# AN EMISSIONS MODEL FOR ARTERIAL STREETS

by

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# SUMMARY

The passage of the Clean Air Act Amendments of 1990 placed a new emphasis on meeting the federal air standards. Thus, many jurisdictions are searching for a recommended methodology to estimate vehicular emissions, and more importantly, the potential benefits to be gained through the application of current traffic management techniques, especially in the area of coordinated signals.

The currently accepted methodology of estimating these emissions, which is based on the average travel speed of the traffic stream, does not adequately address the reduction of stops and idling that can be provided through the coordination of signals. Winfrey documented a more appropriate model in 1969 that considers these factors; however, the constants used within this model are not representative of the current vehicle fleet.

A Modified Winfrey Model may provide the most accurate estimate of the emissions on arterial streets under given conditions. Data currently available through the Environmental Protection Agency can be reduced to obtain updated constants required by this method. However, this process is not direct and requires a number of assumptions.

The application of this modified model, with a number of conservative assumptions, indicates the coordination of traffic signals can significantly reduce emissions. This is shown for two different coordination methods as used within greater Los Angeles. The model suggests that implementing the ATSAC system throughout the City of Los Angeles has the potential of reducing annual arterial emissions by

8,650 tons of CO (33% reduction),
1,432 tons of ROG (20% reduction),
2,022 tons of $NO_x$ (13% reduction), and
1,005,461 tons of $CO_2$ (13% reduction).

These reductions would produce an effective benefit to the city of nearly $2 billion over the design life of the project. An additional $13 billion of non-pollution related benefits would also be produced through the implementation of the system. Finally, most of these emission reductions would occur at or near intersections, which are generally the pollution hot spots along the arteries.

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# INTRODUCTION

With the passage of the Clean Air Act Amendments of 1990 (CAAA), American cities placed a new emphasis on meeting the federal air standards. Many cities realize that meeting these standards will be very challenging, with no guarantee of meeting the standards by the given deadlines. Thus, an intense interest has arisen to determine what impact certain transportation improvements have on vehicular emissions. This determination serves both to guide how fast the city is coming into compliance, as well as to show proof of an effort by the city to come into compliance.

## Problem Statement

The current methodology to estimate vehicular emissions is based on the average travel speed of the traffic stream. For freeway operations this may be a valid method if it is assumed that the average speed indicates the prevailing traffic conditions. However, this may not be an appropriate method to use in determining the potential benefits of implementing Intelligent Vehicle Highway System (IVHS) technologies.

Many IVHS technologies, especially Advanced Traffic Management Systems (ATMS), result in significant decreases in total travel time, and thus, increases in average travel speeds. Yet, this increase in travel speed is a result of a decrease in the number and length of stops with little or no impact on free speeds. Thus, a different method should be used to estimate emissions for these projects.

## Study Objectives

The main objective of this report is to provide the transportation industry and air quality officials with a recommended methodology to be used in analyzing emissions in association with ATMS projects that reduce the number and duration of stops. To achieve this goal, a comparative analysis is performed between the current and recommended methodologies to determine the degree of variation. The data for this analysis are from recent coordinated signal system projects in both Los Angeles County and Los Angeles City. These systems represent two of the more advanced traffic management systems in operation today.

Although the recommended method is a model calibrated with recent data, the data is very limited and the model should be recalibrated when more extensive data is available. The creation of this model does, however, provide the analytical methodology that should be employed to produce a more accurate estimation procedure.

# BACKGROUND

To understand the emission benefits to be gained through improved traffic management, it is important to understand the various pollutants and their impact on society. Most importantly, one should realize that pollution is not only one chemical and should not be treated as such. Instead, each pollutant should be addressed individually. The CAAA reinforces this point by indicating that a city can be classified as a non-attainment area for one chemical while meeting the federal standards for all other chemicals.

