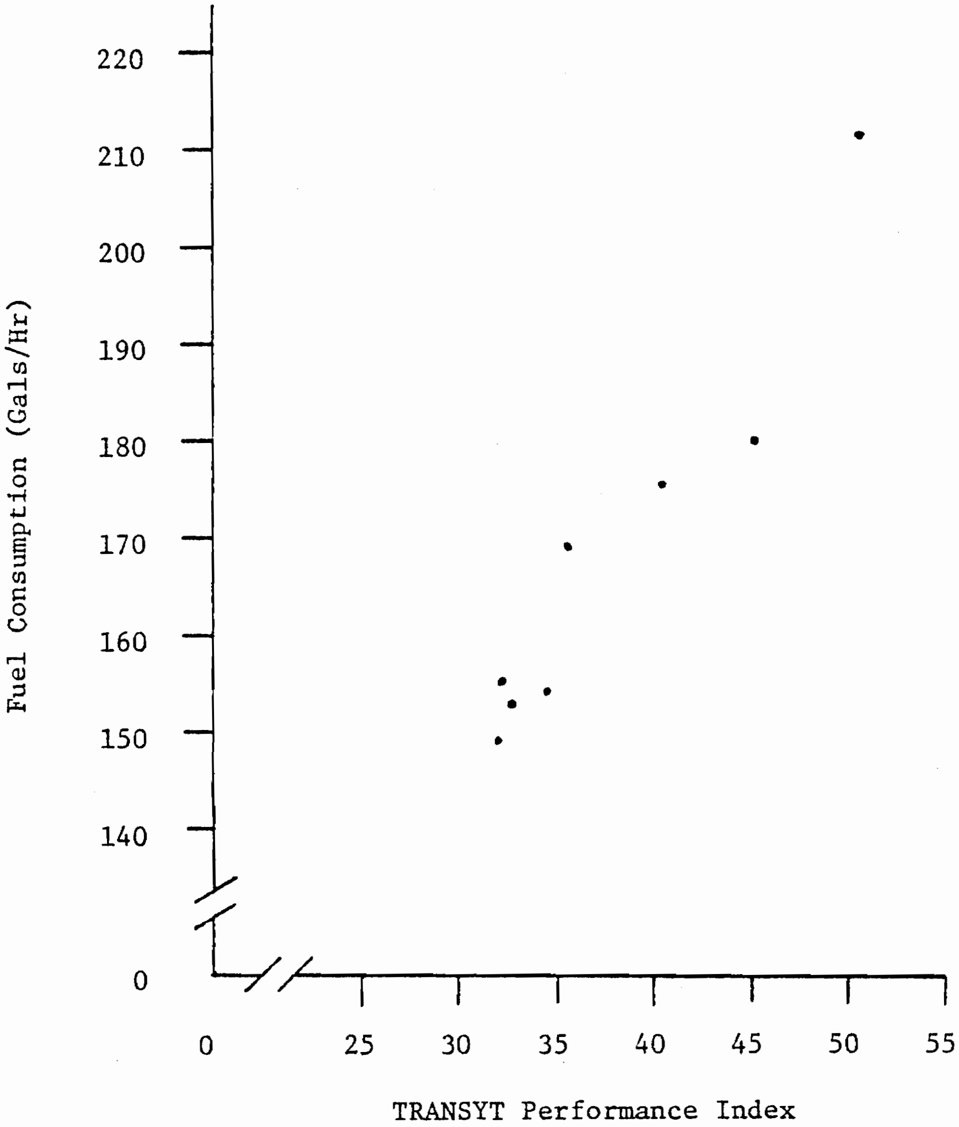

Figure A.28 - <u>Fuel Consumption vs. TRANSYT Performance Index</u>
(Stop Penalty = 6, Prices Fork Road)

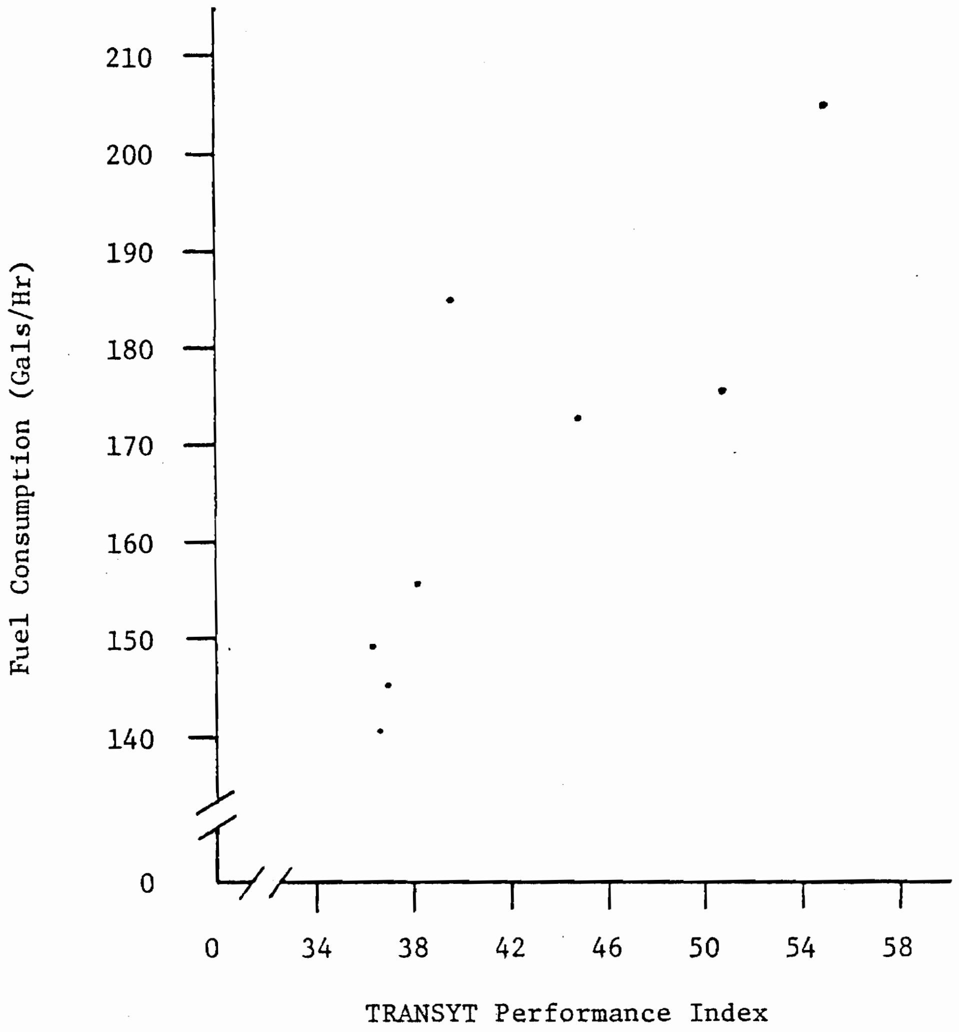

Figure A.29 - <u>Fuel Consumption vs. TRANSYT Performance Index</u>
(Stop Penalty = 10, Prices Fork Road)

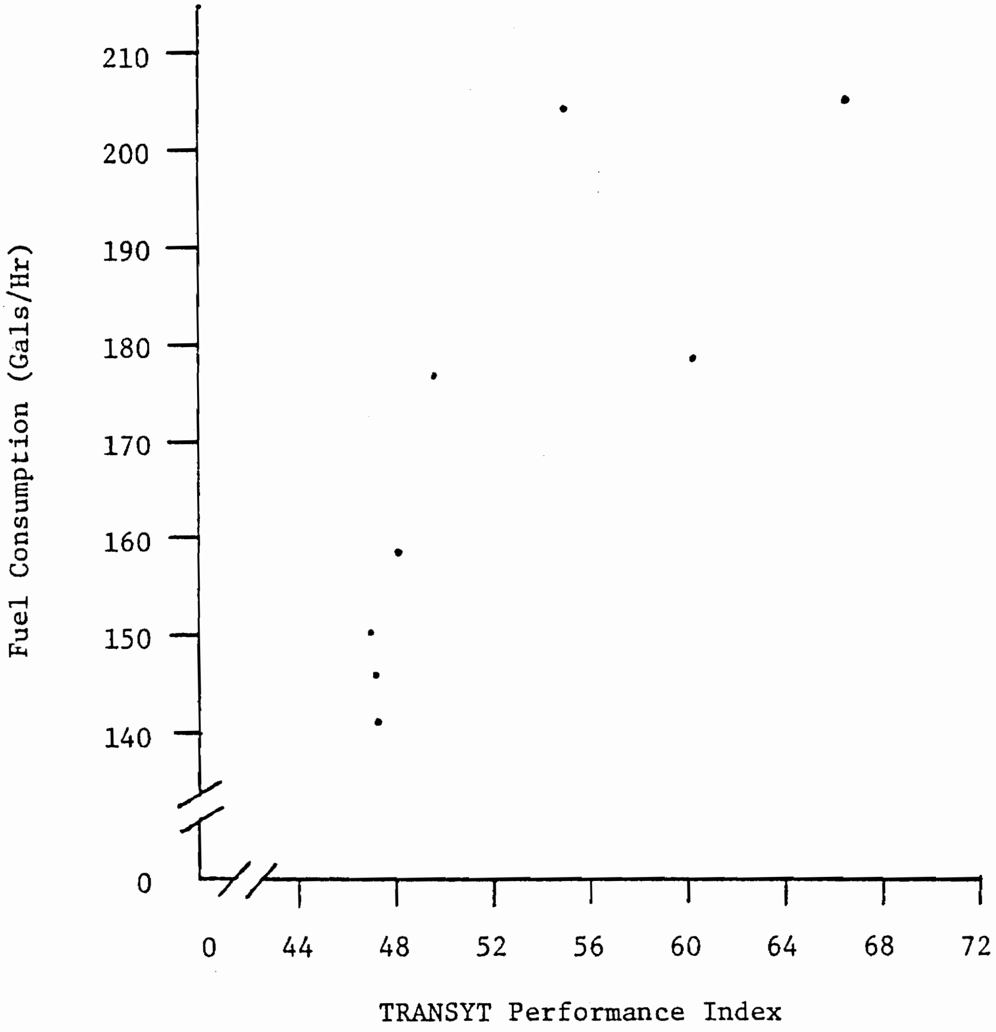

Figure A.30 - Fuel Consumption vs. TRANSYT Performance Index
(Stop Penalty = 20, Prices Fork Road)

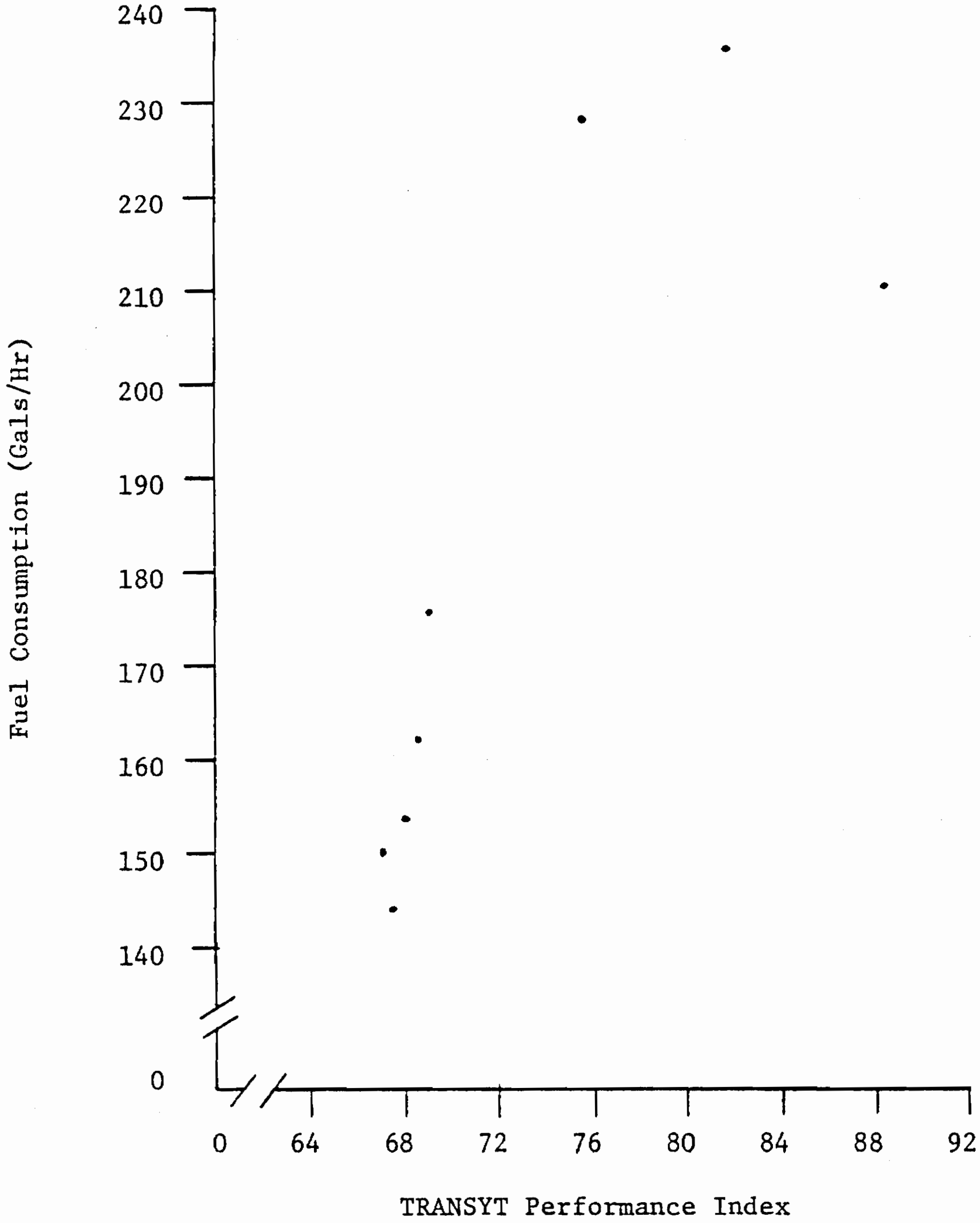

Figure A.31 - Fuel Consumption vs. TRANSYT Performance Index
(Stop Penalty = 40, Prices Fork Road)

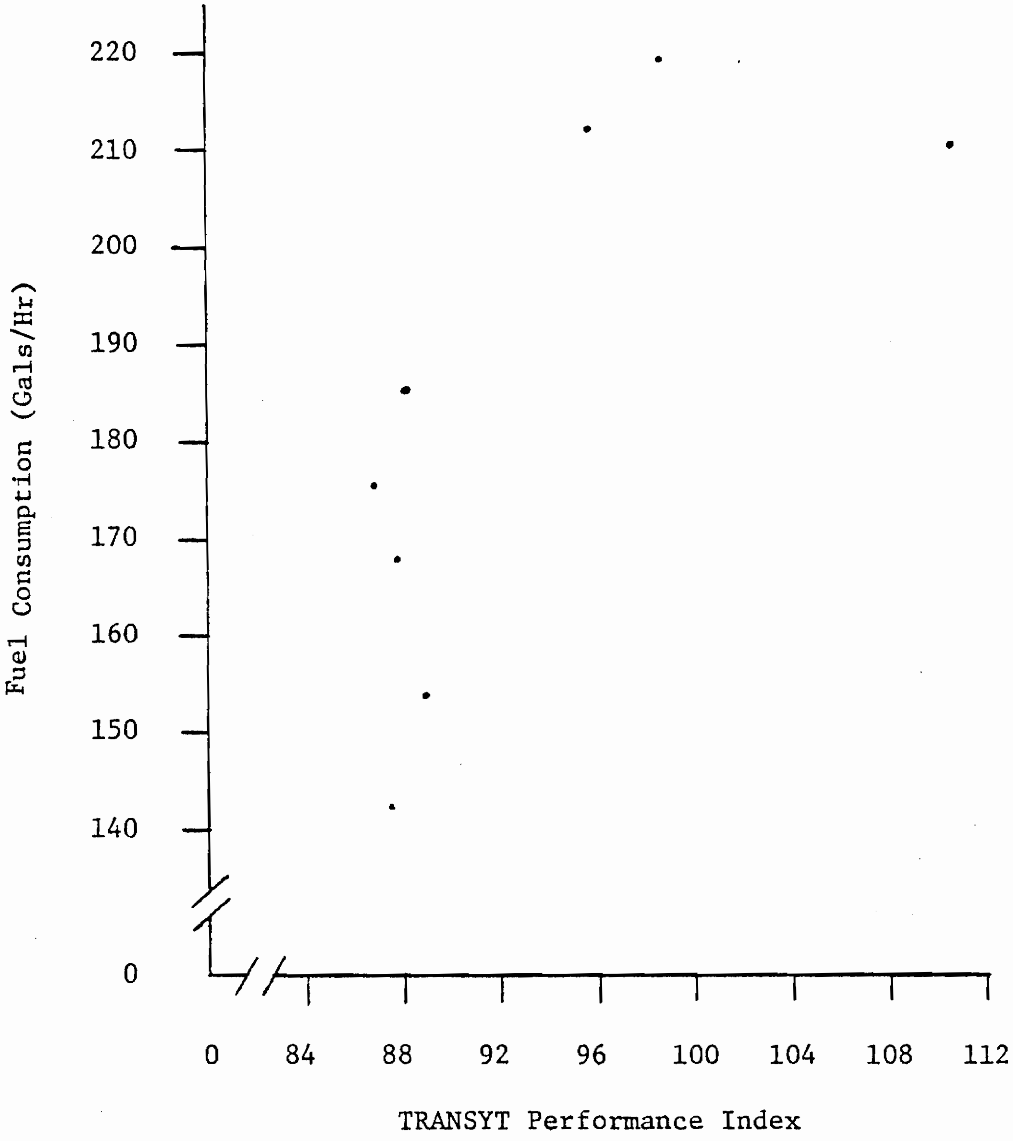

Figure A.32 - Fuel Consumption vs. TRANSYT Performance Index
(Stop Penalty = 60, Prices Fork Road)

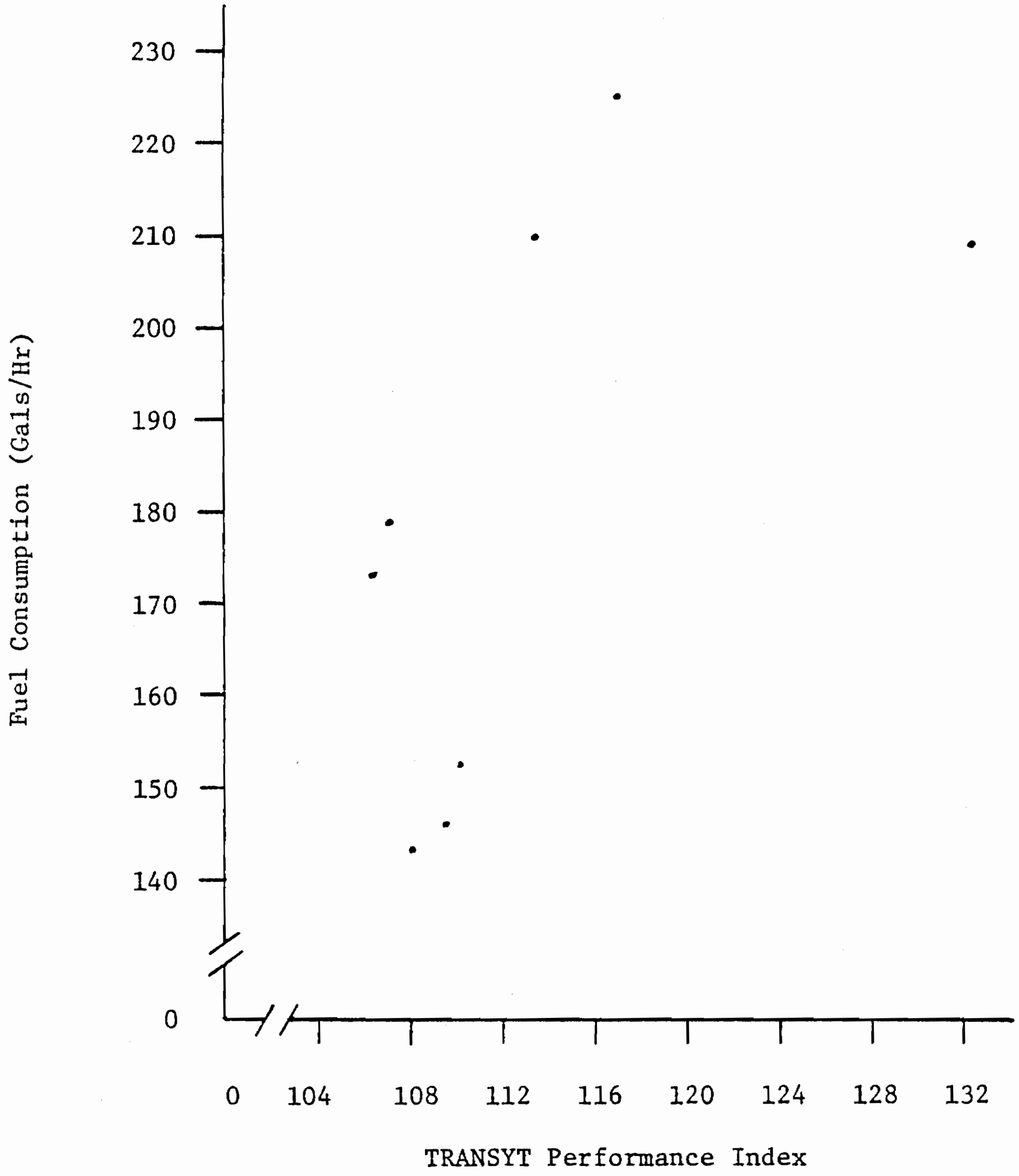

Figure A.33 - Fuel Consumption vs. TRANSYT Performance Index
(Stop Penalty = 80, Prices Fork Road)

