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16. Abstract

Gasoline consumed by vehicles traveling within urban signalized networks constitutes a large portion of the total fuel usage in the United States. In addition, pollutants emitted by these vehicles degrade urban air quality. It is well known that the optimal coordination of traffic signals on urban signalized arterials improves traffic flow and reduces gasoline consumption and vehicular emissions. A number of computer models are available to Traffic Engineers for the optimal coordination of urban traffic signals. However, none of these models have capabilities to estimate both fuel consumption and vehicular emissions to allow better assessment of proposed signal timing plans. The research performed in this project incorporated fuel consumption and emissions estimation procedures into PASSER IV, a program for optimizing bandwidth-based signal timings in traffic networks. The enhanced PASSER IV software will allow Traffic Engineers to better assess the impacts of alternate signal timing plans on fuel consumption and emissions of vehicles traveling in a signalized network.

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Vehicular Emissions and Fuel Consumption Estimation in PASSER IV

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Research Report 465060-1

Fuel Consumption and Fuel Emissions Estimation Models in Signal Timing Optimization Programs

Sponsored by:

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April 1995

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College Station, Texas 77843-3135

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SUMMARY

This report describes in detail the work performed under a one year research project entitled, "Fuel Consumption and Fuel Emission Estimation Models in Signal Timing Optimization Programs." The main objective of the project was to enhance PASSER IV, a program for optimizing network signal timings, and to provide fuel consumption and vehicle emissions estimates for signal timing plans generated by it. These enhancements will allow the traffic engineer to make better judgement about the fuel usage and the environmental impacts associated with specific signal timing plans, and will facilitate the selection of the most appropriate plan when alternate signal timing plans are available.

INTRODUCTION

Background

Traffic signals have a dominant effect on the quality of traffic flow in urban street systems. Uncoordinated or improperly timed traffic signals within a signalized street network result in excessive delays and stops to vehicles. In the process of stopping (decelerating), waiting on a traffic signal (idling), and again moving (accelerating), a vehicle consumes excessive fuel and emits more pollutants. Optimal coordination of traffic signals, on the other hand, provides for smooth flow of traffic by reducing vehicular delay, stops, and travel time on arterials. As a result, fuel consumption and pollutants emitted by vehicles reduces. A number of studies [1, 2, 3, 4] have demonstrated these benefits and shown that millions of dollars in gasoline savings can be achieved by the optimal coordination of traffic signals.

A variety of computer programs are currently available for the analysis and optimization of signal timings strategies in urban traffic networks. TRAF-NETSIM [5], a microscopic simulation program, is the only program that has models for both fuel consumption and vehicular emission estimation. Despite the fact that TRAF-NETSIM has the most elaborate traffic model, its inability to generate an optimum signal timing strategy limits its use. TRANSYT 7F is a macroscopic model for optimizing signal timings based on the delay-minimization principal [6]. TRANSYT, however, does not have a model to estimate vehicular emissions. In addition, it cannot optimize signal phasing sequences which are key signal control variables. Further, solutions generated by TRANSYT do not provide good arterial progression, which is often desirable in Texas. Bandwidth-based signal timing optimization programs such as PASSER II [7] and PASSER IV [8] are extremely popular in Texas due to their abilities to optimize signal phasing sequences in addition to other signal control parameters. PASSER II is applicable to signalized arterials and has a model for the estimation of fuel consumption only. PASSER IV is a network optimization and is applicable to arterials as well as multi-arterial signalized networks; however, it has no model for estimating either fuel consumption or vehicular emissions. The objective of this project was to include fuel consumption and vehicular emission estimation procedures into PASSER IV. It is anticipated that including these models into PASSER IV will provide more benefits to the traffic engineering community, especially in Texas, than enhancing either PASSER II or TRANSYT 7F to include an emissions estimation model.

Characteristics of Bandwidth-Based Signal Timings

Recent experiments conducted by Chaudhary et al. [9] indicate that most multi-arterial networks have numerous alternate (sometimes dozens of) signal timing strategies with very little or no difference in the total progression bands. Further, these alternate solutions, when present, can have a significant difference in systemwide delay, stops to vehicles, fuel consumption, and vehicular emissions. In addition, these experiment indicate that minimizing delay does not necessarily reduce fuel consumption. Thus, an automated capability for further analysis of multiple signal timing strategies, using measures of effectiveness (i.e., fuel consumption and vehicular emissions) not explicitly accounted for by the existing optimization programs, can allow an analyst to make a better choice between these alternate strategies.

Description of PASSER IV

PASSER IV is an optimization program for coordinating traffic signals on single arterials as well as multi-arterial signalized networks. Presently, it is the only practical personal-computer-based network program for generating bandwidth-based signal timings. It is designed for off-line use and for use within present and future Traffic Management systems.

Version 1.1 of PASSER IV, recently released by the Texas Transportation Institute (TTI), can optimize signal timings for signalized networks consisting of up to 35 signals/nodes (i.e., MXNODE=35) and up to 20 arterials (MXART=20). Each arterial can have from two to twenty signals as long as the total number of signals in the network does not exceed 35. One key feature of PASSER IV is its ability to facilitate the generation of alternate signal timing plans and to report a specified number of best signal timing solutions for a given network. This feature allows a user to select the best alternate signal timing plan based on other measures-of-effectiveness (MOEs) that are not explicitly considered during the optimization process. These MOEs include: average approach delay, total intersection delay, volume to capacity ratios, and level of service.

PASSER IV consists of two components: a friendly User Interface (UI), and its core optimization routine, PASSR4. The UI provides functions for manipulating user files and runs PASSR4. The file manipulation functions include capabilities to: create new data sets, edit existing data sets, and view/print signal timing reports. A detailed description of these features is provided in the *PASSER IV-94, User's Manual* [10]. PASSR4, an independent routine that can be used even when the UI is not available, reads its input from a data file and writes its report to an output file. When the *Run* command is selected from the UI, it writes data for the selected problem to a data file and transfers control to PASSR4. Upon receiving control, PASSR4 reads the data from the specified file, performs signal timing optimization, writes its report to an output file, and returns control back to the UI.

Organization of Report

The previous sections provided background and a brief description of the PASSER IV Software. In the following sections, we present issues related to the estimation of vehicular fuel consumption and vehicular emissions, provide a description of models/procedures that have been incorporated into the PASSER IV software, and describe modifications made to PASSER IV to produce Version 2.0. Additional detail is provided in the Appendices.