Vehicular emissions, which are the chemicals emitted from the engines of vehicles, contribute to air pollution. As engines produce a flow of chemicals, emissions are usually described in terms of flow rates, such as grams per second or tons per year.

Air pollution, or more generically air quality, is the presence of certain harmful chemicals within the air at a specific location. Some of these chemicals, such as carbon monoxide (CO), are produced directly from internal combustion engines. Others, such as ozone ($O_3$), are produced from chemical reactions involving some of the chemicals emitted from these engines. Air quality is described in terms of the concentration of the various pollutants, generally in parts per million.

The air quality at a specific location is affected by meteorological, land use and ambient air quality conditions of the surrounding area. However, the time frame of this paper does not allow a detailed analysis of these important air quality factors. Instead, this research is limited to determining the recommended emission estimation method for arterial streets.

The recommended method will allow for the estimation of emission reductions due to operational improvements along a street. The estimated reductions can then be used to estimate changes of spot location and wide area air quality through the application of other models that consider additional factors.

## Definitions

There are six major air pollutants that are regulated by the federal government. (1,2) These are:

- Carbon Monoxide (CO) -- CO is produced during incomplete combustion of fuels due to the lack of an additional oxygen atom being attached to the molecule. CO can (a) combine with hemoglobin in the blood and inhibit its ability to carry oxygen to body cells; (b) aggravate aspects of coronary heart diseases; (c) decrease exercise tolerance by some individuals; (d) Impair central nervous system functions; and (e) increase risk to fetuses.

- Lead (Pb) -- Lead is released into the atmosphere through the combustion of lead based fuels. This is a diminishing problem due to the use of unleaded fuels.

Lead (a) increases body burden; and (b) impairs blood formation and nerve conduction.

- Nitrogen Dioxide ($NO_2$) -- Nitrogen oxides ($NO_x$) are formed by the high temperatures in internal combustion engines, such as automobile engines. $NO_x$ react with reactive organic gases (ROG's), another by-product of gasoline combustion, in the presence of sunlight to form ozone and nitrogen dioxide. $NO_2$ can (a) potentially aggravate chronic respiratory disease and symptoms in sensitive groups; (b) increase risk to public health; (c) contribute to atmospheric discoloration; and (d) form acid rain.

- Ozone ($O_3$) -- $O_3$, which is created by the photo-chemical reactions of ROG's and $NO_x$, causes (a) decreased pulmonary function; (b) increased health risk; (c) respiratory infections; (d) vegetation damage; and (e) property damage.

- Sulfur Dioxide ($SO_2$) -- Sulfur oxides are produced through the combustion of gasoline, which often contain trace amounts of sulfur. $SO_2$ can cause bronchoconstriction and associated symptoms including wheezing and shortness of breath.

- Suspended Particulate Matter (PM10) -- PM10 can be produced through the erosion of the rubber on tires and can cause seasonal decline in pulmonary function, especially in children.

In addition to the above, carbon dioxide ($CO_2$) is also produced through the complete chemical reaction of fuel combustion. Although $CO_2$ is not typically considered a pollutant, it is of increasing concern due to its greenhouse effect on the environment. The South Coast Air Quality Management District (SCAQMD) issued a call for strategies to reduce $CO_2$ in its 1991 Air Quality Management Plan. (1)

Transportation contributes significant proportions of the total CO, ROG, $NO_x$ and $CO_2$ emissions in urban areas. The role that transportation plays in the Southern California region is shown for various pollutants in Figures 1 - 6.

This report focuses on the actual emissions from motor vehicles, as opposed to the air quality of a specific region. Thus, the main chemicals addressed by this paper are CO, ROG and $NO_x$. Information on $CO_2$ is also provided when data is available. Ozone is a secondary pollutant, and thus, cannot be measured in emissions. Lead and $SO_x$ are not considered in this study due to the lack of available data. PM10 is not considered in this study due to the negligible impact that signal timing improvements have on this pollutant.