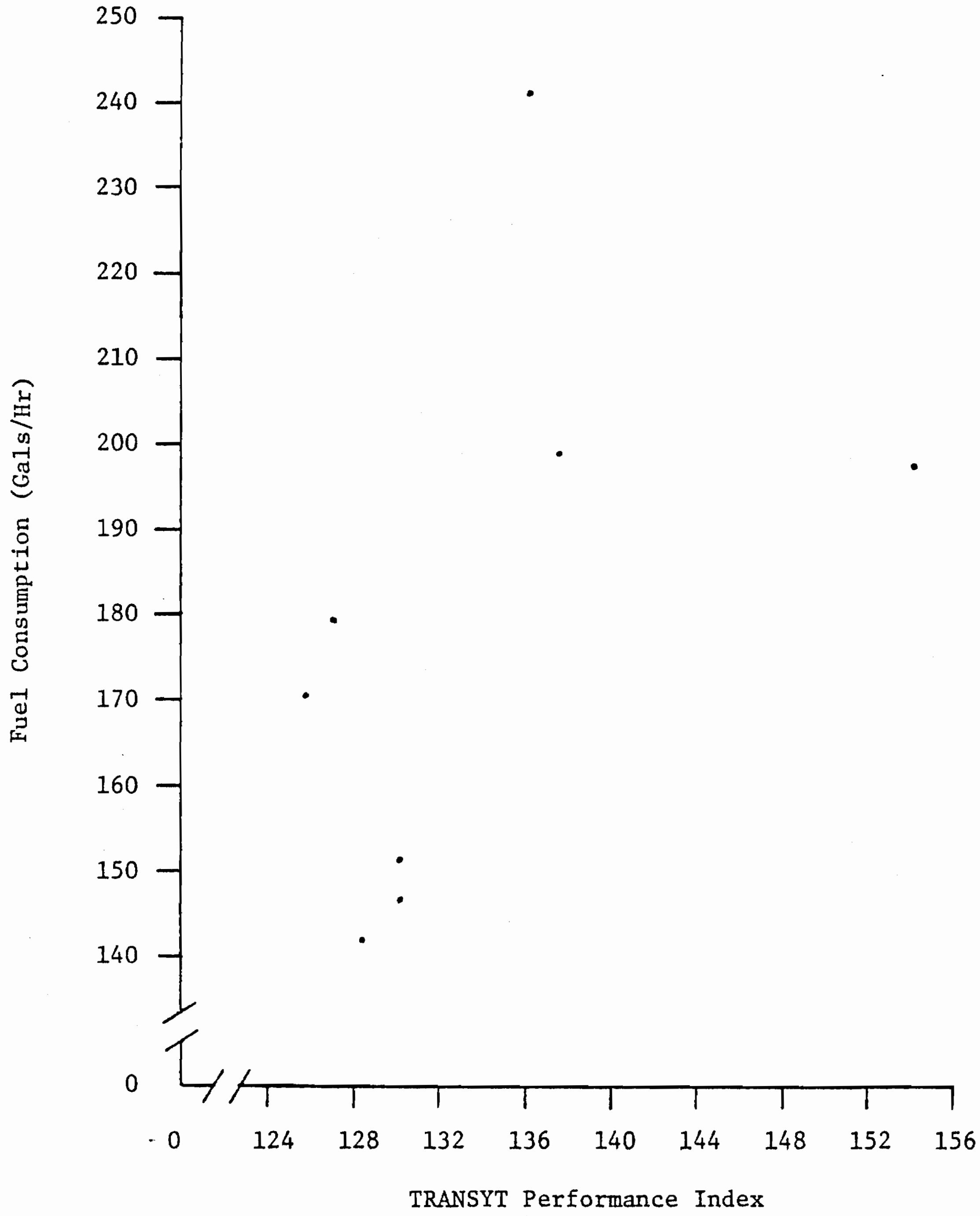

Figure A.34 - Fuel Consumption vs. TRANSYT Performance Index
(Stop Penalty = 100, Prices Fork Road)

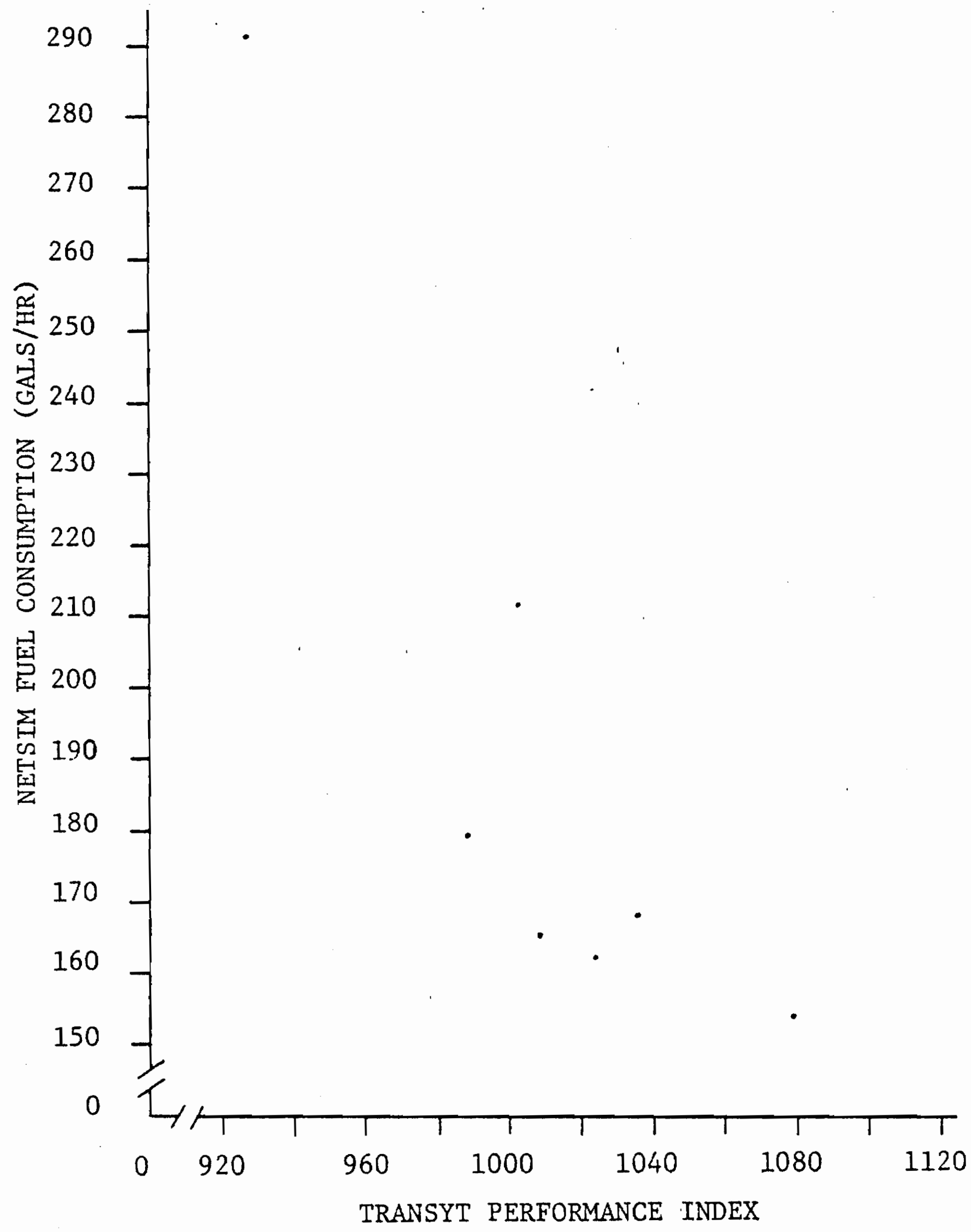

FIGURE A.35 - NETSIM Fuel Consumption vs. TRANSYT Performance Index (Stop Penalty = 1000, Prices Fork Road)

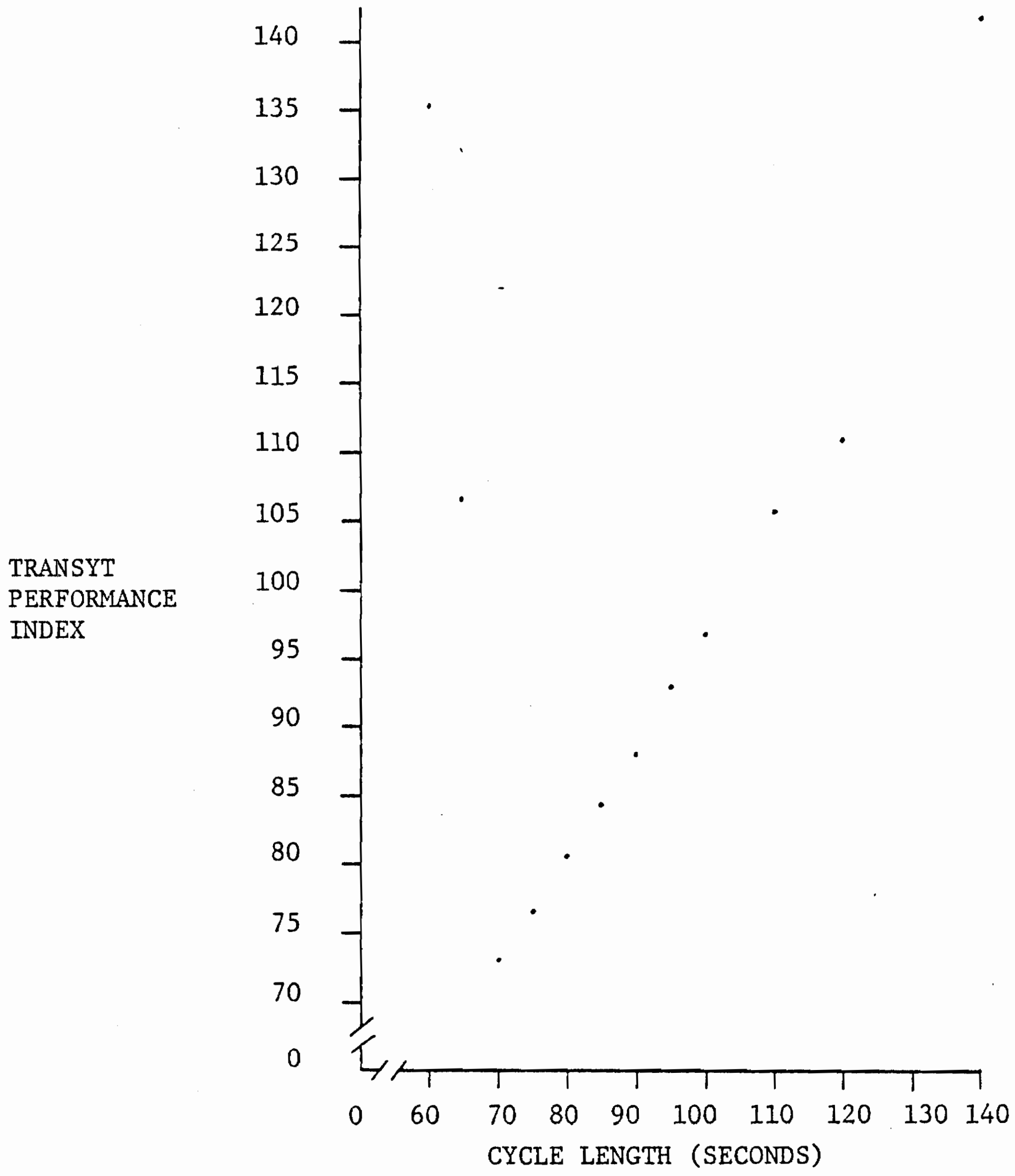

FIGURE A.36 - TRANSYT Performance Index vs. Cycle Length (Stop Penalty = 0, Arlington County)

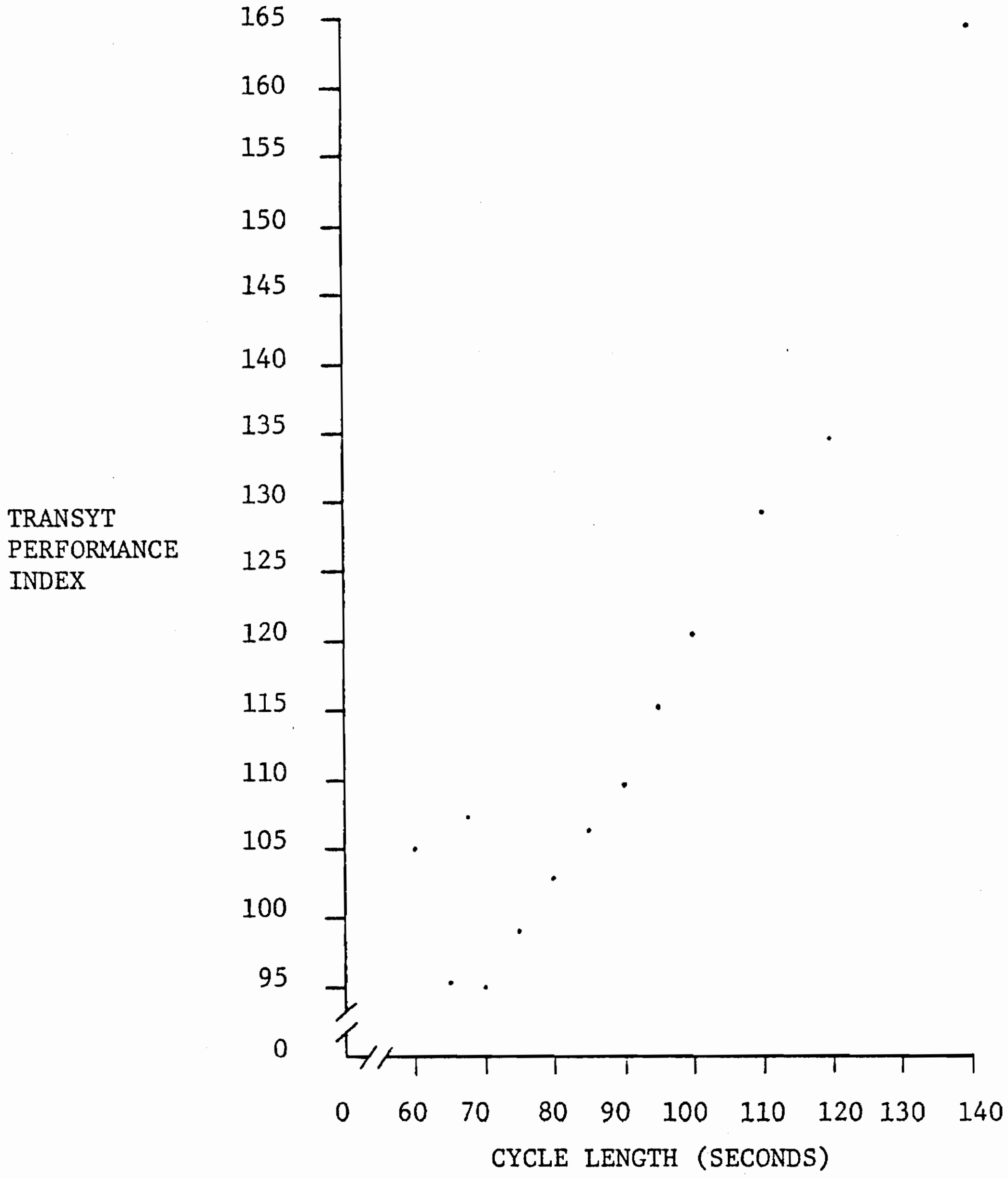

FIGURE A.37 - TRANSYT Performance Index vs. Cycle Length (Stop Penalty = 6, Arlington County)

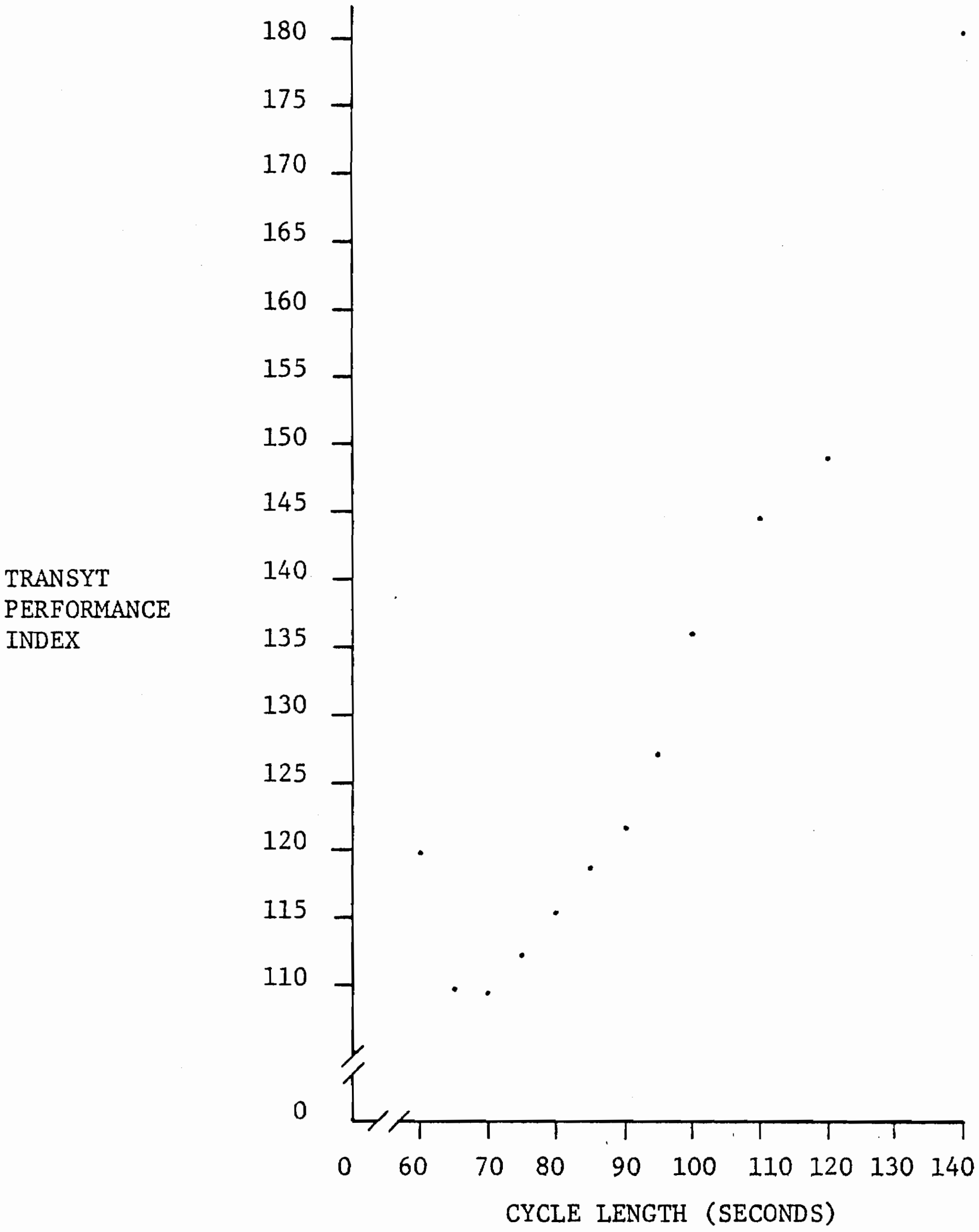

FIGURE A.38 - TRANSYT Performance Index vs. Cycle Length
(Stop Penalty = 10, Arlington County)