FUEL CONSUMPTION AND EMISSIONS

A number of factors/variables affect the consumption of fuel and the emission of pollutants by vehicles traveling within a signalized urban roadway system. These include: vehicle characteristics (type and size of vehicle fleet), atmospheric conditions (ambient temperature), pavement conditions and type (rough, smooth, wet, dry, icy, etc), and traffic flow conditions (quality of signal control, delay, level of service, etc.) [11]. The absolute determination of vehicular fuel consumption and emissions within a metropolitan area cannot be performed unless all variables are simultaneously taken into account and microscopic analysis is performed. This type of analysis, however, requires tremendous amounts of data that are not always available, or is too cumbersome to use for frequent operational analysis. In addition, incorporation of an ability, even if feasible, to simultaneously optimize all desirable variables into a signal timing optimization model can make it computationally inefficient and difficult to calibrate.

The absolute accuracy of fuel consumption and emissions estimates, although important, is not necessary for relative comparisons between existing and proposed signal control strategies and for the comparison of alternate signal timing strategies for a given control period during a specific day of the week. Rather, use of simple procedures, based on the quality of traffic flow (travel time on a link, delay, and stops), are sufficient for two reasons:

1. For a specific metropolitan area or county, vehicle characteristics and physical pavement type experience slow change over a long period of time and can be assumed constant for day-to-day operational analysis.

2. Since a specific signal control period is much shorter (less than a day) than a given season (summer, winter, etc.), the effects of ambient temperatures on the operating characteristics of vehicle engines can also be assumed constant among various signal timing plans for a control period.

Therefore, in this project we only considered models that take into account the effects of traffic conditions on fuel consumption and emissions of vehicles traveling on signalized urban arterials. In addition, selection of these procedures is based on factors such as: ease of use, computational efficiency, and robustness of the PASSER IV model to future enhancements. The models incorporated into PASSER IV are described in the following sections.

Fuel Consumption Estimation

Fuel consumed by vehicles traveling on an arterial link between two intersections can be attributed to three factors related to the traffic conditions and signal coordination: fuel consumed while travelling from the upstream signal to the downstream signal, fuel consumed while stopped at an intersection, and fuel consumed while decelerating to a stop and accelerating back to a desired speed. In this project, we used the same model as that used in both PASSER II-90 [7] and

TRANSYT-7F [6] programs. The following description of this fuel consumption model has been adopted from a recent TTI report by Fambro et al. [12].

$$F = (A_{11} + A_{12}*V + A_{13}*V^2) * TT + (A_{21} + A_{22}*V + A_{23}*V^2) * D + (A_{31} + A_{32}*V + A_{33}*V^2) * S$$

where:
F = estimated total system fuel consumption in gallons per hour;
TT = total travel, in vehicle miles per hour;
D = total delay, in vehicle-hours per hour;
S = total stops, in stops per hour;
V = cruise speed, in miles per hour; and
A_{ij} = regression model beta coefficients, and is given by:

$$A_{ij} = \begin{vmatrix} 0.75283 & -1.5892\text{ E-3} & 1.50655\text{ E-5} \\ 0.73239 & 0.0 & 0.0 \\ 0.0 & 0.0 & 6.14112\text{ E-6} \end{vmatrix}$$

In order to apply the above model, estimates of total travel, vehicular delay, and total stops are needed. Further, the estimation of total stops requires the estimation of queue lengths at signalized approaches. In the following subsections, we describe procedures for the calculation of these quantities. It should be noted that these measures of effectiveness are estimated for each movement at an approach to the traffic signal.

Total Travel

Total travel for the ith traffic movement on the link from signal k to signal j (TT_{ikj}), in vehicle-kilometers (or vehicle-miles) per hour, is obtained using the following relationship:

$$TT_{ikj} = Vol_{ij} \times LL_{kj}$$

Where:

Vol_{ij} = traffic volume, vehicles per hour, for the ith movement at signal j, and,
LL_{kj} = length of link, in kilometers (or miles) from signal k to signal j. Note that each direction of a link between two signals is considered separately.

Total Approach Delay

In PASSER IV, the total delay for through movements is calculated using a methodology that accounts for traffic progression. This procedure is described by Malakapalli and Messer [13]. The delay for non-progressed approaches (all movements at external links and left-turn movements) is calculated using the *Highway Capacity Manual* (HCM) [14] method. The HCM equation for calculating stopped delay consists of two parts: delay due to uniform arrivals (d1) and delay due to random and overflow arrivals (d2). These are described below:

$$d_1 = \frac{0.38C[1 - (g/C)]^2}{[1 - (g/C)(Min(X,1.0))]}$$

where:
- d_1 = uniform delay in seconds per vehicle;
- C = cycle length in seconds;
- g = green time per phase in seconds;
- Min (X,1) = the lesser value of either X (v/c ratio for lane group) or 1.0; and
- X = volume to capacity ratio for that phase.

$$d_2 = 173X^2 \left[(X - 1) + \sqrt{[(X - 1)^2 + mX/c]}\,\right]$$

where:
- d_2 = incremental delay in seconds per vehicle;
- X = volume to capacity ratio for that phase;
- m = a calibration term representing the effect of arrival type and degree of platooning; and
- c = capacity of lane group in vehicles per hour.

The intersection stopped delay is as follows:

$$d = d_1 + d_2$$

Total delay can be obtained from the stopped delay using the following relationship [15]:

$$D = 1.3 * d$$

where:
- D = total delay in seconds per vehicle, and
- d = stopped delay in seconds per vehicle.

Total Stops

Total stops for a specific movement at a signal approach is a product of the total demand volume for that approach and the stop rate. Stop rate is the average number of stops per vehicle and is calculated as follows [16].

$$h = 0.9\left(\frac{1-u}{1-y} + \frac{N_o}{qC}\right)$$

where:
- h = average number of complete stops per vehicle (stop rate);
- u = green time ratio (g/c);
- y = flow ratio (q/s);
- q = flow in vehicles per second;
- C = cycle length in seconds; and
- N_o = average overflow queue in vehicles.

Average Overflow Queue Length

According to Akcelik (16), the average number of vehicles in the queue at the start of the green period can be calculated as follows:

$$N = qr + N_o$$

where:
- N = average number of vehicles in queue, in vehicles;
- q = arrival flow rate in vehicles per second, in vehicles per second;
- r = effective red time in seconds; and
- N_o = average overflow queue in vehicles and given by:

$$N_o = \frac{QT_f}{4}\left(z + \sqrt{z^2 + \frac{12(x-x_o)}{QT_f}}\right)$$

where:
- Q = capacity in vehicles per hour;
- T_f = flow period, in hours;
- z = (x - 1);
- x = degree of saturation (q/Q); and
- x_o = (0.67 + sg/600), where s = saturation flow, in vehicles per second, and g = effective green time for the lane group, in seconds.