Figure 1: CO Emissions: 4987 tons/day

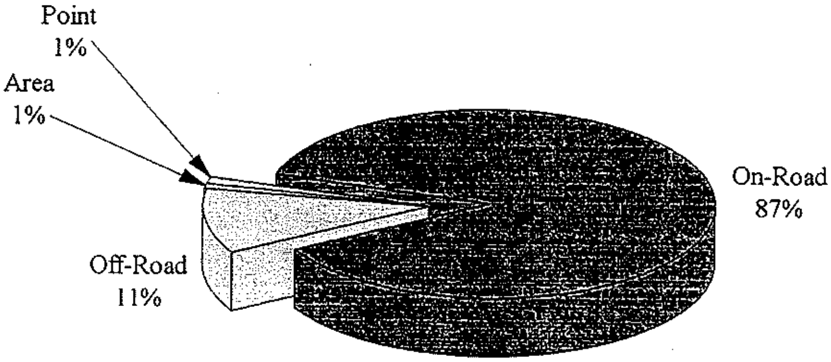


Figure 2: ROG Emissions: 1375 tons/day

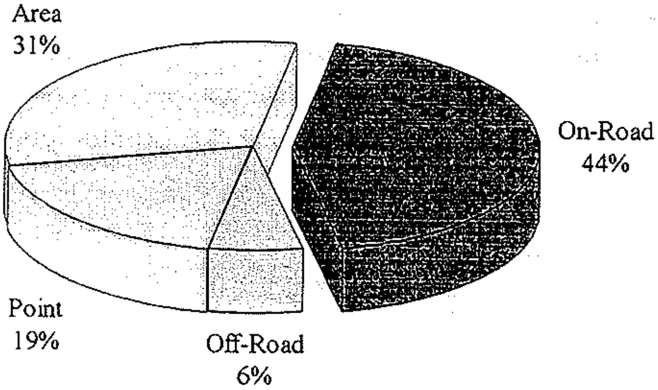


Figure 3: NOx Emissions: 1208 tons/day

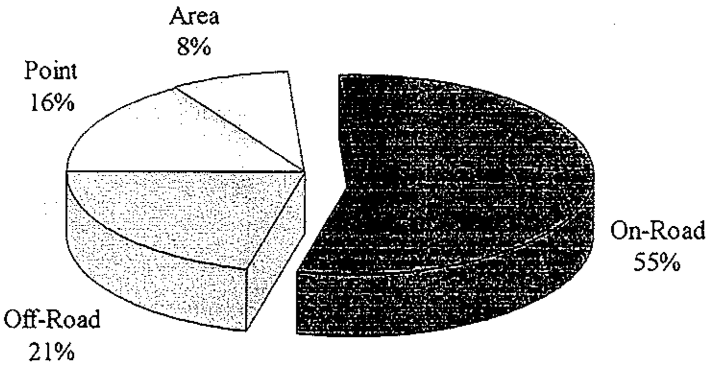


Figure 4: SOx Emissions: 134 tons/day

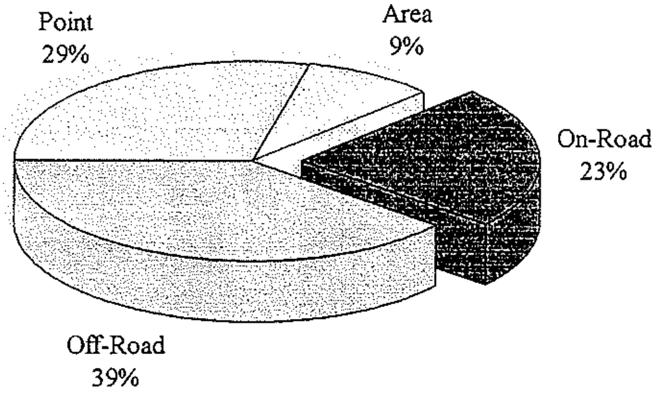


Figure 5: PM10 Emissions: 1075 tons/day

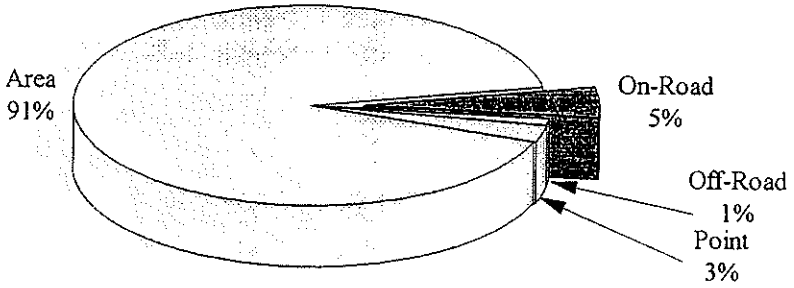
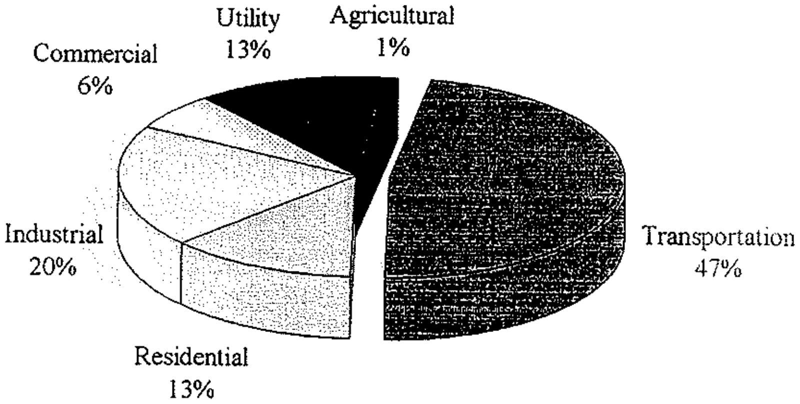


Figure 6: CO2 Emissions: 300,000 tons/day



## Literature Review

Although a great deal of literature is available for air quality, area-wide emission production and intersection carbon monoxide production, literature pertaining specifically to arterial streets is very limited. There is a considerable amount of related research in this technical area at present, however. To access the latest information on the subject, the following agencies were contacted in association with the data collection phase of this project:

- Environmental Protection Agency (EPA),
- ManTech Environmental Sciences (MES),
- California Air Resources Board (CARB),
- Southern California Air Quality Management District (SCAQMD),
- Texas Air Control Board (TxACB),
- Federal Highway Administration (FHWA),
- United States Department of Transportation (USDOT),
- California Department of Transportation (Caltrans),
- City of Los Angeles Department of Transportation (LADOT),
- Los Angeles County Department of Public Works (LADPW),
- North Central Texas Council of Governments,
- General Motors,
- Oak Ridge National Laboratories, and
- Texas A&M University.

In addition, attempts were made to contact the University of California at Los Angeles (UCLA) about a project that they are working on with Ford Motor Company; however, these attempts proved unsuccessful.

## Synthesis of Results

Although a few variations in methodology were found through this search, all of the methodologies encountered can be categorized into one of three technical categories.

### *MOBILE4.1/EMFAC7 Method*

One of the three methods utilizes data for the temperature, humidity, vehicle fleet, average vehicle speed and vehicle miles traveled (VMT) in conjunction with a computer program, either the MOBILE4.1 or EMFAC7, to estimate emissions in grams per mile. This is the most widely accepted method for determining transportation related emissions at present. MOBILE4.1 was produced, and its results are now accepted, by the EPA. The EMFAC7 model was designed and is now the official model for the State of California.

Although a great deal of documentation exists justifying the EMFAC7 method, none was found recommending, or even suggesting, its use for arterial street analyses. This method does not consider the number or duration of stops, and thus, has a significant shortcoming in estimating emissions for such a system. (3)

### *TEXIN2 Method*

Another method estimates the amount of carbon monoxide emitted at intersections. Although this method could be used to estimate emissions along an artery through the analysis of a series of intersections and the setting of appropriate approach lengths, the method still has limitations.