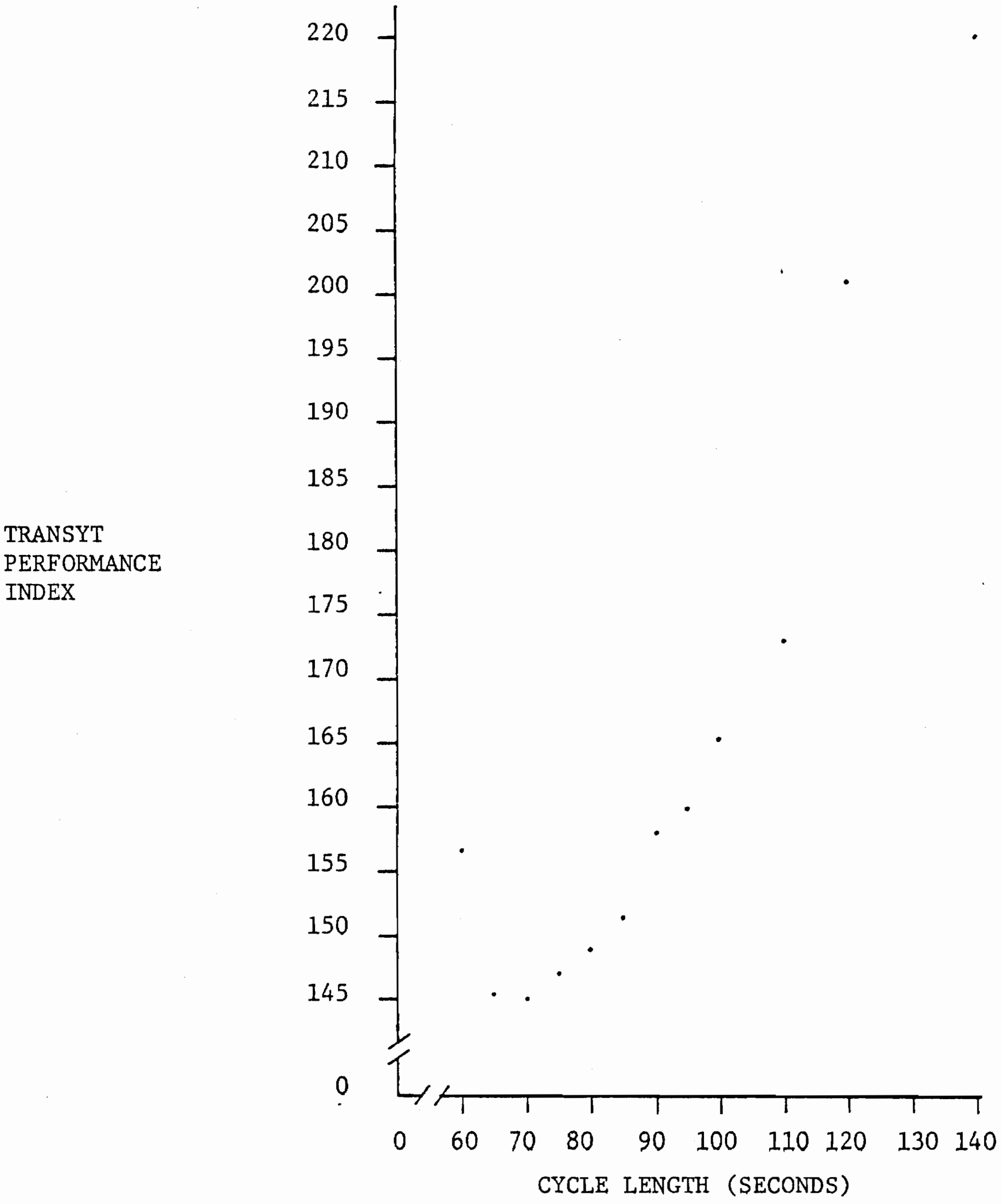

FIGURE A.39 - TRANSYT Performance Index vs. Cycle Length (Stop Penalty = 20, Arlington County)

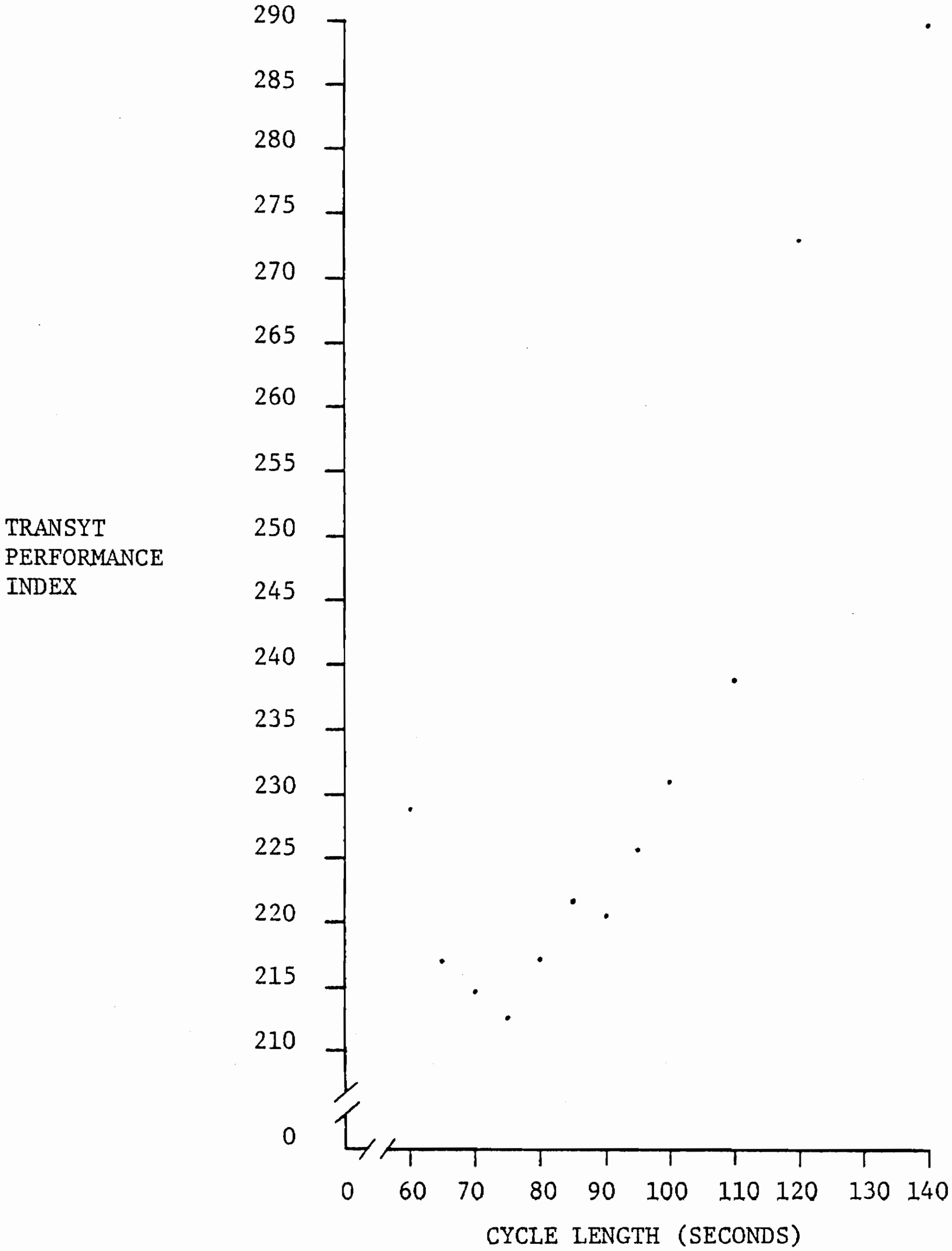

FIGURE A.40 - TRANSYT Performance Index vs. Cycle Length
(Stop Penalty = 40, Arlington County)

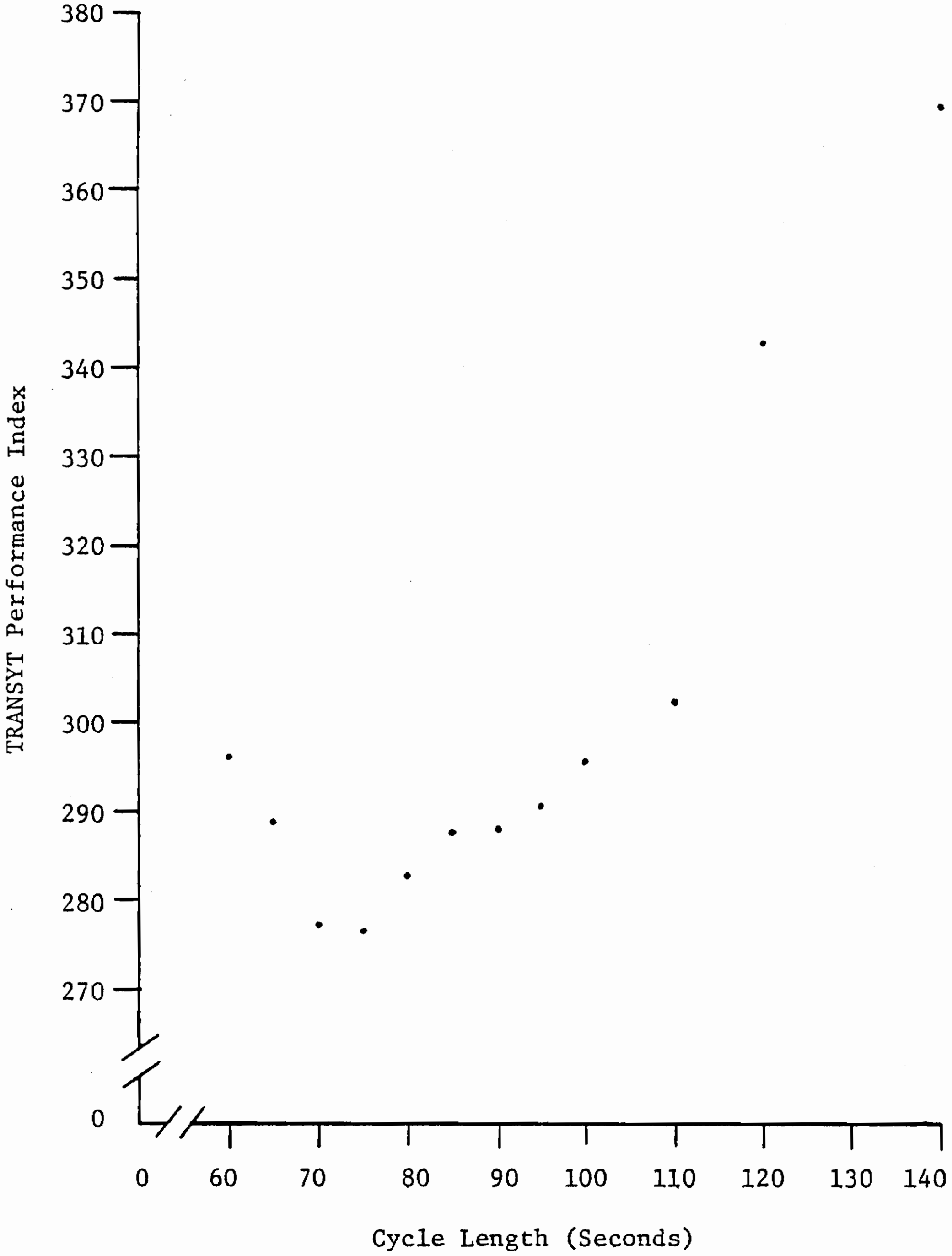

Figure A.41 - TRANSYT Performance Index vs. Cycle Length (Stop Penalty = 60, Arlington County)

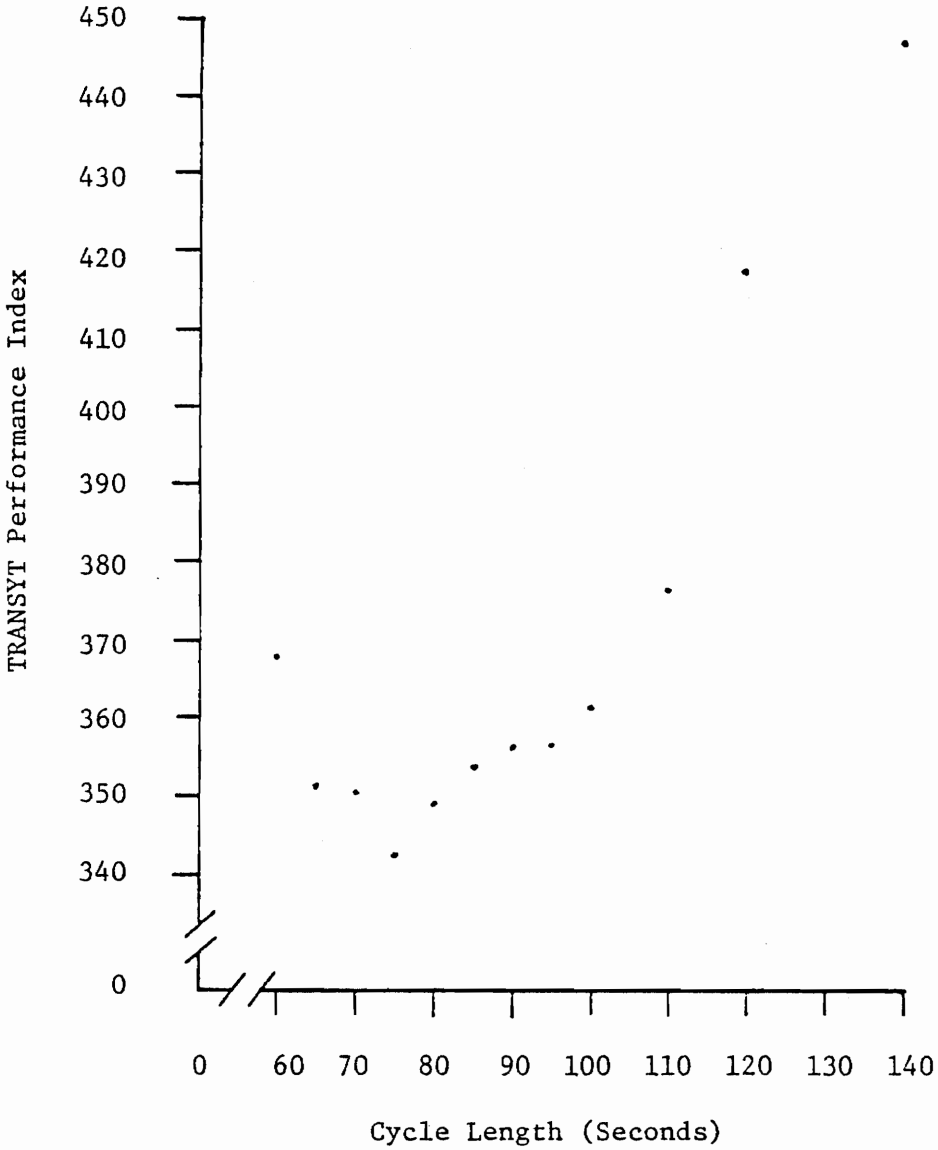

Figure A.42 - TRANSYT Performance Index vs. Cycle Length
(Stop Penalty = 80,
Arlington County)

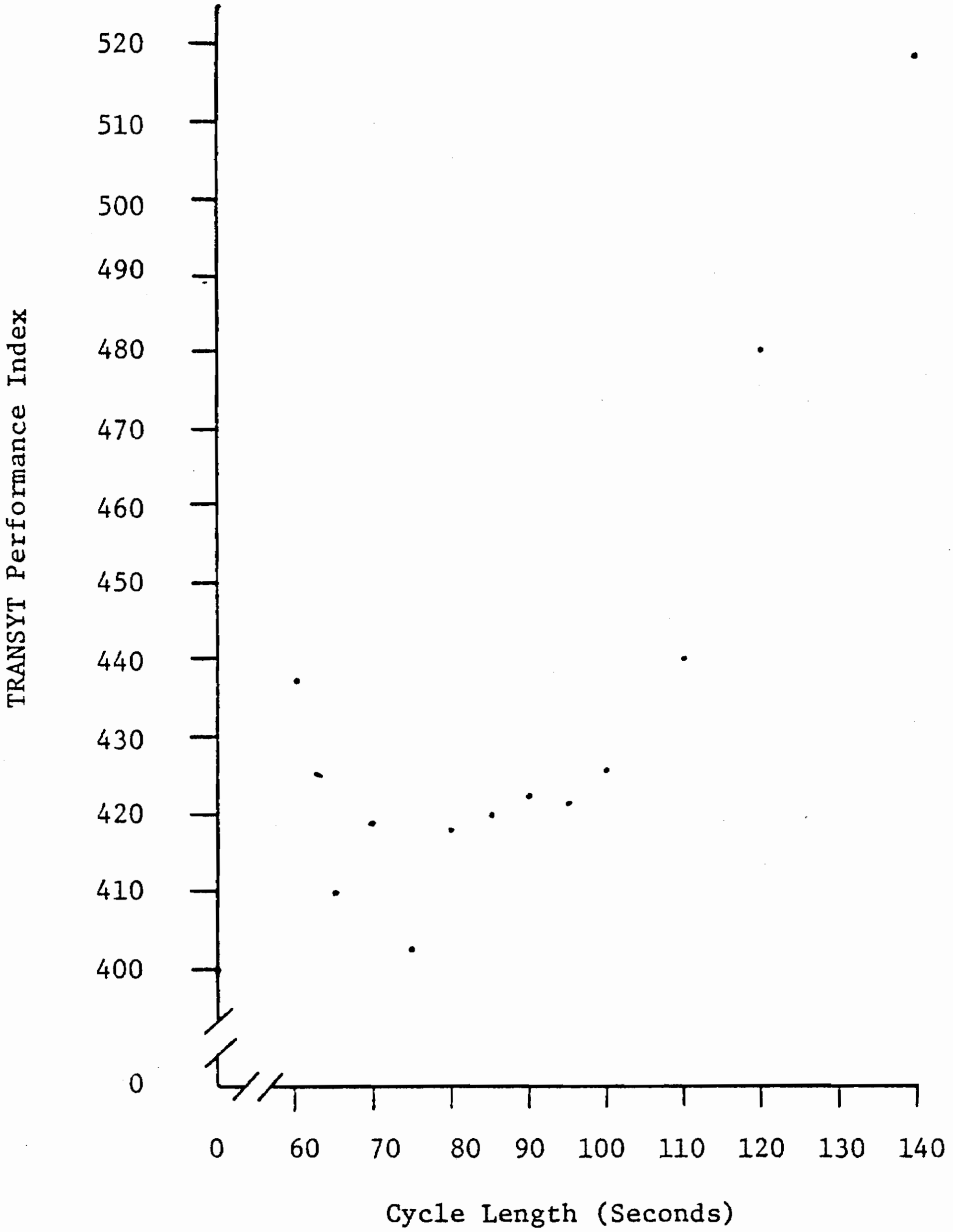

Figure A.43 - <u>TRANSYT Performance Index vs. Cycle Length</u>
(Stop Penalty = 100,
Arlington County)