The above equation for queue length is based on a theoretical model which assumes that vehicles join the queue when they reach the stop-line. Since vehicles actually join the queues before reaching the stop-line, this equation underestimates the maximum queue length. Maximum queue length can be calculated as follows:

$$N_m = \frac{qr}{1 - y} + N_o$$

where: N_m = maximum length of the queue;
q = arrival flow rate in vehicles per second;
r = effective red time in seconds; and
y = flow ratio (volume/saturation flow rate).

Estimation of Vehicular Emissions

The Clean Air Acts Amendments of 1990 established stricter Federal standards for urban air quality [17]. In addition, it requires the Environmental Protection Agency (EPA) to work in cooperation with State Transportation Departments (DOTs) and Metropolitan Planning Organizations (MPOs) to determine conformity to these standards, and to impose sanctions when Federal standards are not achieved by the established date. The DOTs and MPOs have the sole responsibility for implementing transportation control measures (TCM) that are consistent with the most recent mobile source emissions and that provide for quick implementation. EPA requires transportation agencies to use the MOBILE [18] model for determining mobile emission rates. MOBILE is developed by EPA and is updated every three years.

Estimates of three types of vehicular emissions: volatile organic compounds (VOC), carbon monoxide (CO), and oxides of nitrogen (NOx), are needed to determine the impacts of urban vehicular travel on the air quality. VOCs are hydrocarbons emissions from vehicles as measured by the flame ionization detector (FID) used in testing, plus a correction for Aldehydes emitted but not picked up by FID. VOC and NOx are major elements contributing to the formation of fog. CO is a colorless gas produced by incomplete burning of carbon in fuels. It is poisonous and harmful to humans.

The current TxDOT practice is to use the MOBILE model to obtain estimated emissions factors, corresponding to various traffic conditions, for each Texas County. These include: emissions rates (in grams per hour) for idling vehicles, and emissions rates (in grams per mile) for various running speeds. Appendix A provides MOBILE emissions factors for several Texas counties that were obtained from TxDOT. The total emissions resulting from a specific signal timing plan are then manually calculated using travel speeds, stopped delay, and stops associated with that signal timing plan. Appendix B provides a sample of these calculations. We adopted this methodology for vehiclular emissions estimation in PASSER IV. In addition to meeting the EPA requirement regarding the use of the MOBILE model, this will allow PASSER IV to be robust for future enhancements. The equations used in PASSER IV for the calculation of vehicle emissions are given below.

$$VOC_{total} = Delay_{Stopped} \times VOC_{idle} + VMT \times Nox_{speed}$$

$$CO_{total} = Delay_{Stopped} \times CO_{idle} + VMT \times HC_{speed}$$

$$NOx_{total} = Delay_{Stopped} \times NOx_{idle} + VMT \times Nox_{speed}$$

Where:

VOC_{otal}	=	Total VOC emissions (grams/hour);
VOC_{idle}	=	VOC emissions (grams/hour) for an idling vehicles;
VOC_{speed}	=	VOC emissions (grams/mile) for a given speed;
NOx_{otal}	=	Total NOx emissions (grams/hour);
NOx_{idle}	=	NOx emissions (grams/hour) for an idling vehicles;
NOx_{speed}	=	NOx emissions (grams/mile) for given speed;
CO_{otal}	=	Total CO emissions (grams/hour);
CO_{idle}	=	VOC emissions (grams/hour) for an idling vehicles;
CO_{speed}	=	VOC emissions (grams/mile) for a given speed;
$Delay_{stopped}$	=	Stopped delay for a traffic movement; and,
VMT	=	Vehicle-miles-travel per hour.

MODIFICATIONS TO PASSER IV

Initial assessment of PASSER, Version 1.1, was conducted in view of the proposed enhancements. Based on this assessment, it was concluded that significant modifications to data structures in the existing optimization routine (PASSR4) were needed to make efficient utilization of storage memory and to allow addition of new data arrays (needed for implementing vehicular fuel consumption and emission estimation procedures) without increasing the memory requirements. A sophisticated data access scheme was designed and implemented in the program along with revised data structures. The old data access scheme, although simple, required data for a signal to be stored twice. The new scheme removes this requirement and results in a significant reduction in memory requirements. The following examples illustrate the amount of memory savings due to these changes.

Example 1

Before: NEMAA(20,MXART) stored NEMA A direction for each signal (first index: 1 to 20) on an artery (second index; 1 to MXART=a maximum of 20 arterial in the network). This array required 20X20=400 memory locations.

Now: The above array has been replaced by NEMAA(2,MXNODE) to store the NEMA A direction of the two arterials (first index) crossing at each signal (MXNODE=a maximum of 35 signals in the network). This array requires 2X35=70 memory locations, only.

Example 2

Before: TVOL(4,20,MXART) was used to store through traffic volumes for each of the four approaches at a signal. This required 1600 memory locations, each sized at 4 bytes (a total of 6400 bytes).

Now: The above array has been replaced by TVOL(4,MXNODE). The same information is now stored in 40 memory locations. In addition, each of these locations has been made double precision, that is, 8 bytes. Even with the increase in precision, the memory required to save the same data is 1120 bytes.

As illustrated by the above examples, the changes in data structures have enabled the storage of the same information as before, in much less space. In addition, these modifications have provided room for the future implementation of several new features and for expanding the capability of the program to optimize signal timings in larger traffic signal networks. A detailed list of modifications to the program data arrays is provided in Appendix C. Other modifications to the program are described below.

Modifications to the User Interface

The UI was modified for the addition and easy use of existing emission factor tables. Figure 1 illustrates the additions to the UI. The modifications are listed below.

- Ability to create emissions tables.
- Ability to view, modify, or delete an existing emissions table.
- Ability to specify a default emissions table in the program configuration file.
- Ability to select an emissions table other than the default table.
- Ability to insert emissions factors, from the selected table, into the PASSR4 data file.

Modifications to the Data Input File Structure

The structure of the input data file for PASSR4 was modified to add four new records (card) for passing the emissions factors to PASSR4. These records are described below and illustrated in Figure 2.

- The EMISSIONS card informs PASSR4's Input module that the emissions data is provided on the next three cards. In addition, this card provides any user information about the data (i.e., county name and year) and keeps the name of the table from which this data was obtained.