A computer program exists to aid in running this method, but it assumes an optimized pretimed signal. (4) Thus, this program would not be useful in determining the benefits to be gained through a change in signal operation. Instead, all calculations would have to be performed by hand.

In addition, the method only considers carbon monoxide. As this research is interested in all pollutants, this is also a considerable limitation.

Finally, the method uses emission figures based on a modified MOBILE4 program and, thus, may not fully reflect the different emission rates produced at different speeds and accelerations.

Due to these limitations and the time requirements, this method was not analyzed as a part of this study.

### *1969 Winfrey Model*

In 1969, Winfrey documented an economic impact assessment methodology which included the following modal methodology for determining emissions at an intersection: (5,6)

$$C_t = ( N_{sv} * C_{sc} + T_{dv} * C_i ) * V$$

where,
$C_t$ = Total cost in terms of pollutant,
$N_{sv}$ = Number of stops per vehicle,
$C_{sc}$ = Pollution cost of a speed change cycle,
$T_{dv}$ = average time delay per vehicle,
$C_i$ = Pollution cost of idling, and
$V$ = Total volume incurring delay.

Although this equation is only for individual intersections, it is easily modified to produce an equation for emissions along an artery, by adding a factor for cruise emissions incurred at midblock locations.

## **Available Databases**

A table of emission factors produced by EMFAC7 will be used to represent the first methodology. The factors are based on the 1990 Los Angeles County vehicle fleet, i.e., the average of all vehicles on the road in Los Angeles County during 1990. (7)

Currently, there is only limited data to calibrate the Winfrey model. However, due in part to the increasing awareness of the environment, an effort is now underway which will produce new figures for such a method. The EPA, CARB, GM, and UCLA/Ford are all involved in individual efforts to create more detailed emission databases. (8,9,10)

Unfortunately, only the EPA can release any information prior to the deadline of this report. Although EPA data is limited, it is used as the major reference for this report. By the end of this year, it is expected that the CARB and GM will both have released more extensive data. Because attempts at reaching UCLA and Ford have been unsuccessful, the release date for their data is unknown.

### Other Related Research

In addition to the above efforts, there are also other ongoing research projects that are related to this topic. The FHWA is currently sponsoring a project headed by the Transportation Systems Center of the USDOT. (11,12) This project will produce an inventory of the current emission and fuel consumption models as well as propose a new or revised method to address the potential benefits provided by IVHS technologies. (13)

In addition, the CARB, GM, and UCLA/Ford have all acquired equipment that can be attached to vehicles to measure emissions in real-time, under normal driving conditions. This equipment will allow these agencies to produce more accurate results in future research due to the ability to drive vehicles under real-life conditions.

## ANALYSIS PROCEDURE

### Study Methodology

After the research phase of the study was completed, the analysis of the data began. Two of the described methodologies were used to examine two different conditions.

*EMFAC7 Method*

The first analysis used the EMFAC7 tables given in Appendix A in conjunction with average travel speed and total miles traveled to determine the total amount of pollution. Average travel speed was determined by dividing total travel distance by total travel time. The rate of pollution, in grams per mile, was then determined from the tables and multiplied by the total vehicle miles traveled to determine the total pollution emitted.

In the case of Valley Boulevard, the travel data is given for each direction for each peak. Thus, the average speed, and subsequently each emission, is determined for each of the six cases. The results are then totalled to produce the estimated emission for all cases. The ATSAC data represent day-long averages, and emission data is calculated directly. However, it was discovered that when day-long data was computed for Valley Boulevard, the estimated emissions were higher than in the first method. Thus, the results presented for the ATSAC system may be a slight overestimate due to this mathematical anomaly.