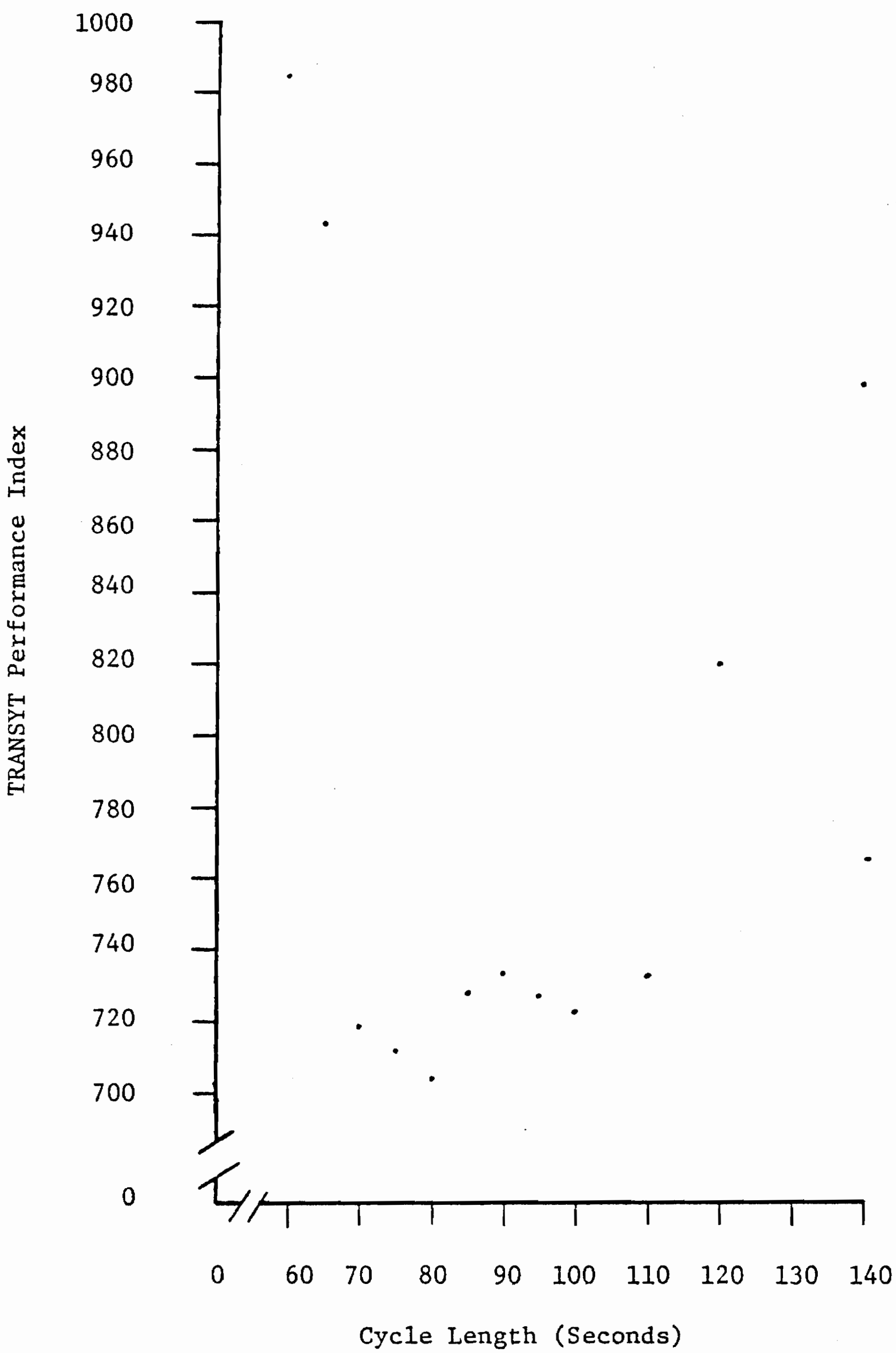

Figure A.44 - <u>TRANSYT Performance Index vs. Cycle Length</u>
(Stop Penalty = 200, Arlington County)

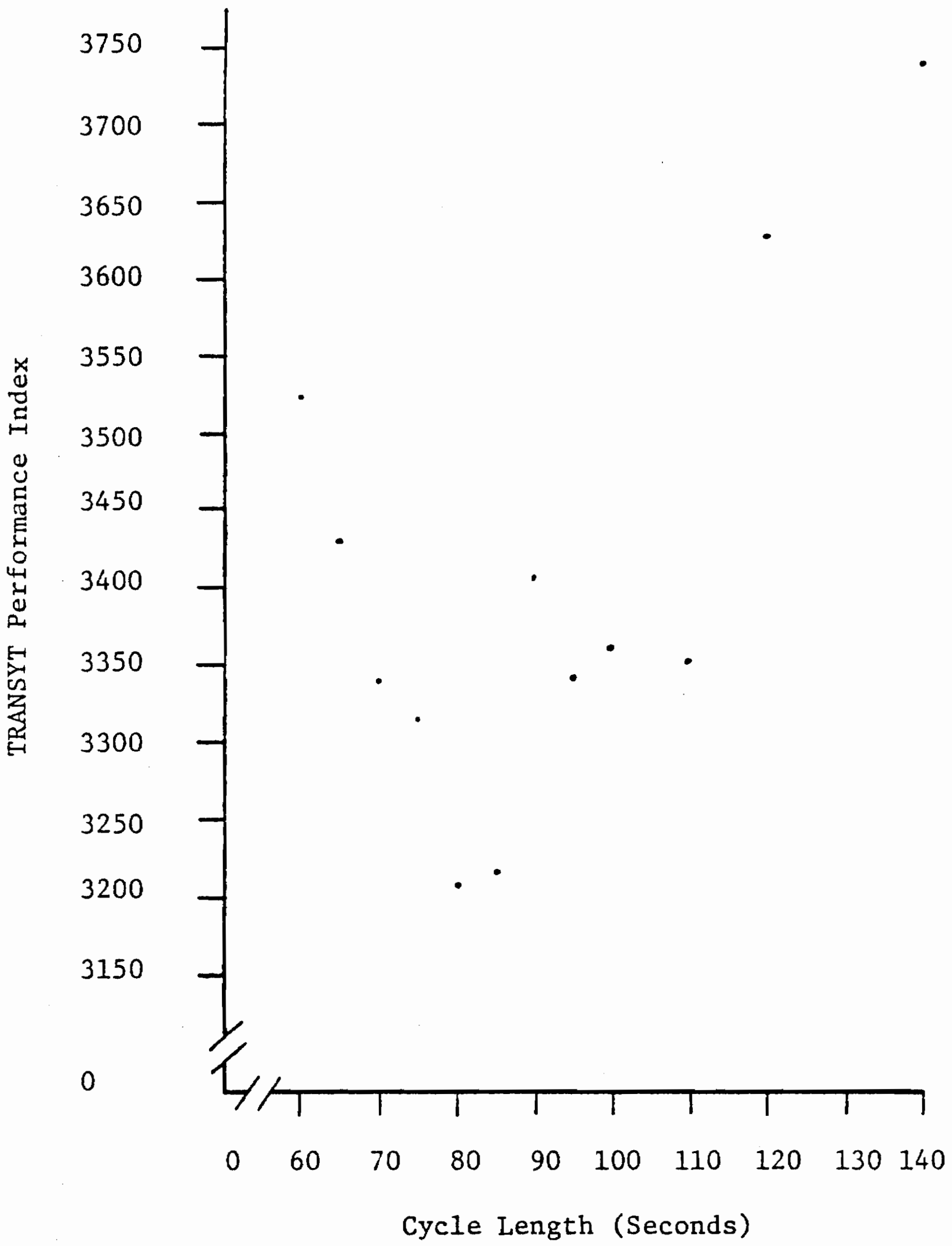

Figure A.45 - <u>TRANSYT Performance Index vs. Cycle Length</u>
(Stop Penalty = 1000, Arlington County)

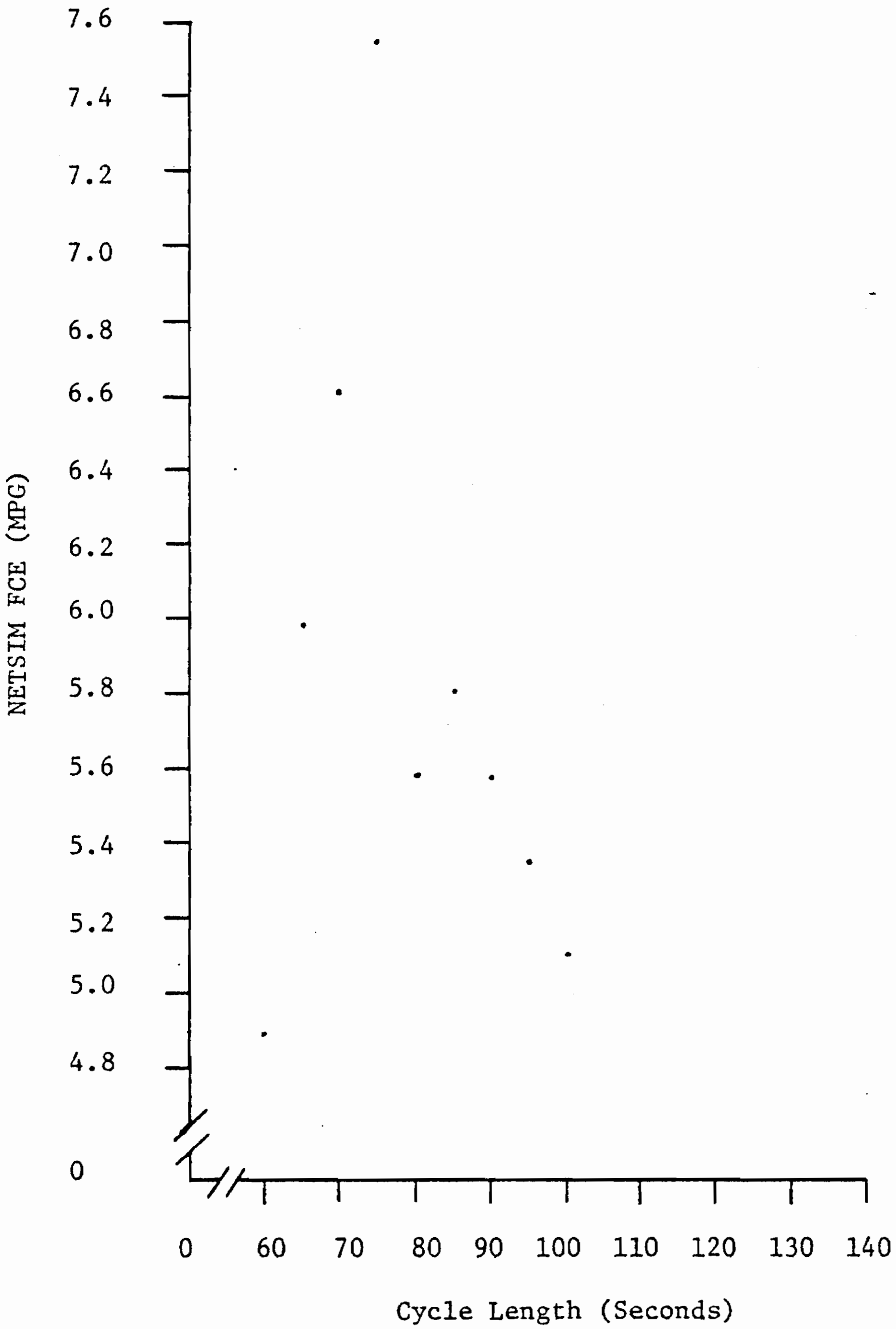

Figure A.46 - <u>NETSIM FCE vs. Cycle Length</u>
(Stop Penalty = 0,
Arlington County)

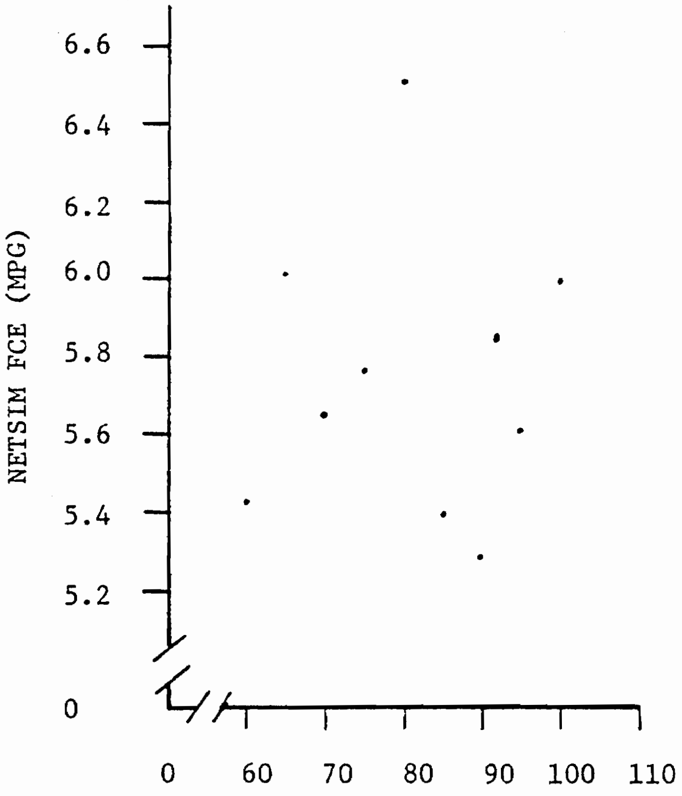

Figure A.47 - NETSIM FCE vs. Cycle Length
(Stop Penalty = 6,
Arlington County)

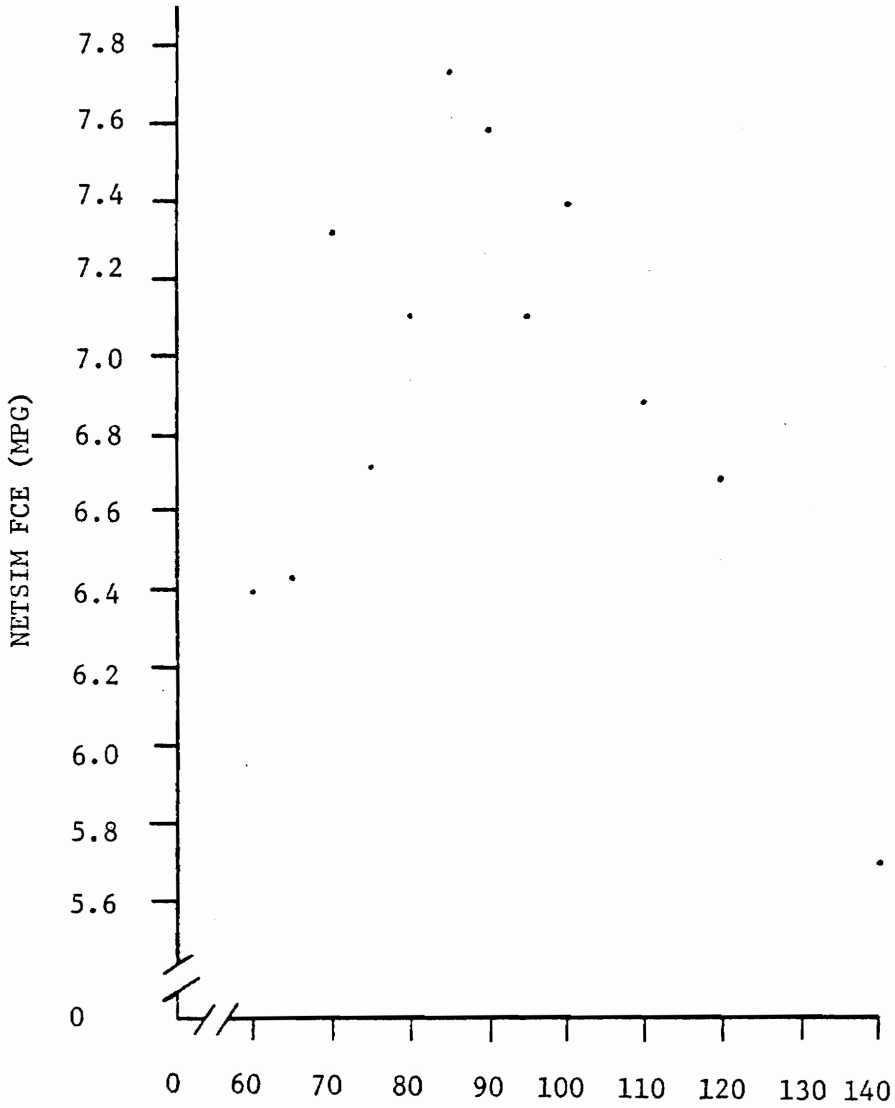

Figure A.48 - <u>NETSIM FCE vs. Cycle Length</u>
(Stop Penalty = 10,
Arlington County)

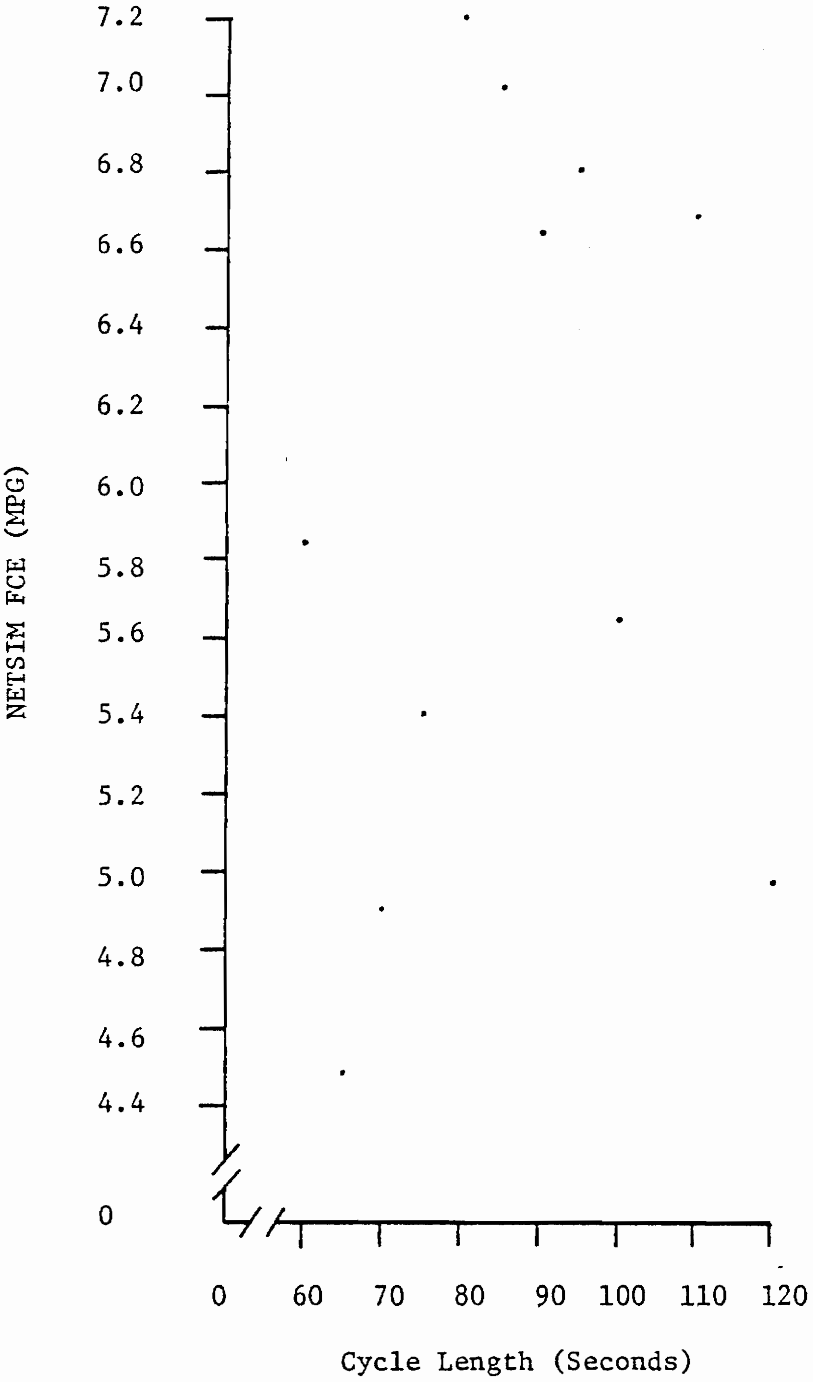

Figure A.49 - NETSIM FCE vs. Cycle Length
(Stop Penalty = 20,
Arlington County)