- The VOC, CO, and NOX cards provide the emission factors for the three pollutants. On these cards, the first value is the idle emissions rate, while the remaining ten numbers are emissions rates for all speeds between 10 and 55 miles per hour (mph), inclusive, with an increment of 5 mph. Emissions factors for actual speeds between the given data are calculated using linear interpolation.

Modifications to the Optimization Routine (PASSR4)

- Ability to read and store emissions data from the new cards.
- Addition of procedure to calculate fuel consumption.
- Addition of procedure to calculate vehicular emissions.
- Modifications of program output to report new measures of effectiveness for each movement at a signal. These include: stops, queues, fuel consumption, and the three types of emissions.
- Addition of total hourly fuel consumption and emissions for each signal.

Figure 3 illustrates the modified portion of the PASSER IV output showing fuel consumption and emission estimates.

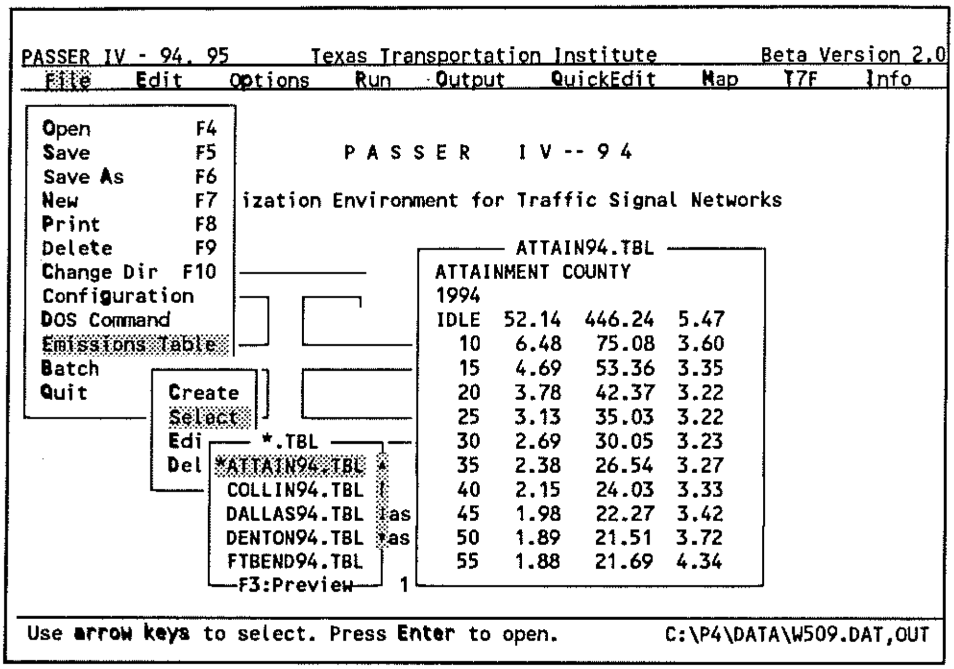

Figure 1: Illustration of Modifications to the PASSER IV User Interface

```
**** PASSER IV-94 -- NETWORK OPTIMIZATION PROGRAM -- VERSION 2.0 ****


                 **** PASSER IV-94 INPUT RECORDS ****

START        0    0                  02
MPCODE          5000  100  500  100   0    1
MPCOD2       3    2    2    1         0          00.500
TOLRN        1 1E-3 1E-3 1E-3 1E-3 5E-4 3E-3 1E-3 1E-1
EMISSION  DENTON           1994DENTON94.TBL
VOC        54.29  5.81  4.24  3.44  2.87  2.48  2.19  1.99  1.83  1.76  1.76
CO        446.29 67.80 48.93 39.45 32.54 27.83 24.47 22.02 20.23 19.39 19.44
NOX         4.11  2.34  2.25  2.21  2.28  2.32  2.36  2.39  2.42  2.62  3.09
NETWORK         9    5          90   90    0    4    1
COMM      ====+====+====+=== ARTERY 1 : MADRONA =+====+====+====+====+====+==
ARTERY          2         2  150                     E     MADRONA
ART2         0  101  101 35.0  3.0  3.0 35.0  3.0  3.0
COMM      ----+----L----T----R----L----T----R----L----T----R----L----T----R--
SIGNAL         25    E    S    S    4                      CARSON
SPEED              35.0  3.0      35.0  3.0      35.0  3.0      35.0  3.0
LENGTH                            2400                          2230
VOLUME              326            608            912            312
SATFLOW            3000           4500           3000           3000
MINGREEN          30.00          30.00          60.00          30.00
COMM      ----+----L----T----R----L----T----R----L----T----R----L----T----R--
SIGNAL         27    E    S                                    TORRENCE
SPEED              35.0  3.0      35.0  3.0      35.0  3.0      35.0  3.0
LENGTH                            2700           2230
VOLUME          44  402         24  168           936            356
SATFLOW       1500 3000       1500 3000          3000           3000
MINGREEN     10.0030.00      10.0030.00         30.00          30.00
LEFTPAT                      1    1    1    1
COMM      ====+====+====+=== ARTERY 2 : HAWTHORNE ====+====+====+====+====+==
ARTERY          5         3  150                     E     HAWTHORNE
ART2         0   -1   -1 45.0  3.0  3.0 45.0  3.0  3.0
COMM      ----+----L----T----R----L----T----R----L----T----R----L----T----R--
SIGNAL          6    E
SPEED                                            45.0  3.0      45.0  3.0
LENGTH                                           1050           1120
VOLUME              292            166        132 1400       154  786
SATFLOW            1200           1000       2400 6000      1500 6000
MINGREEN          25.00          25.00      10.0025.00     10.0025.00
LEFTPAT      1    1    1    1
COMM      ----+----L----T----R----L----T----R----L----T----R----L----T----R--
SIGNAL          7    E    S    S    4                      CARSON
SPEED              35.0  3.0      35.0  3.0      45.0  3.0      45.0  3.0
LENGTH             2400           2700           1120            780
VOLUME          38  284        120  472         34 1622       112  836
SATFLOW       1500 3000       1500 3000      1500 6000      2400 6000
MINGREEN     10.0025.00      10.0025.00     10.0030.00     10.0030.00
LEFTPAT      1    1    1    1    1    1    1    1
COMM      ----+----L----T----R----L----T----R----L----T----R----L----T----R--
SIGNAL          8    E
```