In addition, the Valley Boulevard data includes estimates of side street impacts created by the system. The idle data was multiplied by MOBILE4 idle emission rates as given in Appendix A.(14) Although both EMFAC7 and MOBILE4 are macroscopic models, MOBILE4 has the ability to estimate idle emission rates in grams per hour. EMFAC7 does not have this ability, and neither of these programs have the ability to generate emissions at a specific speed, acceleration, or deceleration. The additional stops created on the side street were ignored due to the inability of the method to handle the data.

The EMFAC7 tables give emission factors for various speeds in increments of 5 mph. Intermediate factors were determined through a linear extrapolation between the two nearest supplied factors.

*TEXIN2 Method*

The intersection carbon monoxide method has not been employed due to (a) its inability to determine city-wide benefits, (b) the amount of time required to analyze even the Valley Boulevard System, and (c) its omission of ROG and $NO_x$ estimates.

*Winfrey Method*

The other method employed was a Modified Winfrey Model given by the equation:

$$C_t = ( N_{sv}*(T_d*C_d + T_a*C_a) + T_{iv}*C_i + T_{cv}*C_{cv} ) * V$$

where,
$C_t$ = Total cost in terms of pollutant (grams/day),
$N_{sv}$ = Number of stops per vehicle (stops/veh),
$T_d$ = Average time for deceleration (sec/stop),
$C_d$ = Pollution cost of decelerating (gr/sec),
$T_a$ = Average time for acceleration (sec/stop),
$C_a$ = Pollution cost of accelerating (gr/sec),
$T_{iv}$ = Average idle time along route (sec/veh),
$C_i$ = Pollution cost of idling (gr/sec),
$T_{cv}$ = Average cruise time along route (sec/veh),
$C_c$ = Pollution cost of cruising (gr/sec), and
$V$ = Total volume incurring delay (veh/day).

This equation is similar to the Winfrey Model equation except for the addition of a cruising emission factor and the separation of the speed change cycle into deceleration and acceleration components. The equation is further modified to units of VMT to produce an area-wide model. Data for the various pollution costs are determined through an analysis of raw data obtained from the EPA.

The side street impacts were considered in addition to the floating car data. The additional delay and stops were added to the figures totalled from the floating car data.

*Financial Detriment of Disutilities*

Any major capital improvement in the public sector must be justified, especially in light of current budget constraints. Modern traffic signal coordination systems require expenditures significant enough to need such a justification.

Construction and engineering costs for the Valley Boulevard system totaled almost $22,000 per intersection, while costs for the ATSAC system total $80,000 per intersection. (15,16) These costs include significant capital outlays for upgrading traffic signals to current design standards and for installation of inductive loop detectors. While these costs would be incurred through standard upgrade projects, one could argue that they are an integral part of the system implementation.

In justifying these expenditures, the transportation community has traditionally cited reductions in travel time, wear and tear on vehicles and fuel consumption. However, reduction of pollution is another important benefit that should be included in such an analysis.

Dollar values for each of these factors can be obtained through experts in the respective fields. These values can then be used to form a dollar based index, the Swinton Index, of the various possible operations. (17) The difference in the index for two operations indicates the net benefit of the system. This can then be used to justify the expenditures required to design, construct and maintain the signal improvements. The dollar values used in this study are indicated in Table 1.

The EPA states that "the dollar value of removed emissions is simply the cost of the next-most-expensive alternative emission control measure." (18,19,20) The EPA conducted an analysis of the CAAA tailpipe standards to determine the average costs for these reductions over the entire United States for ROG and $NO_x$. Previous EPA analyses have determined an avoided-cost value for CO, but this value is not based on the latest CAAA.

However, these values are heavily dependant upon location. In major cities, the cost to reduce pollution to the federal standards may be quite high compared to other parts of the country.

Because both study sites are located within Greater Los Angeles, values obtained through SCAQMD documentation are used in this study.(1) EPA values are also given for reference of a more national perspective.