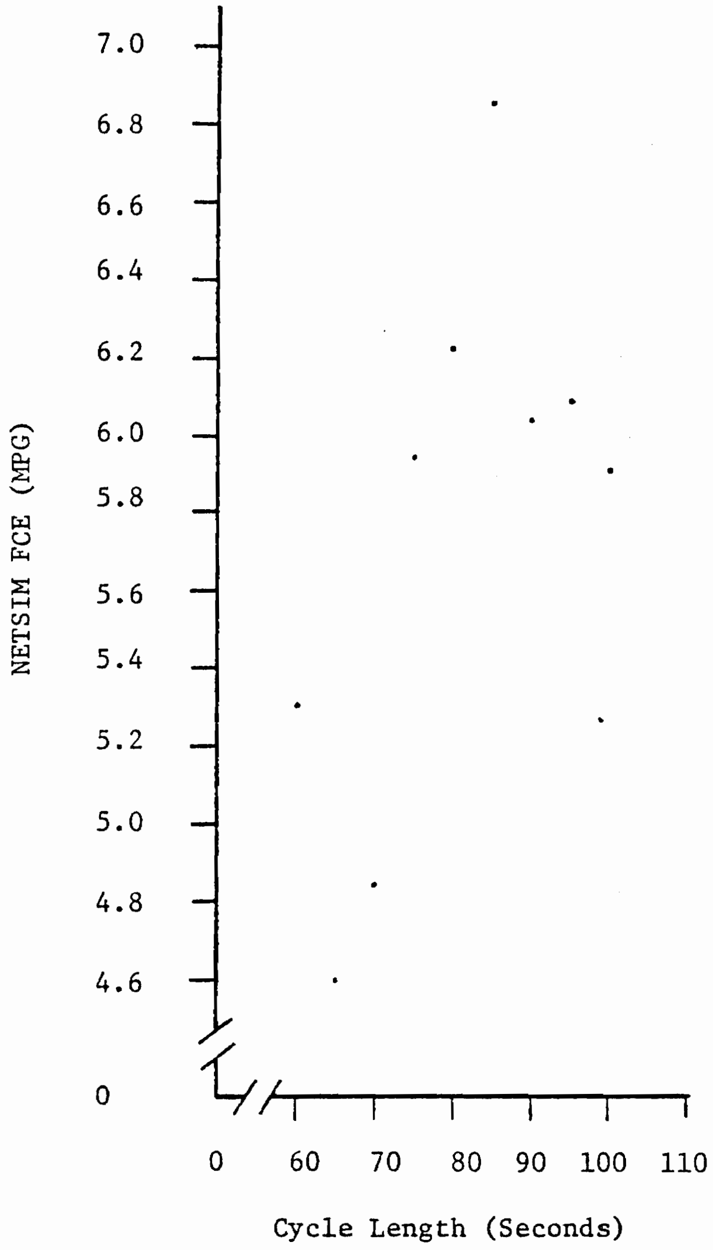

Figure A.50 - NETSIM FCE vs. Cycle Length
(Stop Penalty = 40,
Arlington County)

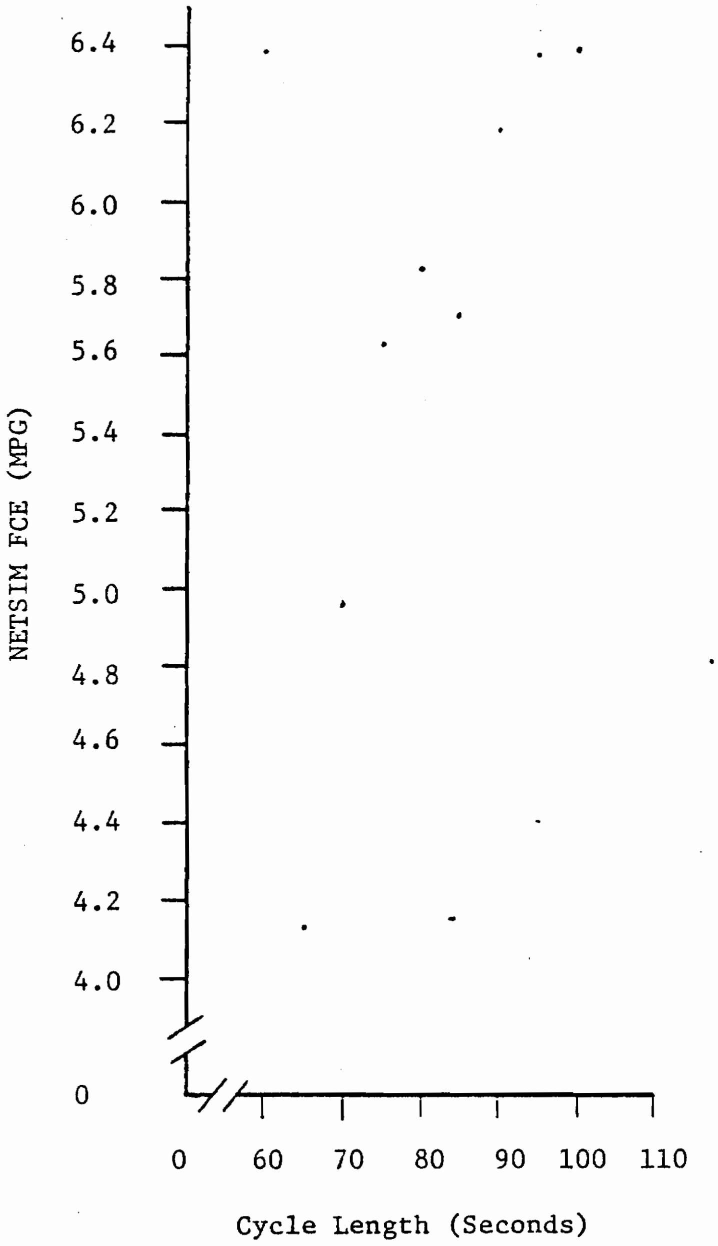

Figure A.51 - NETSIM FCE vs. Cycle Length
(Stop Penalty = 60,
Arlington County)

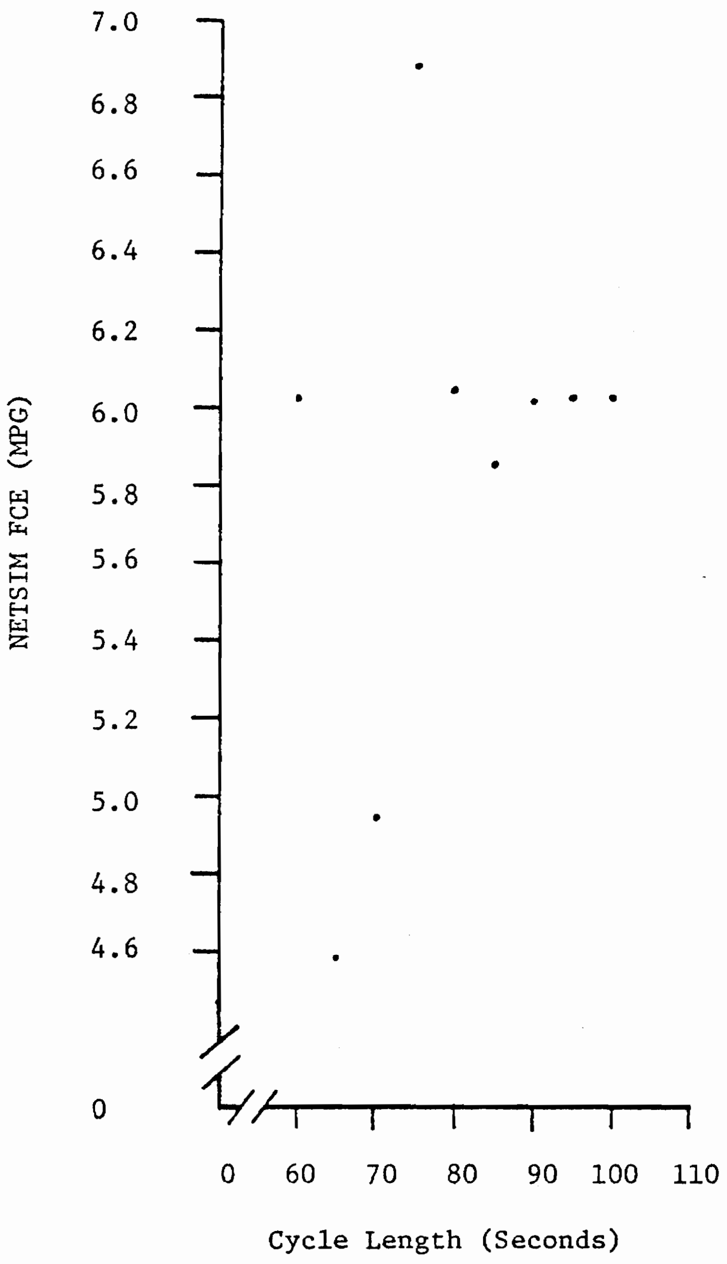

Figure A.52 - <u>NETSIM FCE vs. Cycle Length</u>
(Stop Penalty = 80,
Arlington County)

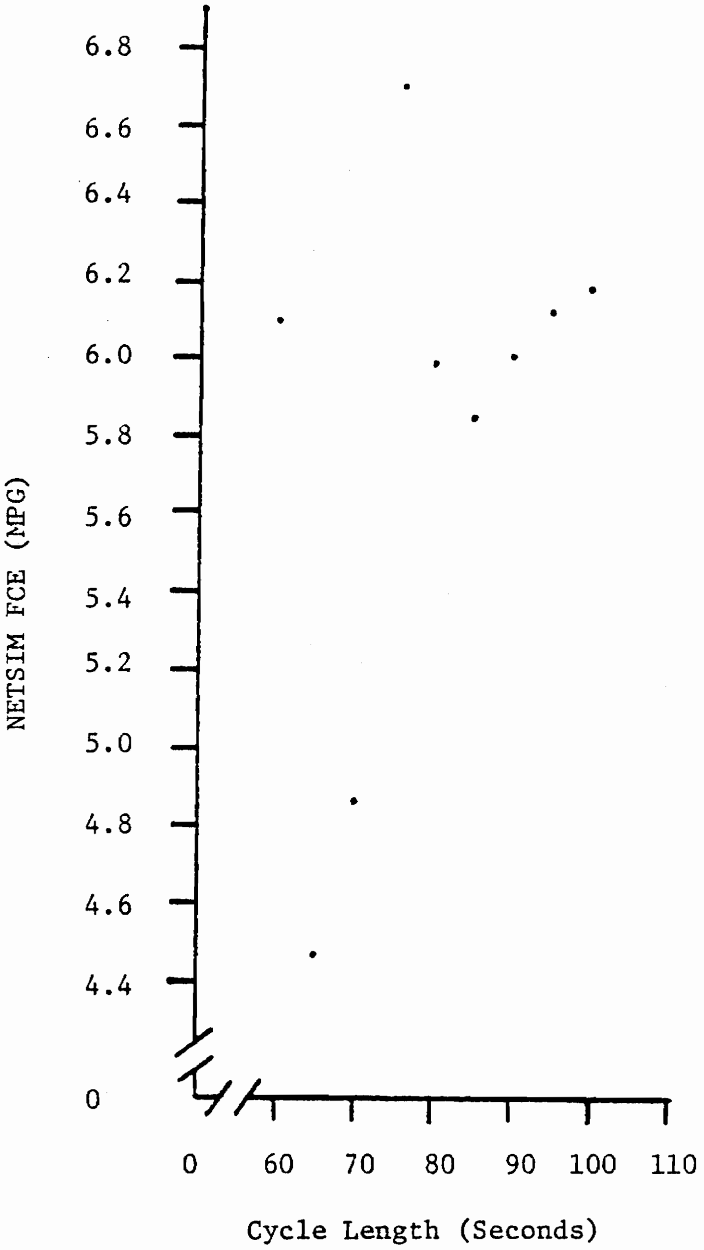

Figure A.53 - NETSIM FCE vs. Cycle Length
(Stop Penalty = 100,
Arlington County)

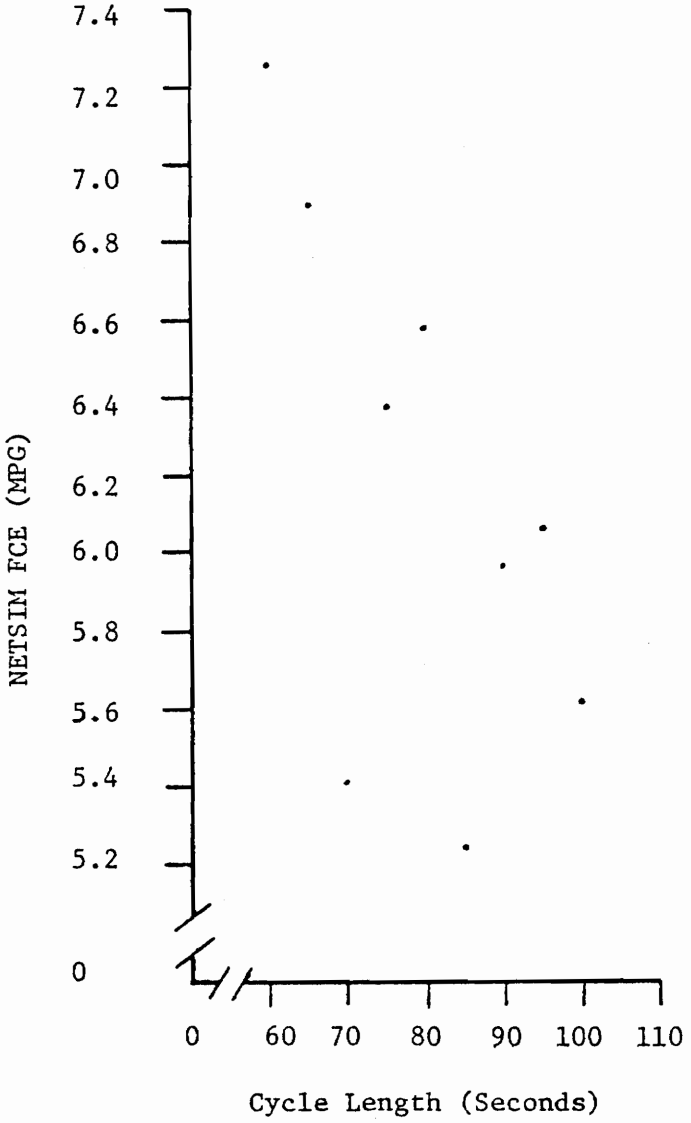

Figure A.54 - <u>NETSIM FCE vs. Cycle Length</u>
(Stop Penalty = 200,
Arlington County)

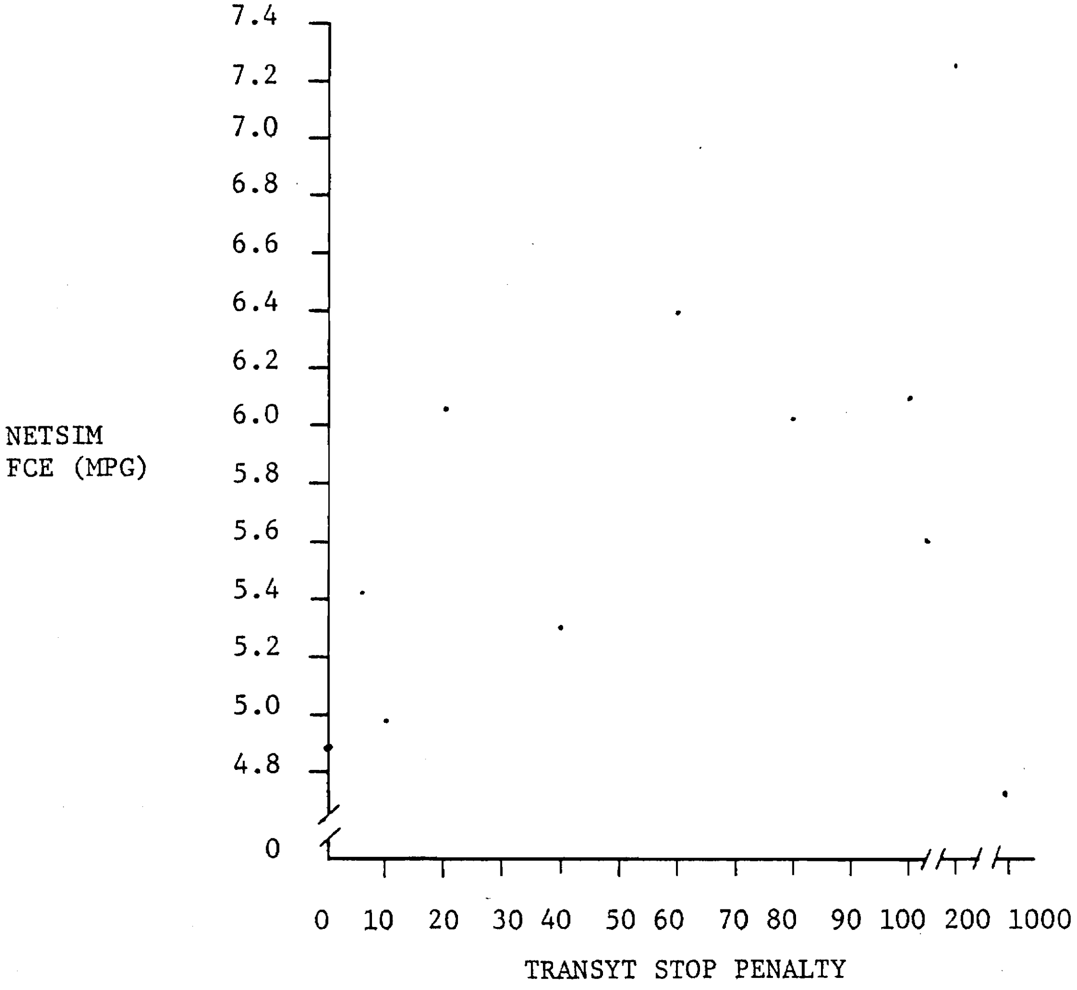

FIGURE A.55 - <u>NETSIM FCE vs. TRANSYT Stop Penalty</u>
(Cycle Length = 60 Seconds,
Arlington County)

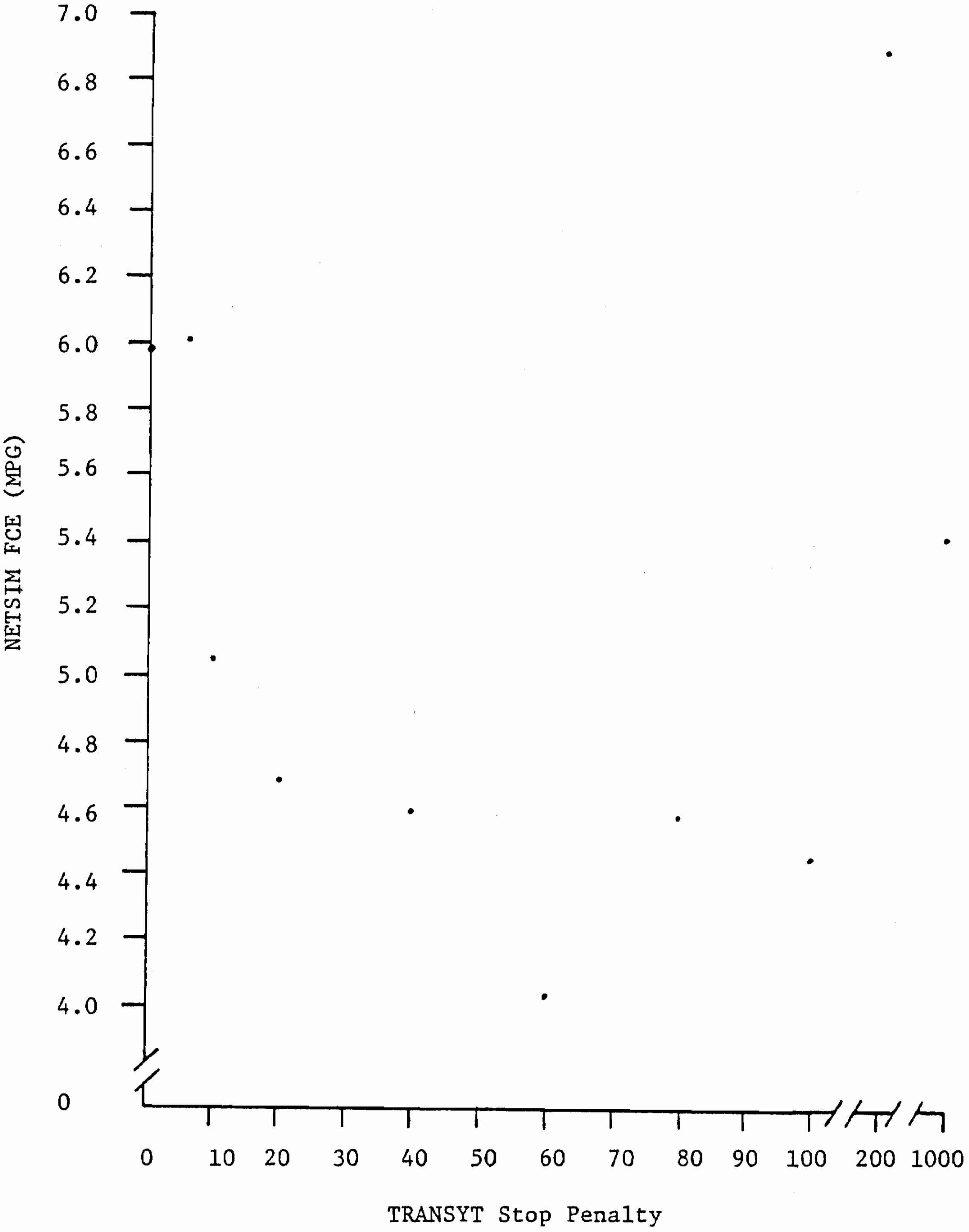

Figure A.56 - NETSIM FCE vs. TRANSYT Stop Penalty
(Cycle Length = 65 Seconds,
Arlington County)