Figure 2: Top Section of PASSER IV, Version 2.0, Data File

NODE NO. 7 : SIGNAL 2 ON ARTERY 2 AND SIGNAL 2 ON ARTERY 4
HAWTHORNE (W-E) CARSON (N-S)
NEMA 2 MOVEMENT : SOUTHBOUND

** PHASE AND CONTROLLER SETTING TABLE **

PHASE SEQUENCE	1		2	3	4	5
NEMA PHASES	7+3	-	8+4	2+6	2+5	1+5
PHASE SPLIT (SEC)	10.0	-	40.2	25.0	4.8	10.0
PHASE SPLIT (%)	11.1	-	44.6	27.8	5.4	11.1
PHASE INTERVAL (%)	.0	-	11.1	55.7	83.5	88.9

OFFSET: 56.8 SEC (63.1%) -- REFERENCE: START OF PHASE 1 AT MASTER SIGNAL

** MOVEMENT-WISE MEASURES OF EFFECTIVENESS **

NEMA PHASE	7	8	1	2	3	4	5	6
SPLITS (SEC)	10.0	40.2	10.0	29.8	10.0	40.2	14.8	25.0
ST DEL(SEC/VEH)	40.1	4.1	32.1	14.8	31.6	12.5	35.1	5.1
DELAY (SEC/VEH)	52.1	5.3	41.8	19.2	41.1	16.2	45.7	6.7
DELAY LOS	E	A	D	B	D	B	D	B
VOLUME (VEH/HR)	112.	1622.	38.	472.	34.	836.	120.	284.
V/C RATIO	.70	.67	.38	.55	.34	.35	.66	.41
V/C RATIO LOS	B	B	A	A	A	A	B	A
LINK LEN (FEET)	780.	1120.	2400.	2700.	1120.	780.	2700.	2400.
TRA TIME (SECS)	11.1	15.9	43.1	48.4	15.9	11.1	48.4	43.1
AVG SPEED(MPH)	48.0	48.0	38.0	38.0	48.0	48.0	38.0	38.0
QUEUE LEN (VEH)	2.7	24.3	.9	8.4	.8	12.5	2.6	5.4
STOPS (PER VEH)	.92	.74	.86	.76	.86	.63	.86	.76
FUELS (GAL/HR)	59.7	284.1	40.2	198.5	49.2	122.5	72.4	116.9
TOT VOC(GR/HR)	97.3	715.8	54.2	604.9	29.1	377.8	190.5	289.2
TOT CO (GR/HR)	883.	7614.	549.	6417.	276.	3727.	1934.	3149.
TOT NOX(GR/HR)	47.2	881.5	42.5	581.9	19.5	325.6	150.7	308.6

TOTAL INTERSECTION DELAY (VEH-HRS/HOUR): 13.19
TOTAL FUEL CONSUMPTION (GAL/HR): 943.5
TOTAL EMISSIONS(GR/HR): VOC: 2358.8, CO: 24548., NOX: 2357.6

Figure 3: Modified Section of PASSER IV, Version 2.0, Output

PROJECT BENEFITS

PASSER IV, Version 1.1 was released several months ago. To this date, there are fifty -five reported users of the software. Version 2.0 of PASSER IV, produced under this project, is planned for release within a few months and will provide users significant benefits. At the time of the release of Version 1.1, it was estimated that over six million barrels of gasoline can be saved through the use of the program over the next six years. This figure is also valid for the updated version of the program. Detailed calculations leading to that figure are given below. These calculations are only performed for the six largest urban areas of Texas and assume that the number of users will increase as time passes.

Target Population

The target population is defined as the residents of six largest urban areas in Texas who travel through the signalized urban street network. These urban areas include: Houston, Dallas, Austin, Fort Worth, San Antonio, and El Paso.

Projected Gasoline Use in Texas (Million Barrels)

Following are the steps used to obtain these estimates:

1. Projected gasoline use in USA (Billion Barrels) [19]

Year	1994	1995	1996	1997	1998	1999
Gas	2.05	2.07	2.10	2.13	2.16	2.18

2. Projected Gasoline for the target population defined above

= Projected Gasoline Use in USA x (A/B) x (C/D) x (E+F)/G

Where:

A = Vehicle miles in Texas [20] = 156,458 million vehicle miles
B = Total US vehicle miles [20] = 2,025,586 million vehicle miles
C = Population of six urban areas named above [21] = 9,670,000
D = Population of Texas = 16,841,000
E = Proportion of travel on major arterials = 19,606 million vehicle miles
F = Proportion of travel on minor arterials = 15,320 million vehicle miles
G = Total urban vehicle miles in Texas = 102,744 million vehicle miles

Thus, Projected Texas Gasoline Use
= Projected USA Gasoline Use X 0.0772 X 0.5742 X 0.34

= Projected USA Gasoline Use X 0.0151

Year	1994	1995	1996	1997	1998	1999
Gas	30.96	31.36	31.76	32.16	32.57	32.97

Gasoline Saving Estimates

Several signal re-timing studies have resulted in significant gasoline savings [1, 2 ,3, 4]. The gasoline savings reported ranged from 6 to 12 percent. Since PASSER IV is a better tool for signal timing optimization than the optimization tools used in the previous studies, we anticipate that using this program will result in even more savings. However, here we will use a conservative savings factor of 8 percent.

Penetration Factor

Since PASSER IV is a new program, its use is expected to begin with a few users and gradually increase over time. The penetration factor is used to account for the fraction of users (Traffic Engineers) to whom PASSER IV will be available for use and who are adequately trained in the use of the program. The following is our estimate of the penetration factor.

Year	1994	1995	1996	1997	1998	1999
Factor	0.30	0.45	0.60	0.75	0.90	1.00

Adoption Factor

All the users, who have access to PASSER IV and are trained to use the program will not necessarily use the program for one reason or another. The adoption factor is used here to account for this. We estimate that this factor will be 60 percent. That is, during any given year only 60 percent of the potential users are expected to use the program.

Estimated Gasoline Savings in Texas (Million Barrels)

Now the gasoline savings can be estimated by the following formula given below:

Gasoline Usage X Saving estimate X Penetration Factor X Adoption Factor

= Gasoline Usage X 0.08 X Penetration Factor X 0.6

Year	1994	1995	1996	1997	1998	1999
Savings	0.45	0.68	0.91	1.16	1.41	1.58

Total Estimated gasoline savings over six Years is 6.19 Million Barrels.

(Note: The savings in diesel fuel are not included here. Using the above procedure, the savings in diesel fuel are anticipated to be approximately 1.7 million barrels.)