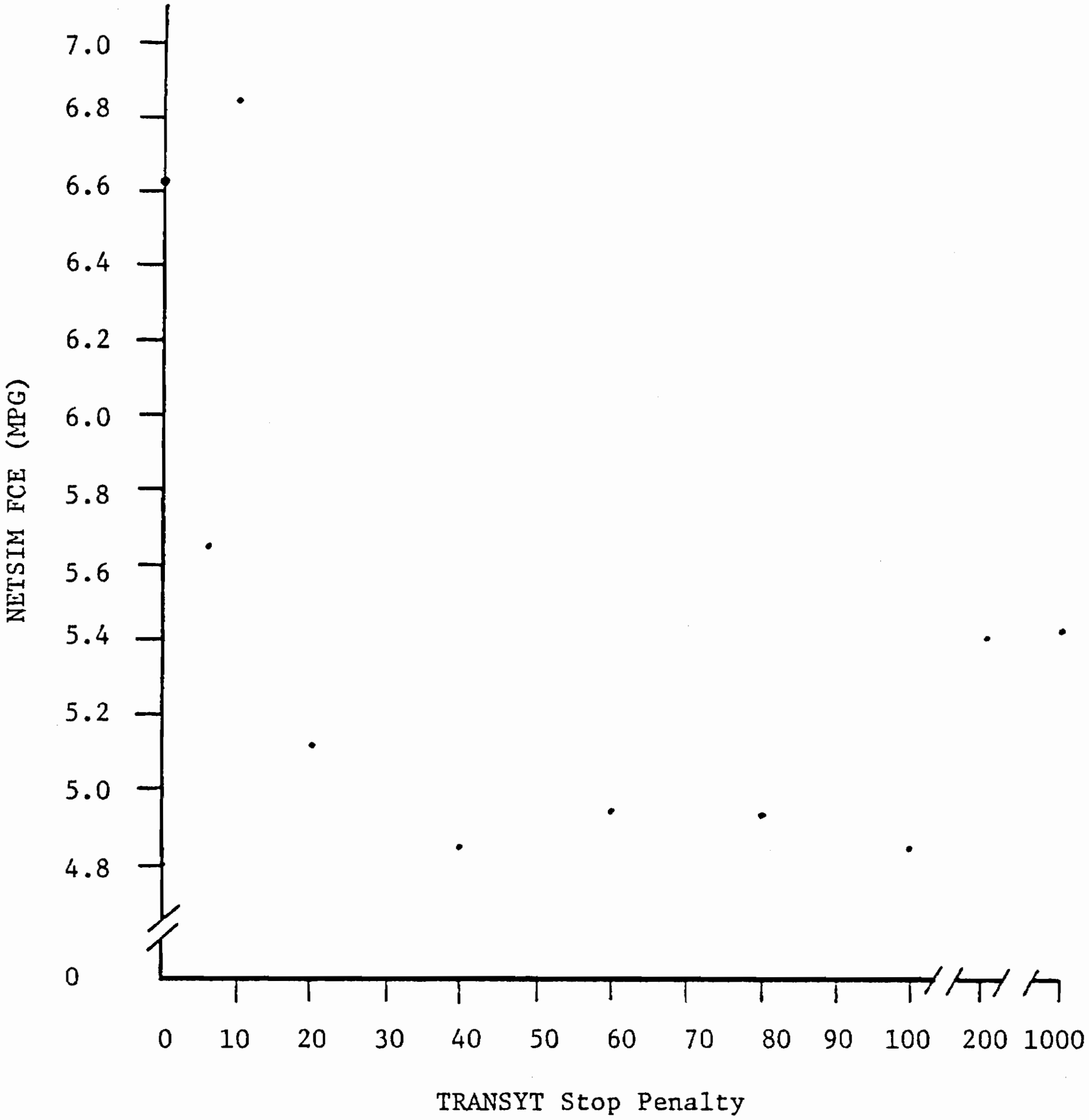

Figure A.57 - NETSIM FCE vs. TRANSYT Stop Penalty
(Cycle Length = 70 Seconds,
Arlington County)

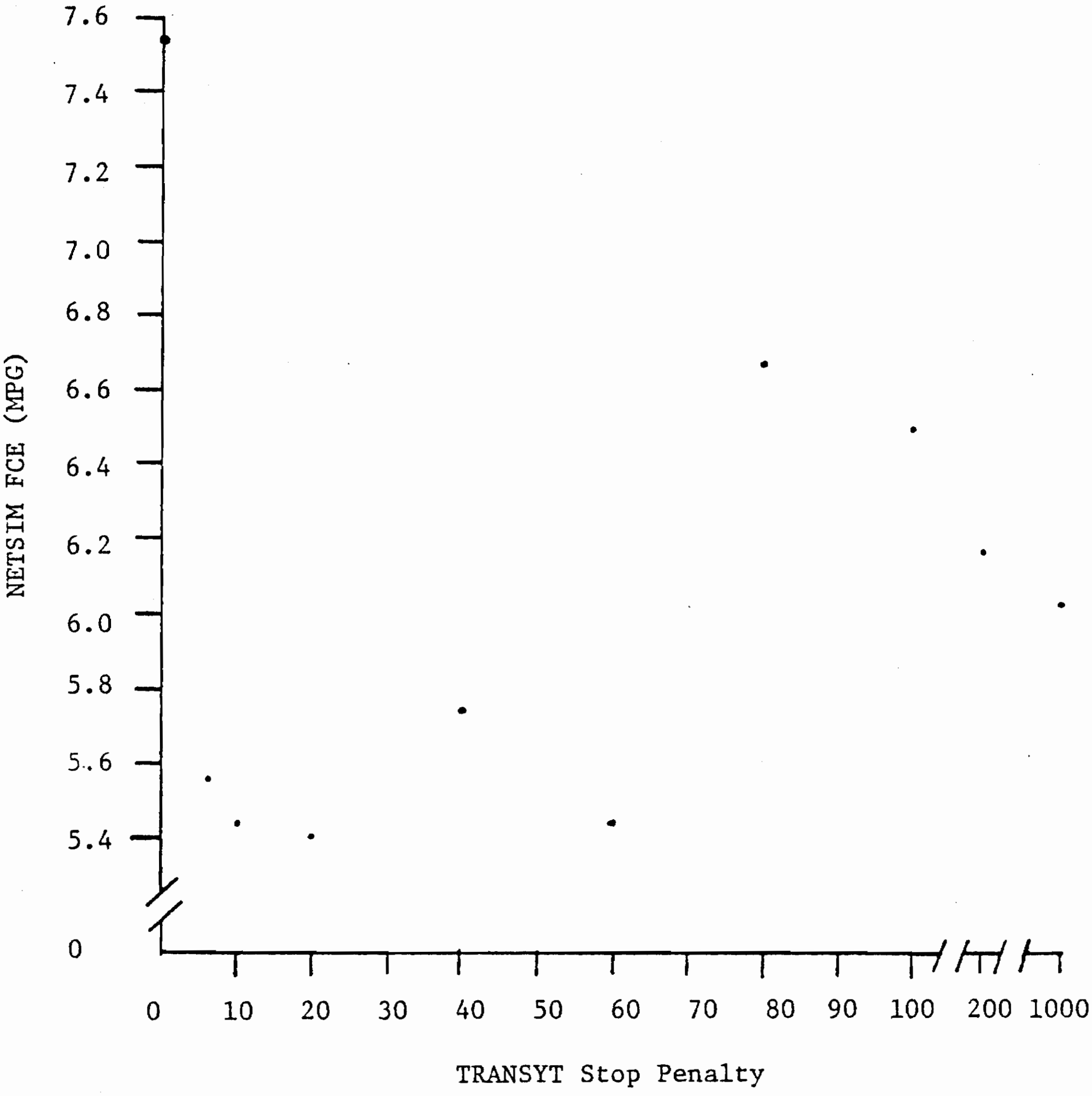

Figure A.58 - NETSIM FCE vs. TRANSYT Stop Penalty
(Cycle Length = 75 Seconds,
Arlington County)

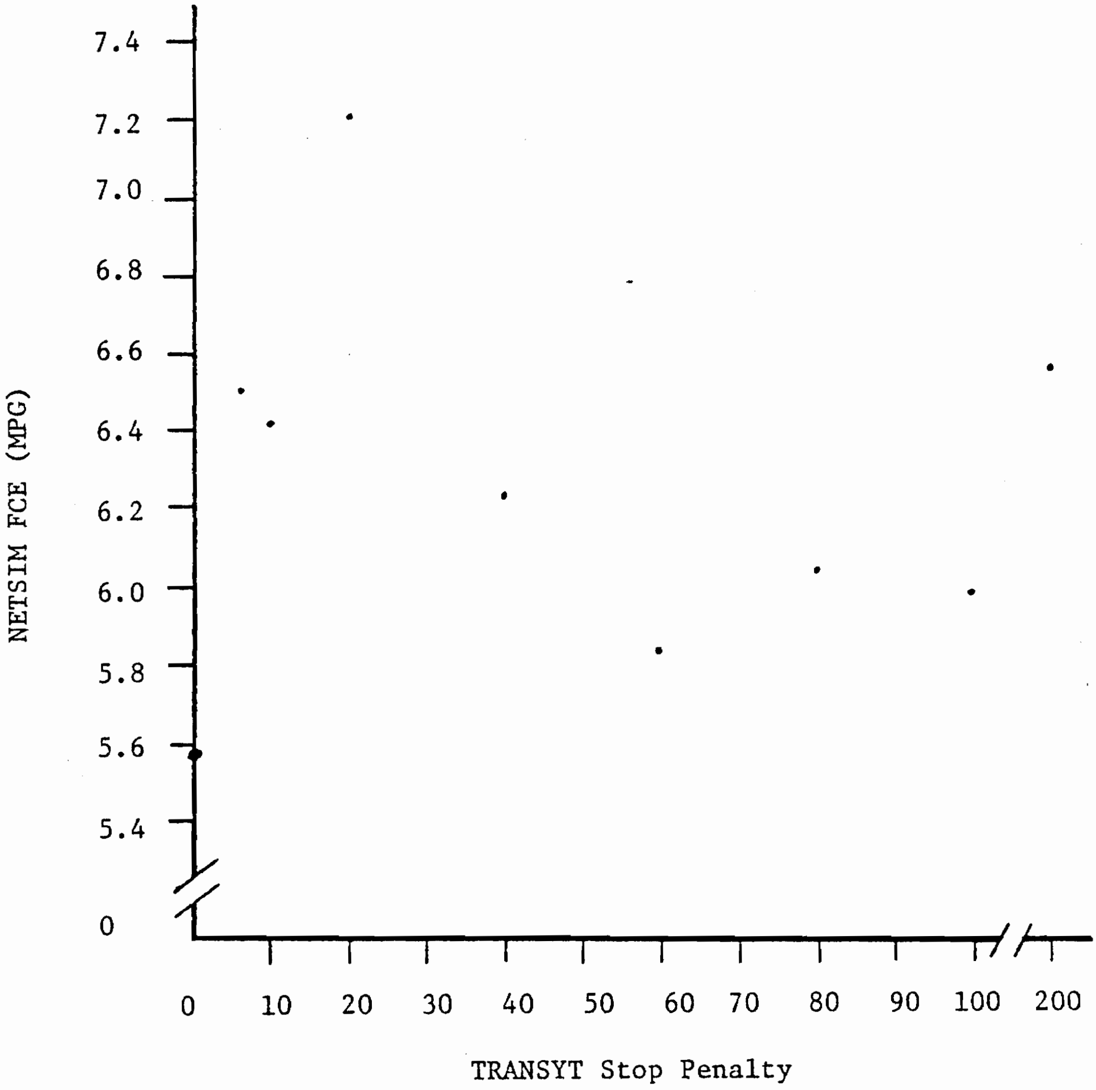

Figure A.59 - <u>NETSIM FCE vs. TRANSYT Stop Penalty</u>
(Cycle Length = 80 Seconds,
Arlington County)

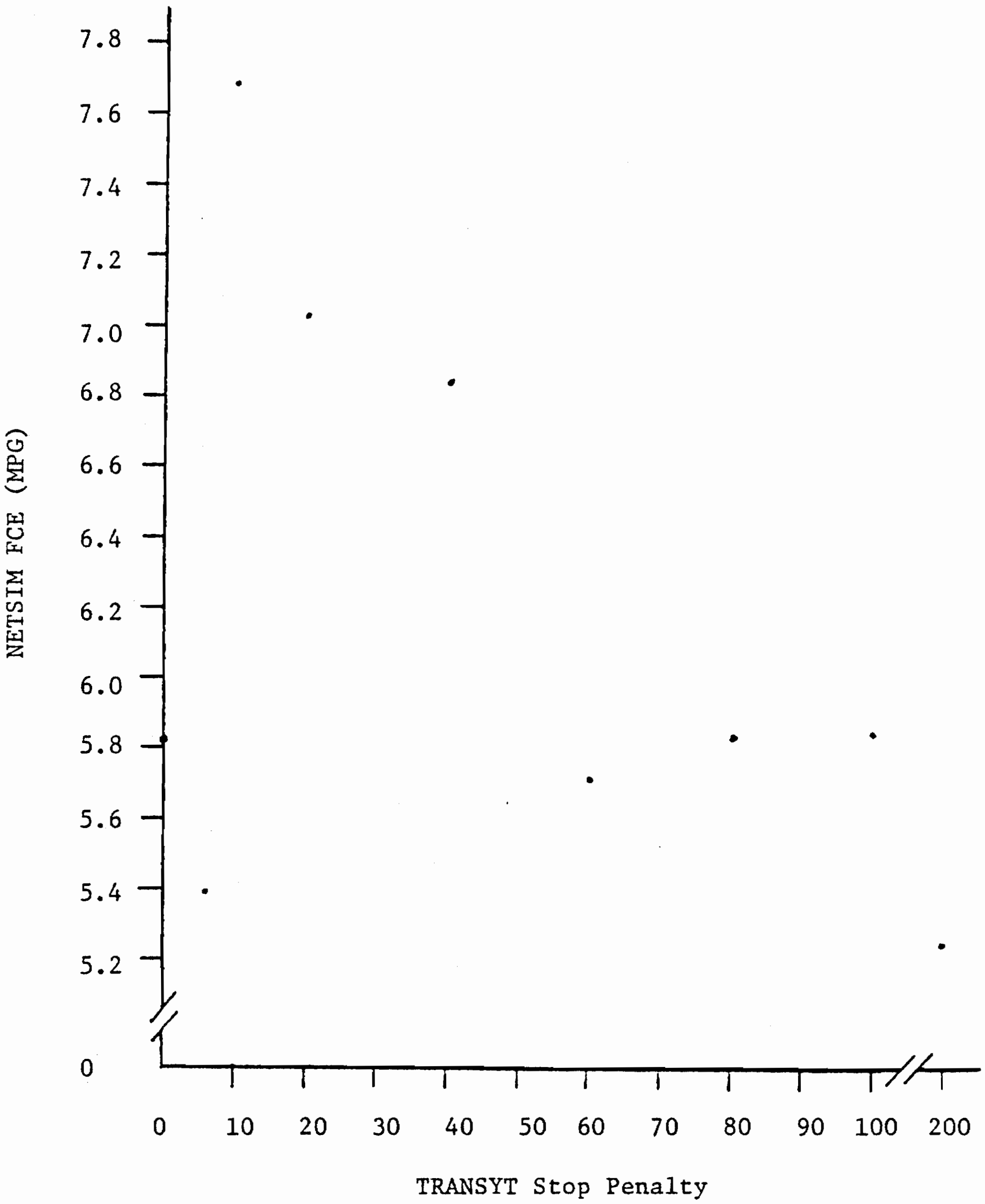

Figure A.60 - NETSIM FCE vs. TRANSYT Stop Penalty
(Cycle Length = 85 Seconds,
Arlington County)

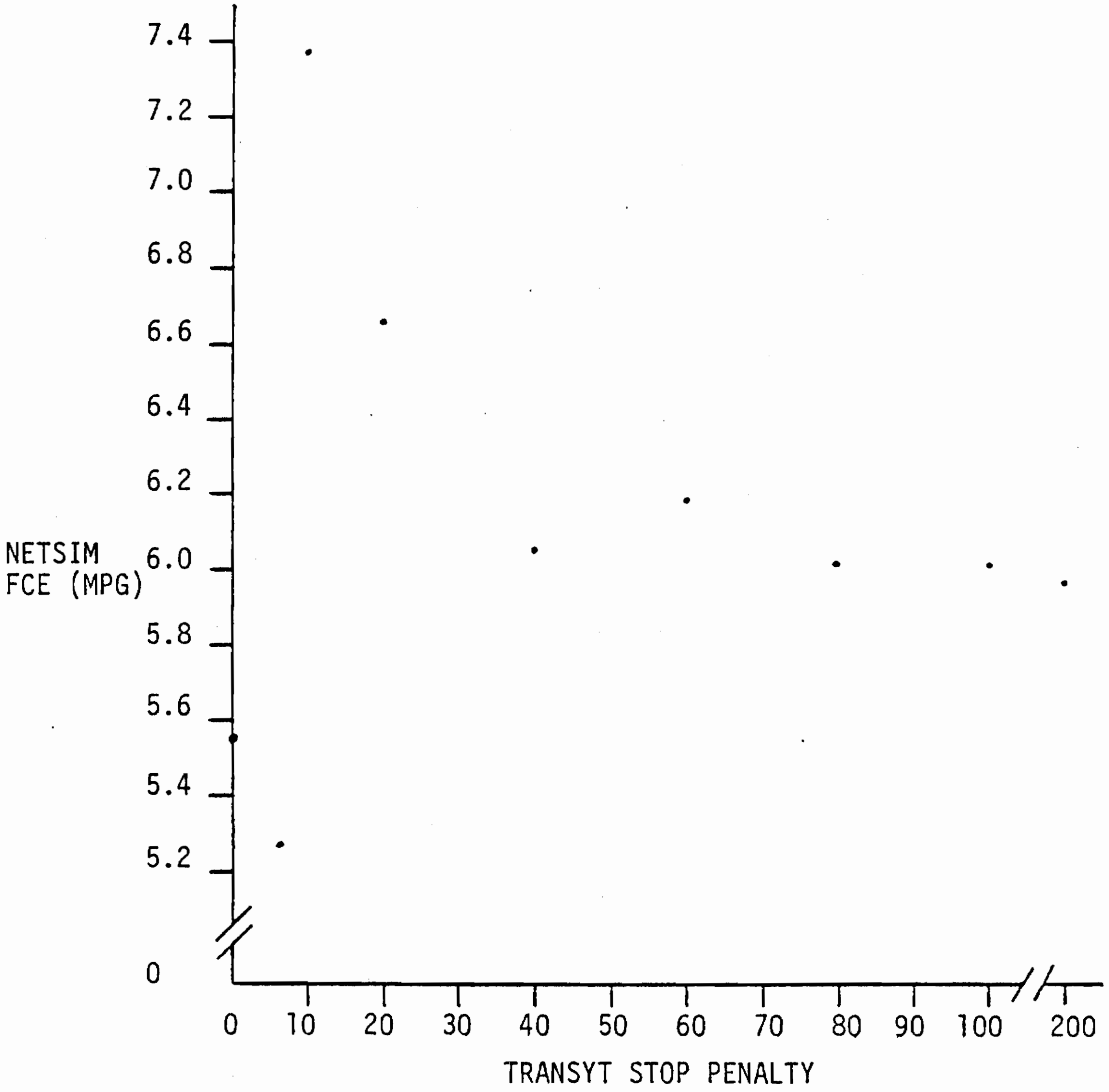

FIGURE A.61 - NETSIM FCE vs. TRANSYT STOP PENALTY
(Cycle Length = 90 Seconds,
Arlington County)

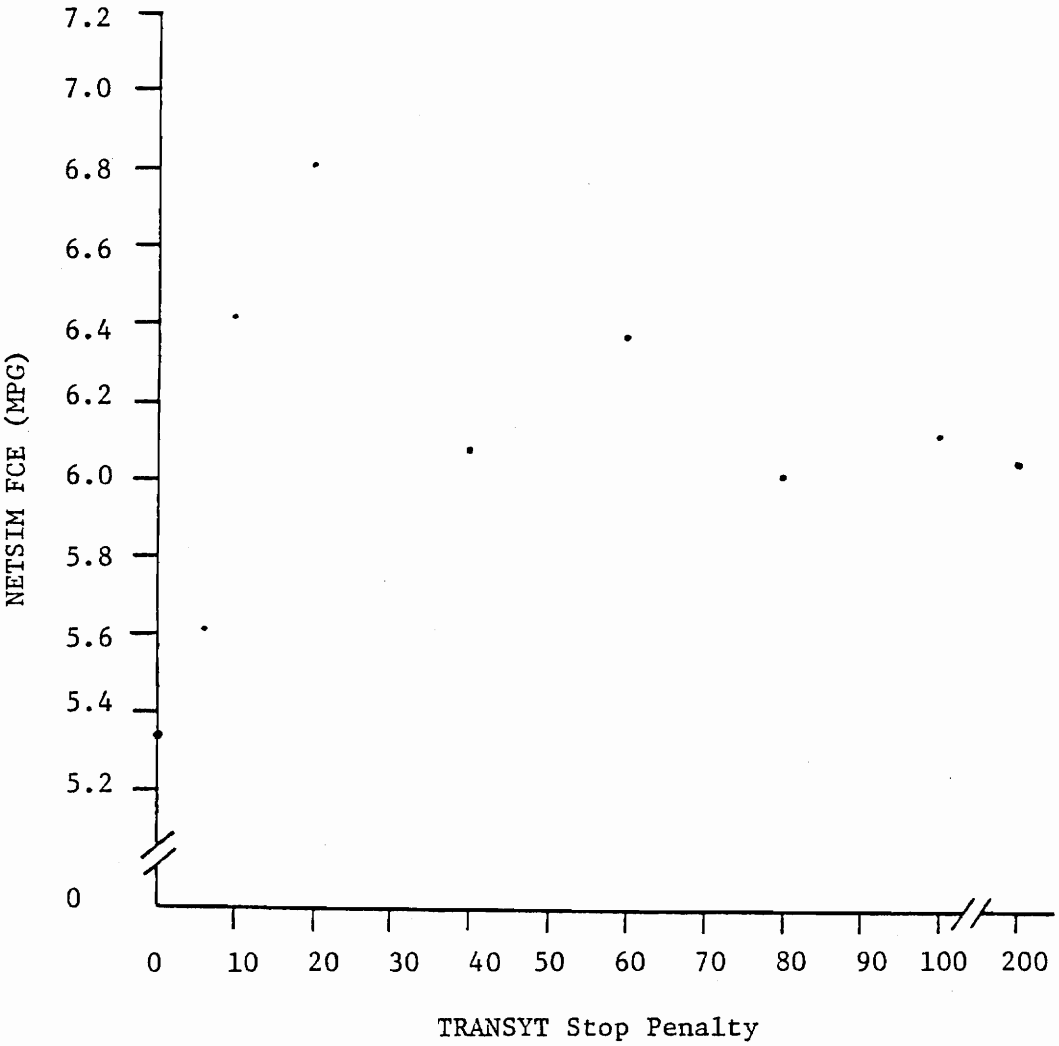

Figure A.62 - <u>NETSIM FCE vs. TRANSYT Stop Penalty</u>
(Cycle Length = 95 Seconds,
Arlington County)

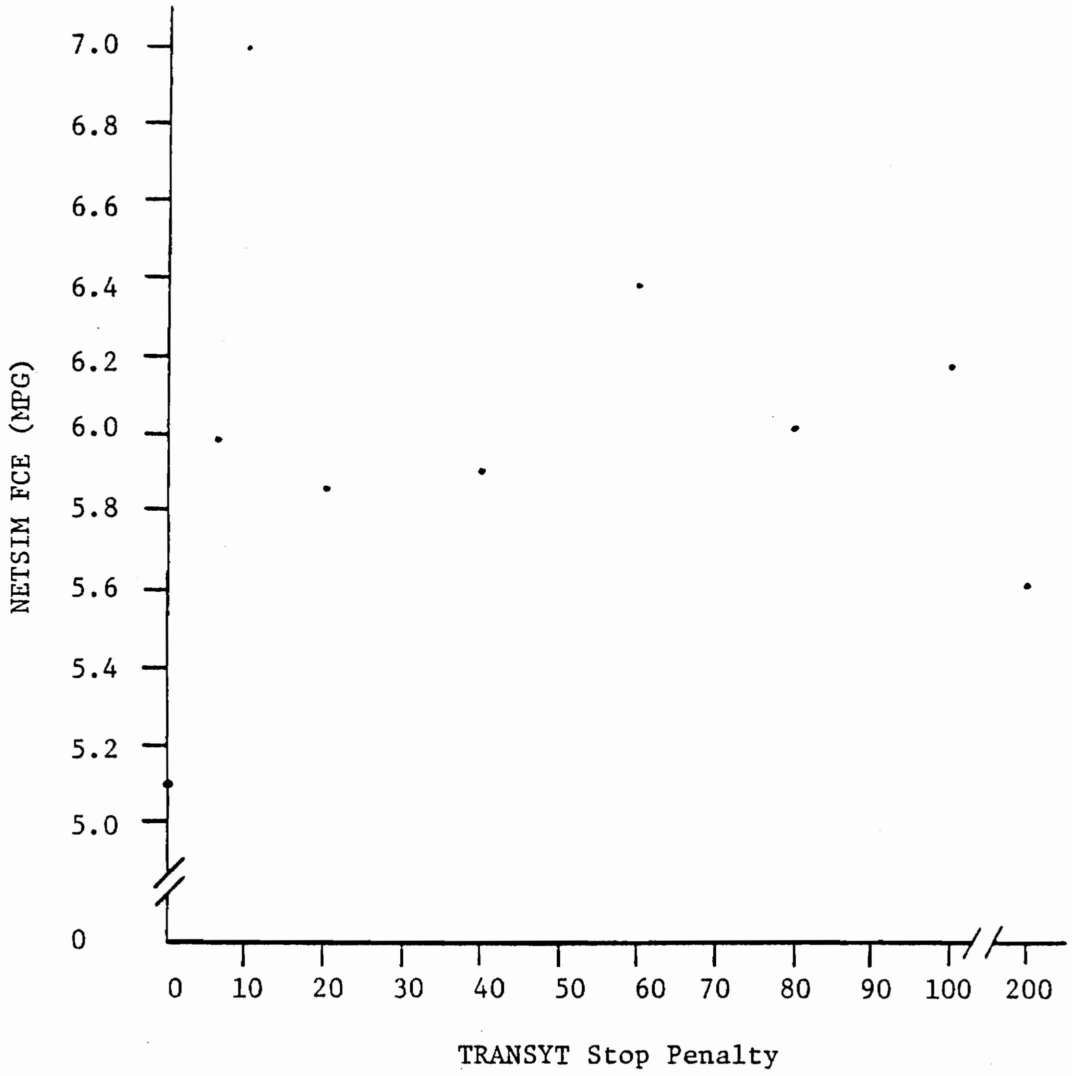

Figure A.63 - NETSIM FCE vs. TRANSYT Stop Penalty
(Cycle Length = 100 Seconds, Arlington County)

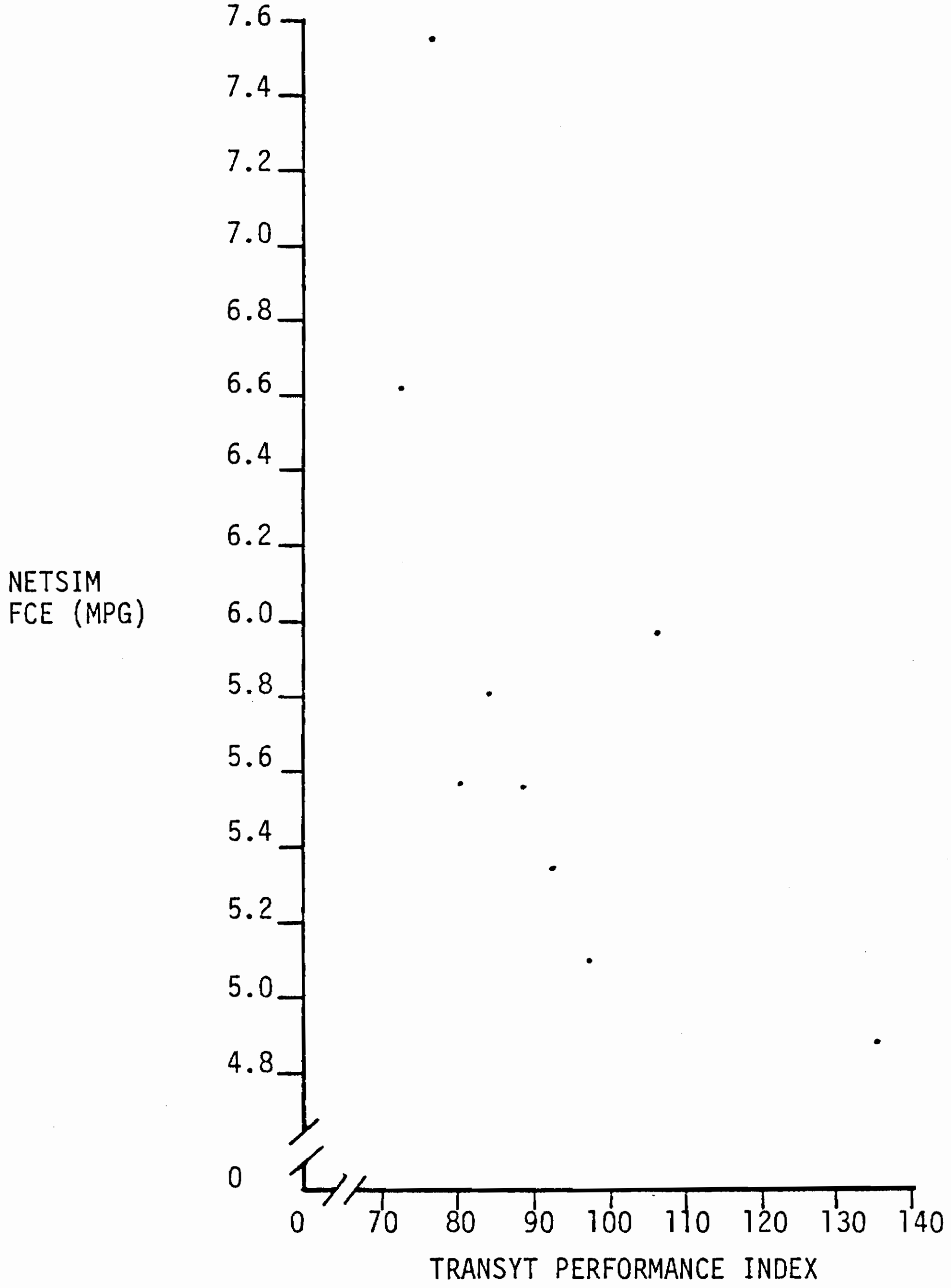

FIGURE A.64 - NETSIM FCE vs. TRANSYT Performance Index (Stop Penalty = 0, Arlington County)

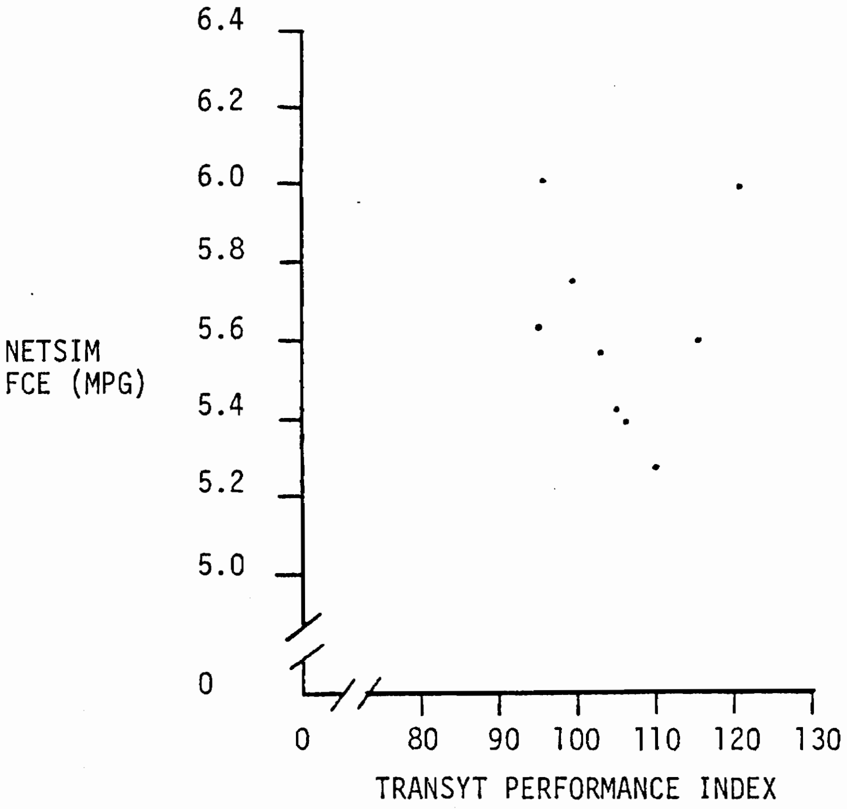

FIGURE A.65 - NETSIM FCE vs. TRANSYT Performance Index (Stop Penalty = 6, Arlington County)

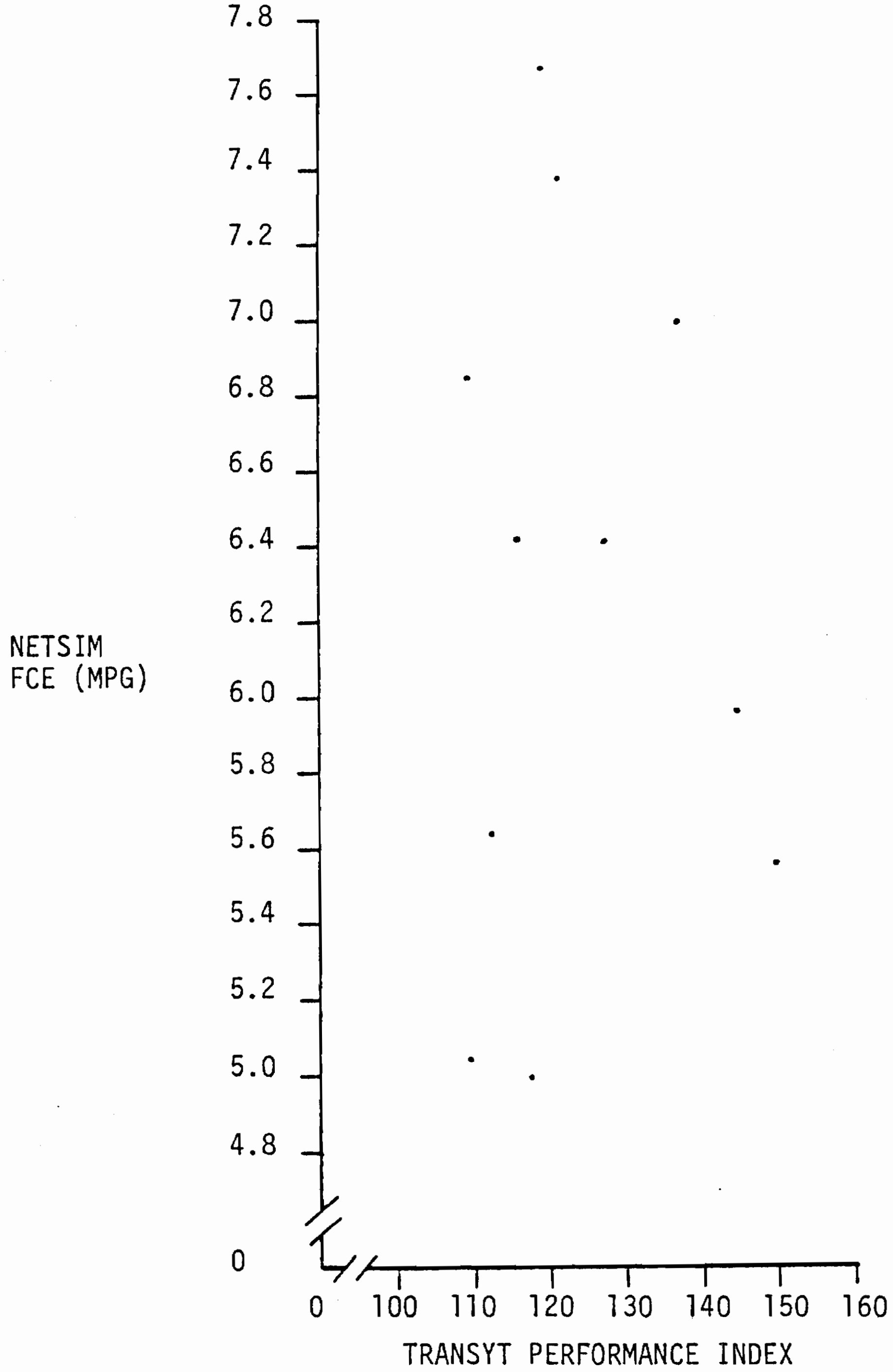

FIGURE A.66 - NETSIM FCE vs. TRANSYT Performance Index (Stop Penalty = 10, Arlington County)

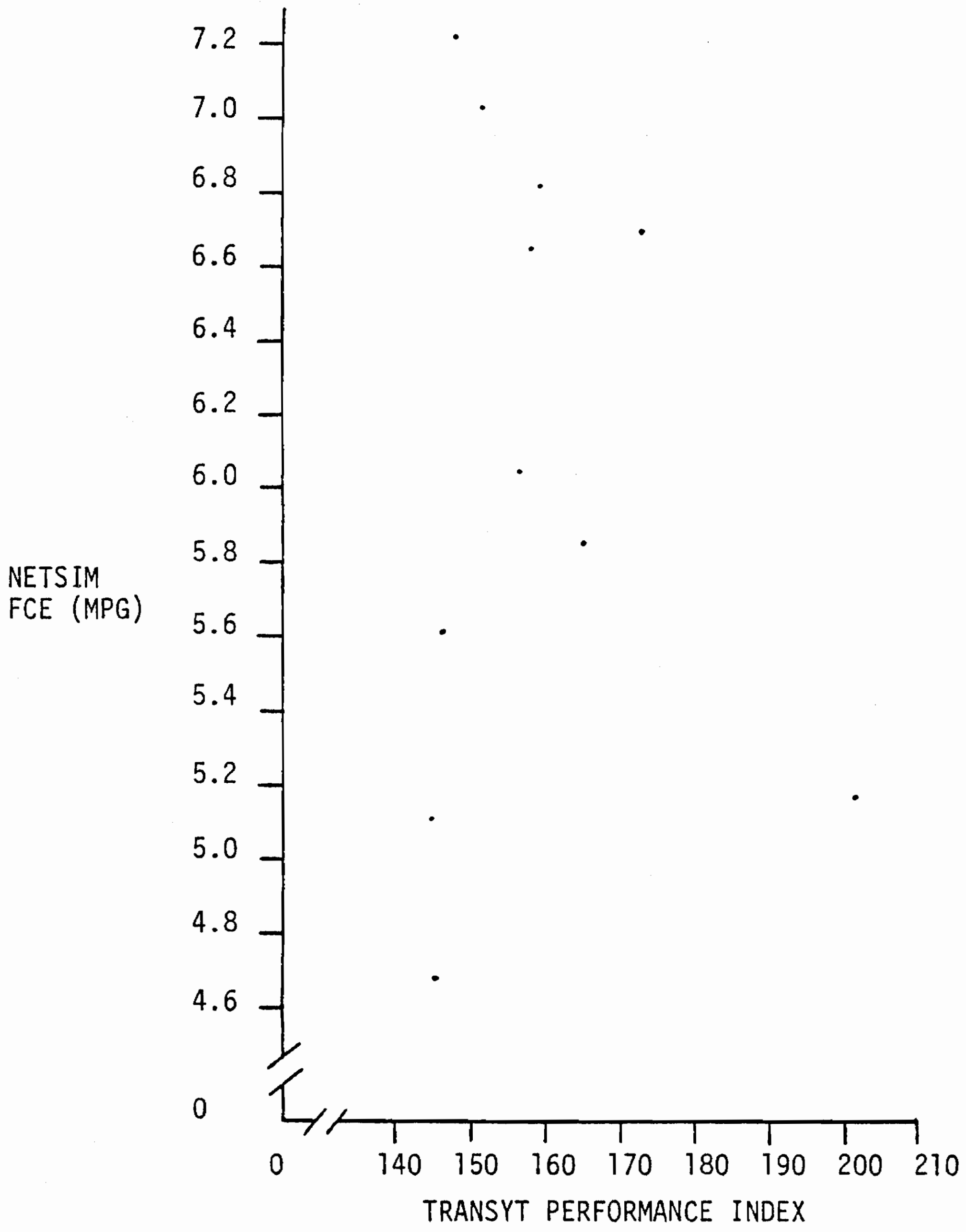

FIGURE A.67 - NETSIM FCE vs. TRANSYT Performance Index (Stop Penalty = 20, Arlington County)