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Appendix A: MOBILE Emissions Data from Texas Counties

MOBILE 4A IDLE EMISSION RATES (g/hr) 1994 EMISSIONS			
COUNTY	VOC	CO	NOX
Ft. Bend	39.52	322.29	3.49
Hardin	54.04	458.56	4.36
Orange	55.61	493.91	4.51
Jefferson	49.54	437.13	4.24
Brazoria	49.71	428.59	4.24
Montgomery	52.95	451.73	4.30
Waller	55.21	445.13	4.35
Liberty	56.97	498.89	4.74
Chambers	51.21	436.18	4.25
Galveston	44.77	396.78	4.26
Harris	40.14	369.12	3.93
Collin	48.77	401.11	3.86
Denton	54.29	446.29	4.11
Tarrant	48.68	428.61	4.19
Dallas	47.37	415.99	4.11
El Paso	59.03	536.10	4.71
Attainment	52.14	446.24	5.47

MOBILE 5.0 EMISSIONS (g/mi) **ATTAINMENT COPY** **1994**			
SPEED	VOC	CO	NOx
10	6.48	75.08	3.60
15	4.69	53.36	3.35
20	3.78	42.37	3.22
25	3.13	35.03	3.22
30	2.69	30.05	3.23
35	2.38	26.54	3.27
40	2.15	24.03	3.33
45	1.98	22.27	3.42
50	1.89	21.51	3.72
55	1.88	21.69	4.34
60	2.39	38.27	5.02
65	2.90	55.08	5.79

MOBILE 5.0 EMISSIONS (g/mi) **DALLAS** **1994**			
SPEED	VOC	CO	NOx
10	5.27	62.47	2.33
15	3.84	44.91	2.23
20	3.11	36.13	2.20
25	2.59	29.87	2.26
30	2.24	25.61	2.30
35	1.98	22.56	2.34
40	1.79	20.34	2.37
45	1.65	18.71	2.40
50	1.59	17.94	2.61
55	1.59	17.97	3.07
60	2.02	32.01	3.54
65	2.45	46.08	4.02

MOBILE 5.0 EMISSIONS (g/mi) DENTON 1994			
SPEED	VOC	CO	NOx
10	5.81	67.80	2.34
15	4.24	48.93	2.25
20	3.44	39.45	2.21
25	2.87	32.54	2.28
30	2.48	27.83	2.32
35	2.19	24.47	2.36
40	1.99	22.02	2.39
45	1.83	20.23	2.42
50	1.76	19.39	2.62
55	1.76	19.44	3.09
60	2.22	34.28	3.56
65	2.69	49.17	4.03

MOBILE 5.0 EMISSIONS (g/mi) HARRIS 1994			
SPEED	VOC	CO	NOx
10	4.58	56.34	2.28
15	3.34	40.41	2.17
20	2.70	32.43	2.13
25	2.25	26.96	2.19
30	1.95	23.26	2.23
35	1.73	20.61	2.26
40	1.56	18.68	2.30
45	1.44	17.26	2.33
50	1.38	16.59	2.53
55	1.38	16.63	2.97
60	1.75	29.44	3.43
65	2.12	42.30	3.90

MOBILE 5.0 EMISSIONS (g/mi)

TARRANT
1994

SPEED	VOC	CO	NOx
10	5.43	64.21	2.36
15	3.95	46.12	2.26
20	3.21	37.07	2.23
25	2.67	30.64	2.29
30	2.30	26.26	2.33
35	2.04	23.12	2.37
40	1.85	20.84	2.41
45	1.70	19.18	2.44
50	1.63	18.40	2.65
55	1.63	18.44	3.12
60	2.08	32.85	3.60
65	2.52	47.31	4.08

MOBILE 5.0 EMISSIONS (g/mi)

FT.BEND
1994

SPEED	VOC	CO	NOx
10	4.98	60.14	2.32
15	3.64	43.30	2.21
20	2.96	34.85	2.17
25	2.47	28.93	2.23
30	2.13	24.93	2.27
35	1.90	22.08	2.30
40	1.72	19.99	2.33
45	1.59	18.44	2.36
50	1.52	17.71	2.56
55	1.52	17.76	3.02
60	1.92	31.18	3.47
65	2.32	44.66	3.94

MOBILE 5.0 EMISSIONS (g/mi)			
GALVESTON 1994			
SPEED	VOC	CO	NOx
10	5.00	60.31	2.50
15	3.63	43.02	2.38
20	2.95	34.41	2.32
25	2.46	28.69	2.37
30	2.13	24.80	2.42
35	1.89	22.02	2.45
40	1.71	20.00	2.49
45	1.58	18.52	2.53
50	1.52	17.83	2.75
55	1.52	17.87	3.24
60	1.93	32.15	3.75
65	2.35	46.48	4.28

MOBILE 5.0 EMISSIONS (g/mi)			
COLLIN 1994			
SPEED	VOC	CO	NOx
10	5.13	60.91	2.16
15	3.75	44.23	2.07
20	3.06	35.82	2.04
25	2.54	29.40	2.09
30	2.20	25.05	2.13
35	1.94	21.93	2.17
40	1.76	19.65	2.19
45	1.62	17.97	2.22
50	1.55	17.17	2.40
55	1.55	17.20	2.82
60	1.96	30.02	3.25
65	2.36	42.87	3.67

MOBILE 5.0 EMISSIONS (g/mi) **WALLER** **1994**			
SPEED	VOC	CO	NOx
10	5.96	70.32	2.47
15	4.32	50.11	2.37
20	3.49	39.97	2.34
25	2.91	33.23	2.41
30	2.51	28.64	2.46
35	2.22	25.38	2.50
40	2.01	23.05	2.54
45	1.86	21.40	2.58
50	1.78	20.68	2.80
55	1.78	20.81	3.29
60	2.28	37.19	3.79
65	2.77	53.73	4.29

MOBILE 5.0 EMISSIONS (g/mi) **LIBERTY** **1994**			
SPEED	VOC	CO	NOx
10	6.46	75.69	2.82
15	4.67	53.65	2.69
20	3.77	42.66	2.64
25	3.15	35.69	2.71
30	2.72	30.94	2.76
35	2.41	27.57	2.81
40	2.19	25.15	2.86
45	2.02	23.43	2.90
50	1.94	22.67	3.16
55	1.94	22.80	3.71
60	2.49	41.22	4.29
65	3.04	59.78	4.88