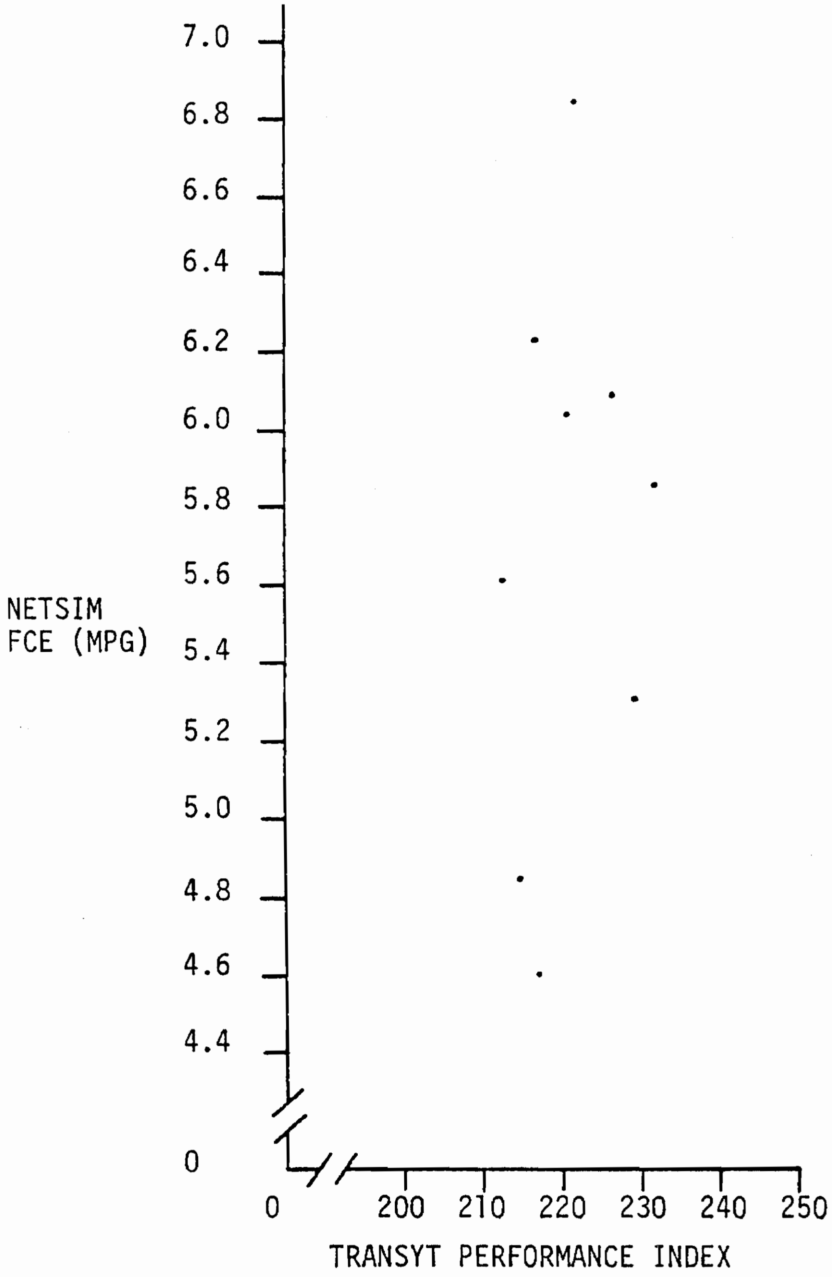

FIGURE A.68 - NETSIM FCE vs. TRANSYT Performance Index (Stop Penalty = 40, Arlington County)

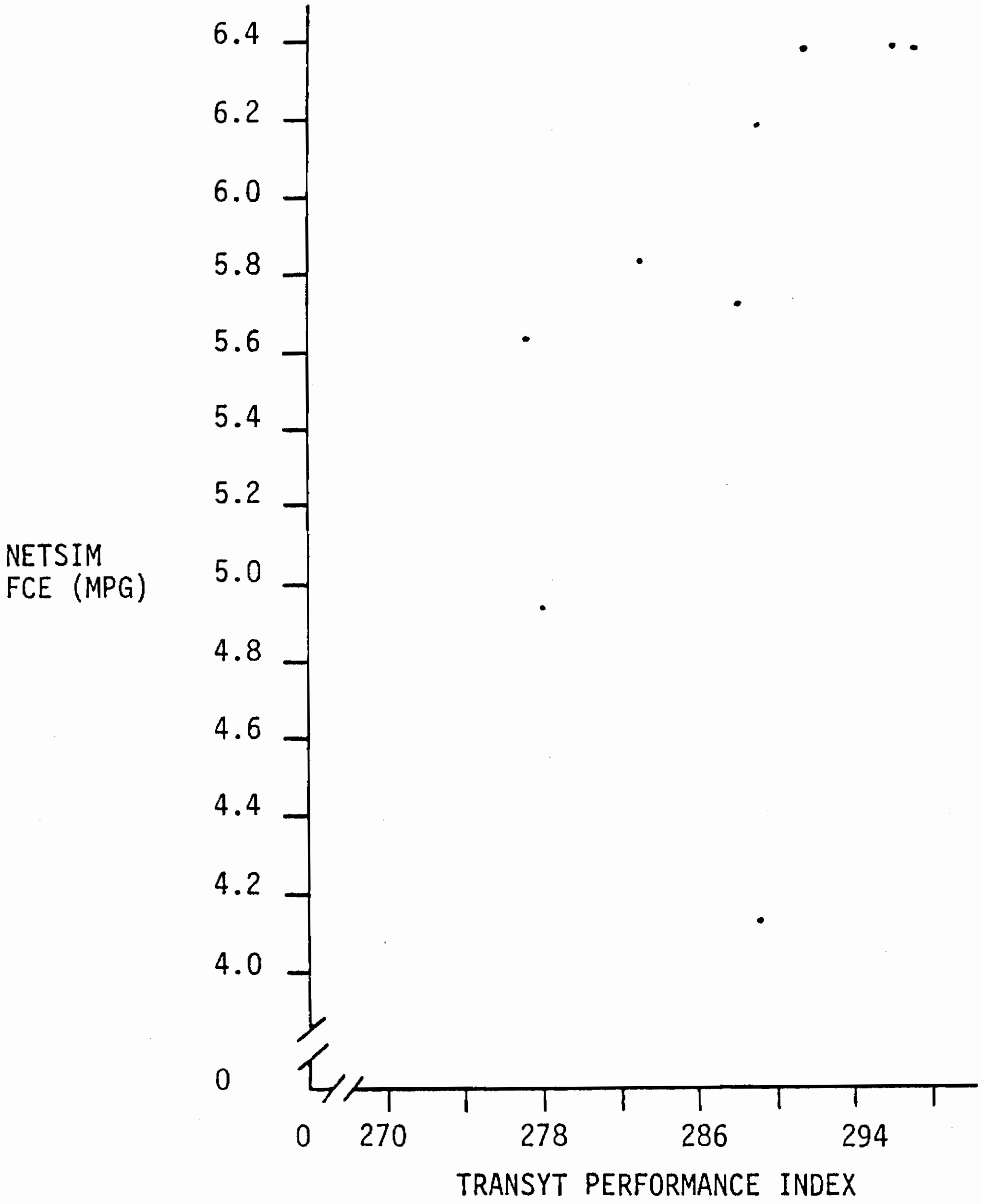

FIGURE A.69 - <u>NETSIM FCE vs. TRANSYT Performance Index</u>
<u>(Stop Penalty = 60, Arlington County)</u>

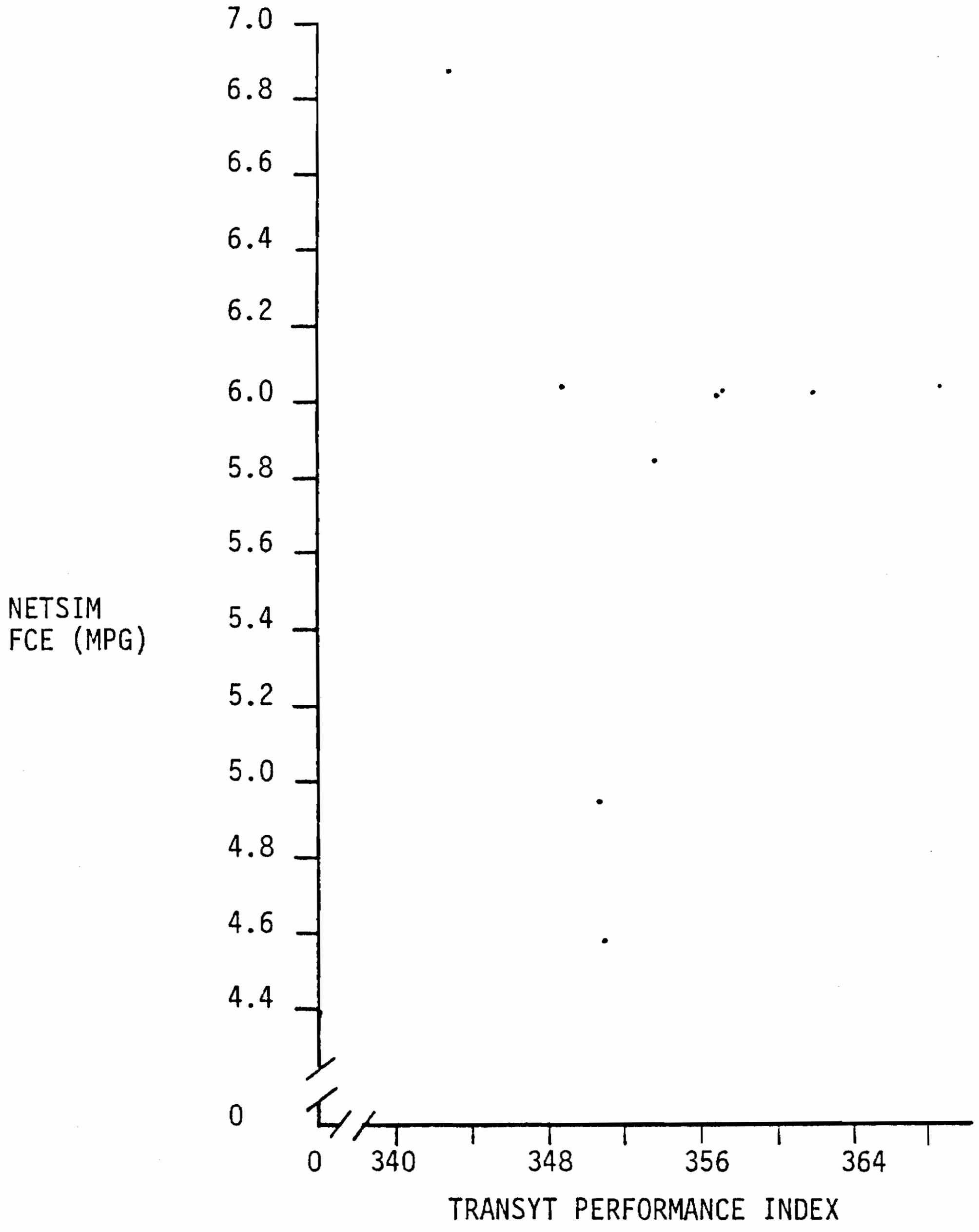

FIGURE A.70 - NETSIM FCE vs. TRANSYT Performance Index (Stop Penalty = 80, Arlington County)

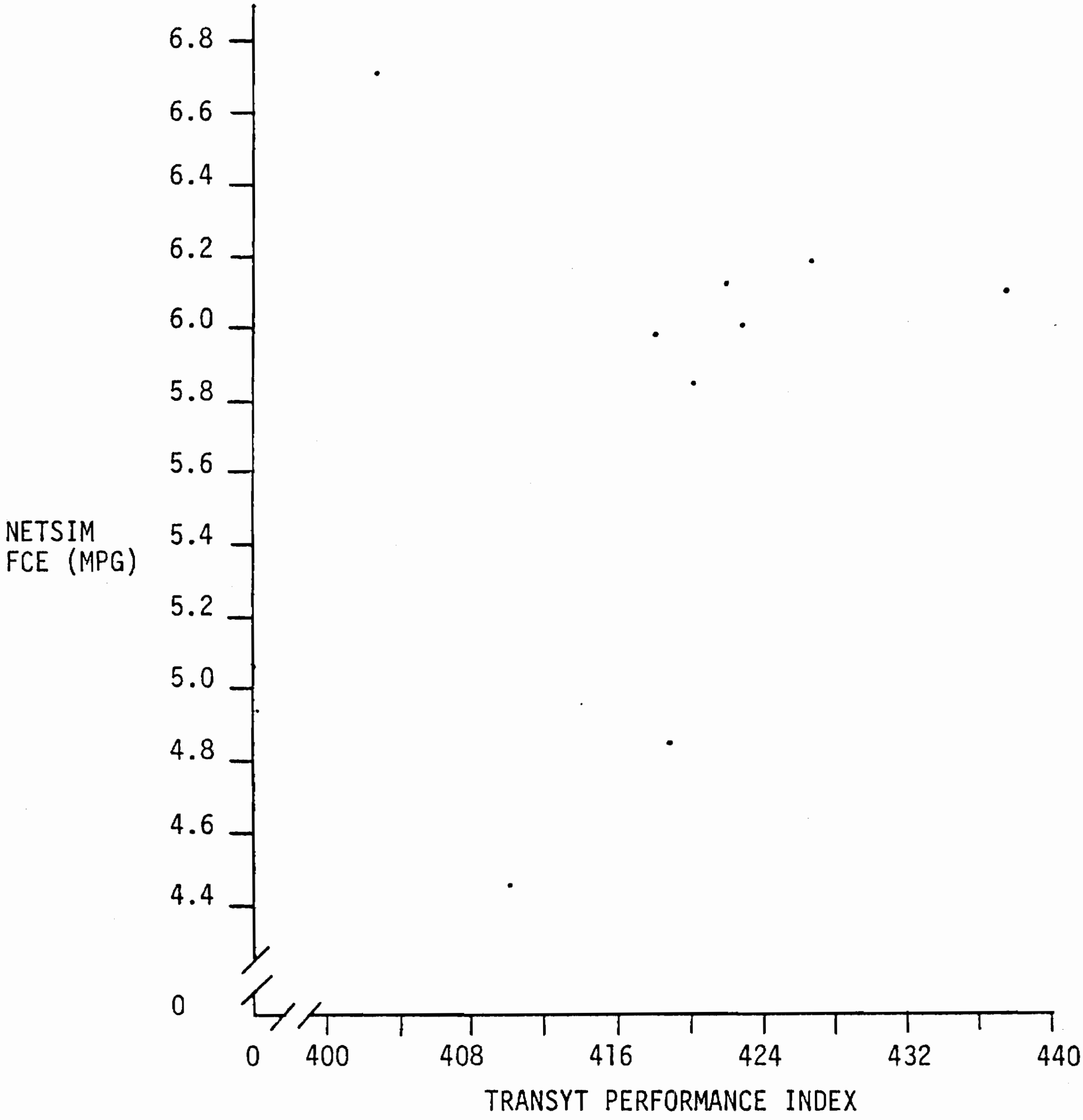

FIGURE A.71 - NETSIM FCE vs. TRANSYT Performance Index (Stop Penalty = 100, Arlington County)

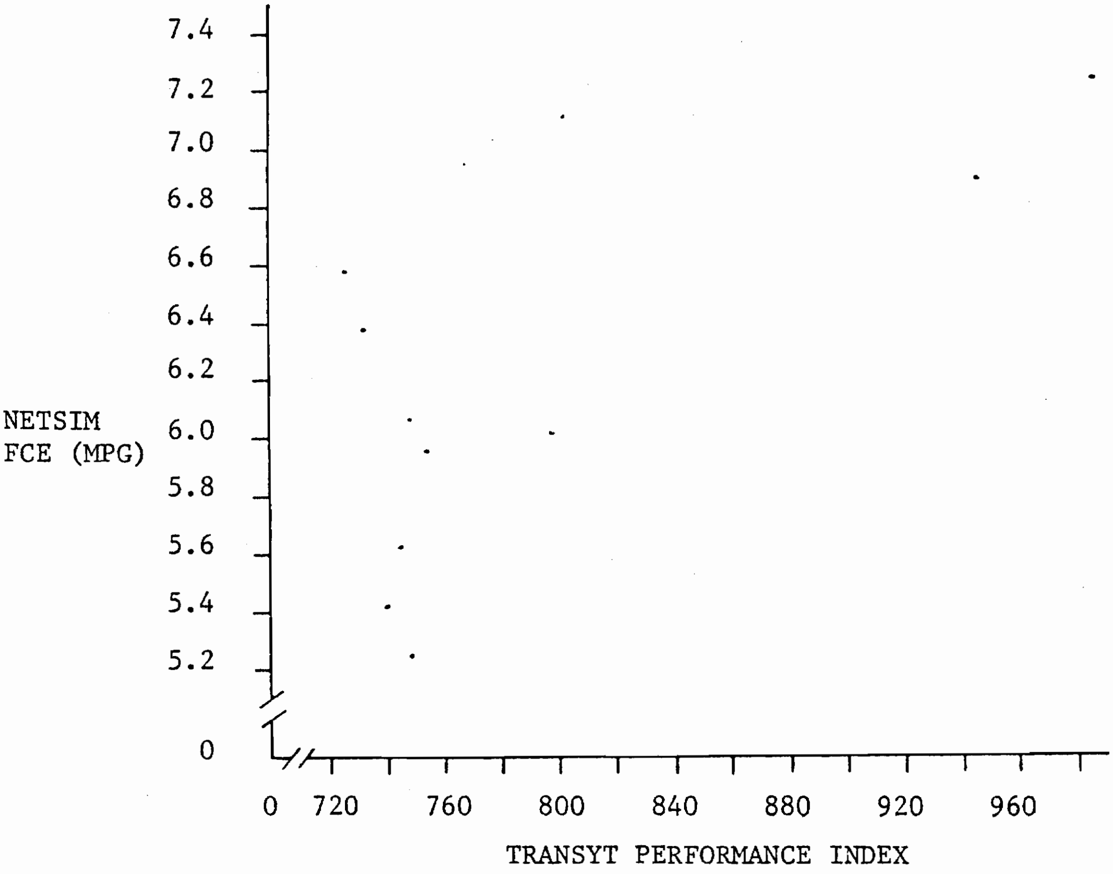

FIGURE A.72 - NETSIM FCE vs. TRANSYT Performance Index (Stop Penalty = 200, Arlington County)

VITA

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David E. Hill

AN ENERGY INVESTIGATION OF SIGNALIZED NETWORK OPTIMIZED BY TRANSYT 7

By

David Easterly Hill

(ABSTRACT)

In the traffic engineering field today, much attention is being given to the area of intersection control. The intersection has long been recognized as the most critical element in our highway system. Accidents, delay, wasted fuel and congestion are greatest at intersections. The variable having the greatest effect on traffic flow at an intersection or in a network of intersections is the traffic signal timing.

In recent years, several computer programs have been developed to aid the traffic engineer in signal timing. This thesis examines the effect of the signal timing plans generated by one of the more widely used programs, TRANSYT 7, on the energy consumption of two signalized networks. Also examined are the relationships of delay and stops to fuel consumption.

The TRANSYT 7 program was used to generate signal timing plans over a range of cycle lengths and stop penalties. The TRANSYT 7 signal timing plans were entered into NETSIM, a microscopic traffic simulation program, to determine their effect on fuel consumption in the two study networks.