MOBILE 5.0 EMISSIONS (g/mi)			
CHAMBERS **1994**			
SPEED	VOC	CO	NOx
10	5.73	68.86	2.54
15	4.17	49.24	2.44
20	3.37	39.33	2.41
25	2.80	32.71	2.48
30	2.42	28.24	2.53
35	2.15	25.08	2.58
40	1.95	22.81	2.62
45	1.80	21.19	2.65
50	1.73	20.48	2.87
55	1.72	20.63	3.37
60	2.18	36.25	3.87
65	2.65	52.05	4.38

MOBILE 5.0 EMISSIONS (g/mi)			
JEFFERSON **1994**			
SPEED	VOC	CO	NOx
10	5.53	65.93	2.43
15	4.02	47.06	2.33
20	3.25	37.66	2.29
25	2.71	31.36	2.36
30	2.34	27.07	2.40
35	2.08	24.00	2.44
40	1.88	21.78	2.48
45	1.74	20.15	2.51
50	1.67	19.40	2.73
55	1.67	19.45	3.22
60	2.13	35.05	3.72
65	2.60	50.71	4.23

MOBILE 5.0 EMISSIONS (g/mi)

BRAZORIA
1994

SPEED	VOC	CO	NOx
10	5.45	65.16	2.46
15	3.97	46.55	2.35
20	3.22	37.26	2.31
25	2.69	31.06	2.38
30	2.33	26.85	2.43
35	2.07	23.84	2.47
40	1.88	21.66	2.50
45	1.73	20.07	2.54
50	1.66	19.34	2.75
55	1.66	19.41	3.24
60	2.12	34.69	3.74
65	2.57	50.05	4.25

MOBILE 5.0 EMISSIONS (g/mi)

MONTGOMERY
1994

SPEED	VOC	CO	NOx
10	5.79	68.08	2.48
15	4.21	48.67	2.38
20	3.41	38.99	2.34
25	2.85	32.46	2.40
30	2.46	28.02	2.45
35	2.19	24.84	2.49
40	1.98	22.54	2.52
45	1.83	20.86	2.56
50	1.76	20.08	2.78
55	1.76	20.14	3.28
60	2.24	36.09	3.78
65	2.73	52.12	4.29

MOBILE 5.0 EMISSIONS (g/mi) **ORANGE** **1994**			
SPEED	VOC	CO	NOx
10	6.20	72.75	2.57
15	4.50	51.68	2.46
20	3.64	41.24	2.43
25	3.04	34.49	2.50
30	2.63	29.88	2.55
35	2.34	26.58	2.60
40	2.12	24.18	2.64
45	1.96	22.45	2.67
50	1.88	21.65	2.91
55	1.88	21.70	3.44
60	2.42	39.60	3.98
65	2.96	57.56	4.52

MOBILE 5.0 EMISSIONS (g/mi) **EL PASO** **1994**			
SPEED	VOC	CO	NOx
10	6.85	78.55	2.64
15	4.94	55.83	2.54
20	3.98	44.53	2.50
25	3.31	36.95	2.57
30	2.85	31.74	2.63
35	2.52	28.01	2.67
40	2.28	25.32	2.71
45	2.10	23.40	2.75
50	2.01	22.52	3.00
55	2.01	22.57	3.55
60	2.59	41.09	4.10
65	3.18	59.67	4.66

MOBILE 5.0 EMISSIONS (g/mi)

HARDIN
1994

SPEED	VOC	CO	NOx
10	5.88	69.01	2.49
15	4.28	49.36	2.38
20	3.47	39.57	2.34
25	2.90	3297	2.41
30	2.51	28.47	2.46
35	2.23	25.25	2.50
40	2.02	22.92	2.54
45	1.87	21.23	2.57
50	1.80	20.46	2.79
55	1.79	20.52	3.30
60	2.29	36.88	3.80
65	2.78	53.32	4.32

Appendix B: TxDOT Procedure for Estimating Air Quality Benefits

Traffic Signalization Project
SH 105 from Loop 336W to FM 1485
0338-03-900 and 0338-04-900

1. **Adjust existing hourly delay to daily delays**

	Hourly Delay	* Number of Hours	= Daily Hours of Delay
AM Peak	133.3	2	266.6 Hours
PM Peak	202.2	2	404.4 Hours
Off Peak	215	12	2580Hours
Total			3251Hours

2. **Adjust Projected Hourly Delay to Daily Delays**

	Hourly Delay	* Number of Hours	= Daily Hours of Delay
AM Peak	80.5	2	161 Hours
PM Peak	108.3	2	216.6 Hours
Off Peak	115.3	12	1383.6 Hours
Total			1761.2 Hours

3. **Calculate Daily Differences**

Existing Total	- Projected Total	= Daily Delay Benefits
3251	1761.2	1489.8 Hours

4. **Convert Daily Benefits to Annual Benefits**

Daily Delay Benefits	* Annual Days Travel	= Annual Benefit
1489.8	300	446940

5. **Calculate Annual Air Quality Benefits**

	Annual Benefits	* Idle Emission Rate (G/HR)	= Annual Air Quality Benefit	
VOC	446940 HR	25.67	11,472,950	(11473 KG) Removed
CO	446940 HR	253.48	113,290,351	(113290 KG) Removed
NOX	446940 HR	3.46	1,546,412	(1546 KG) Removed

6. **Amorize Project Cost**

Project Cost/	Useful Life of Project	= Annual Costs
1,254,000	5	250,800

7. **Calculate Annual Cost Per KG of Pollutant Removed**

	Annual Cost /	Annual AQ Benefits	
VOC	250,800	11473	$21.86/ KG
CO	250,800	113290	$2.21/ KG
NOX	250,800	1546	$162.18/ KG

APPENDIX C: List of Modifications to PASSER IV Data Structures

BEFORE	AFTER	ARTERY 1 ENTRY	ARTERY 2 ENTRY
	SIGIDX(MXNODE,MXART)		
	AMAIN(MXNODE)		
	ACROSS(MXNODE)		
INODNO(20,MXART)	INODNO(MXNODE)		
NODENO(20,MXART)	NODENO(MXNODE)		
NEMAA(20,MXART)	NEMAA(2,MXNODE)	1	2
DIRCS(20,MXART)	DIRCS(2,MXNODE)	1	2
IINAME(2,20,MXART)	IINAME(4,MXNODE)	1,2	3,4
INAME(2,20,MXART)	INAME(4,MXNODE)	1,2	3,4
LOSTIME(20,MXART)	LOSTIME(MXNODE)		
IL(4,20,MXART)	IL(4,MXNODE)		
G(4,20,MXART)	G(4,MXNODE)		
LENGTH(4,20,MXART)	LENGTH(4,MXNODE)		
ISPEED(4,20,MXART)	ISPEED(4,MXNODE)		
ITOL(4,20,MXART)	ITOL(4,MXNODE)		
ITAU(4,20,MXART)	ITAU(4,MXNODE)		
TVOL(4,20,MXART)	TVOL(4,MXNODE)		
LVOL(4,20,MXART)	LVOL(4,MXNODE)		
RVOL(4,20,MXART)	RVOL(4,MXNODE)		
TCAP(4,20,MXART)	TCAP(4,MXNODE)		
LCAP(4,20,MXART)	LCAP(4,MXNODE)		
RCAP(4,20,MXART)	RCAP(4,MXNODE)		
TMING(4,20,MXART)	TMING(4,MXNODE)		
LMING(4,20,MXART)	LMING(4,MXNODE)		
LENGFC(20,MXART)	LENGFC(MXNODE)		
VOLFC(20,MXART)	VOLFC(MXNODE)		
CAPFC(20,MXART)	CAPFC(MXNODE)		
SPECFC(20,MXART)	SPECFC(MXNODE)		
SPDFC(20,MXART)	SPDFC(MXNODE)		
QUEFC(20,MXART)	QUEFC(MXNODE)		
MINGFC(20,MXART)	MINGFC(MXNODE)		
LEFTFC(20,MXART)	LEFTFC(MXNODE)		
LPAT(8,20,MXART)	LPAT(8,MXNODE)	1,2,3,45,6,7,8	
LEFT(20,MXART)	LEFT(2,MXNODE)	1	2
LS(2,20,MXART)	LS(4,MXNODE)	1,2	3,4
RS(2,20,MXART)	RS(4,MXNODE)	1,2	3,4
R(20,MXART)	R(2,MXNODE)	1	2
RBAR(20,MXART)	RBAR(2,MXNODE)	1	2
L(20,MXART)	L(2,MXNODE)	1	2

BEFORE	AFTER	ARTERY 1 ENTRY	ARTERY 2 ENTRY
LBAR(20,MXART)	LBAR(2,MXNODE)	1	2
TAU(20,MXART)	TAU(2,MXNODE)	1	2
TAUBAR(20,MXART)	TAUBAR(2,MXNODE)	1	2
D(19,MXART)	D(2,MXNODE)	1	2
DBAR(19,MXART)	DBAR(2,MXNODE)	1	2
E(19,MXART)	E(2,MXNODE)	1	2
EBAR(19,MXART)	EBAR(2,MXNODE)	1	2
F(19,MXART)	F(2,MXNODE)	1	2
FBAR(19,MXART)	FBAR(2,MXNODE)	1	2
IG(18,MXART)	IG(2,MXNODE)	1	2
IGBAR(18,MXART)	IGBAR(2,MXNODE)	1	2
IH(18,MXART)	IH(2,MXNODE)	1	2
IHBAR(18,MXART)	IHBAR(2,MXNODE)	1	2
BSEC(10,20,MXART)	BSEC(20,MXNODE)	1-10	11-20
ESEC(10,20,MXART)	ESEC(20,MXNODE)	1-10	11-20
DSEC(8,20,MXART)	DSEC(16,MXNODE)	1-8	9-16
TAUSEC(2,20,MXART)	TAUSEC(4,MXNODE)	1,2	3,4
ROFF(20,MXART)	ROFF(2,MXNODE)	1	2
GOFF(20,MXART)	GOFF(2,MXNODE)	1	2
LOFF(20,MXART)	LOFF(2,MXNODE)	1	2
BOFF(20,MXART)	BOFF(2,MXNODE)	1	2
RBOFF(20,MXART)	RBOFF(2,MXNODE)	1	2
GBOFF(20,MXART)	GBOFF(2,MXNODE)	1	2
LBOFF(20,MXART)	LBOFF(2,MXNODE)	1	2
BBOFF(20,MXART)	BBOFF(2,MXNODE)	1	2
EROFF(20,MXART)	EROFF(2,MXNODE)	1	2
EGOFF(20,MXART)	EGOFF(2,MXNODE)	1	2
ELOFF(20,MXART)	ELOFF(2,MXNODE)	1	2
EBOFF(20,MXART)	EBOFF(2,MXNODE)	1	2
ERBOFF(20,MXART)	ERBOFF(2,MXNODE)	1	2
EGBOFF(20,MXART)	EGBOFF(2,MXNODE)	1	2
ELBOFF(20,MXART)	ELBOFF(2,MXNODE)	1	2
EBBOFF(20,MXART)	EBBOFF(2,MXNODE)	1	2
MOFF(20,MXART)	MOFF(2,MXNODE)	1	2
COFF(20,MXART)	COFF(2,MXNODE)	1	2
EMOFF(20,MXART)	EMOFF(2,MXNODE)	1	2
ECOFF(20,MXART)	ECOFF(2,MXNODE)	1	2
W(20,MXART)	W(2,MXNODE)	1	2
BAR(20,MXART)	WBAR(2,MXNODE)	1	2
G(20,MXART)	G(2,MXNODE)	1	2

BEFORE	AFTER	ARTERY 1 ENTRY	ARTERY 2 ENTRY
GBAR(20,MXART)	GBAR(2,MXNODE)	1	2
MAIN(20,MXART)	MAIN(2,MXNODE)	1	2
CROSS(20,MXART)	CROSS(2,MXNODE)	1	2
TIME(19,MXART)	TIME(2,MXNODE)	1	2
TIMBAR(19,MXART)	TIMBAR(2,MXNODE)	1	2
SPD(19,MXART)	SPD(2,MXNODE)	1	2
SPDBAR(19,MXART)	SPDBAR(2,MXNODE)	1	2
TT(19,MXART)	TT(2,MXNODE)	1	2
TBAR(19,MXART)	TBAR(2,MXNODE)	1	2
PHI(19,MXART)	PHI(2,MXNODE)	1	2
DELTA(20,MXART)	DELTA(2,MXNODE)	1	2
SLPAT(20,MXART)	SLPAT(2,MXNODE)	1	2
DEL(20,MXART)	DEL(2,MXNODE)	1	2
DELBAR(20,MXART)	DELBAR(2,MXNODE)	1	2
ORIGIN(20,2)	ORIGIN(MXNODE,2)		
DELAY(2,20,MXART)	DELAY(4,MXNODE)	1,2	3,4
ILBM(19,MXART)	ILBM(2,MXNODE)	1	2
IUBM(19,MXART)	IUBM(2,MXNODE)	1	2
FIXM(19,MXART)	FIXM(2,MXNODE)	1	2