The SCAQMD has a very aggressive 20 year plan developed to achieve reductions in emissions per mile of vehicle travel. The plan will effectively reduce all emissions by roughly 5% per mile of travel per year. To reflect this effort, all emission improvements are assumed to decrease by 5% per year in the financial projections.

## Table 1:
## Values for Swinton Index

| Factor | Source | Value |
|---|---|---|
| Value of Vehicle Time | Caltrans, Div. of Highways | $7.20 /hr |
| Vehicle Operating Costs | Caltrans, FETSIM Division | $2.00 /hr |
| Cost of Vehicle Stops | American Assoc. of State Highway and Transportation Officials | $0.04 /stop |
| Gasoline | Local Prices minus Taxes | $0.80 /gal |
| CO | SCAQMD | $1,000 /ton |
| ROG | SCAQMD / EPA interpretation | $25,000 /ton |
| NOx | SCAQMD | $62,200 /ton |
| CO | EPA | $300 /ton |
| ROG | EPA | $3,050 /ton |
| NOx | EPA | $2,750 /ton |
| Cost of Money | LADOT | 8% |
| Inflation Rate | Prodigy Services (6/91 - 6/92) | 3.1% |
| Emission Reduction Rate | SCAQMD | 5% |

# STUDY DESIGN

## Sources of Field Data

### *Valley Boulevard*

The first condition analyzed is the Valley Boulevard system, from Cabrillo Avenue/Westminster Avenue to New Avenue, located in Alhambra, California. This system is part of the Traffic Signal Synchronization Project sponsored by Los Angeles County and designed by LADPW.

This project upgrades existing controllers to Type 170 microprocessor controllers. These controllers are equipped with a customized controller program, LACO-1 WWV, that allows the controller's internal clock to be set according to communications received via the WWV radio frequency. Offsets are entered for each traffic signal for each dial according to a time-space diagram specifically designed for the route.

The signals then operate in a unique, full-actuated, time-based coordinated mode through the application of force-offs, holds, pedestrian restrictions, and various other controller settings. This operation utilizes roughly 12 detectors per intersection and is currently being implemented at roughly 800 intersections within Los Angeles County. *(21)*

As a part of the project, floating car studies are typically performed on each route for each direction and for each system dial to provide an estimate of the benefits gained. This data was obtained from the LADPW and provides the necessary information for the emission models to be tested.(15) At the time of the before study on Valley Boulevard, most of the signals were of a semi-actuated design; however, a number of the loops may not have been operational.

### *City of Los Angeles ATSAC System*

For a broader scope, existing sections of the Automated Traffic Surveillance and Control (ATSAC) system in Los Angeles, California were analyzed to estimate the potential emission benefits of a city-wide implementation of the system. The original phase of this system was installed one month prior to the 1984 summer Olympics, which were held in Los Angeles, and is widely credited as being a key component of the transportation success of that event.

The ATSAC system is generally regarded as representing the state-of-the-art in computer controlled traffic signals and has been selected for various National Cooperative Research Program studies. Features of the system include:

- The first implementation of the UTCS Enhanced software package developed by the Federal Highway Administration;
- The first use of fiber optic cables for traffic signal system trunk communications;

- The first extensive use of Critical Intersection Control in computer controlled networks;
- The first extensive use of Traffic Responsive Operation to implement optimum timing plans in computer controlled networks;
- The first implementation of 1.5 Generation Control in a traffic signal system to automate the development and evaluation of timing plans;
- The standardized use of California Type 170 controllers at intersections;
- The extensive use of detectorization for the collection of surveillance data (currently over 3000 detectors at 785 intersections);
- The real time computation of performance evaluation data;
- The ability to upload/download backup timing plans to local controllers;
- The ability to remotely control a traffic signal system with a laptop computer communicating with the central computer via radio communication; and
- The ability to monitor and control Light-Rail vehicle signals.

The system will be a key component in the SMART Corridor Project, which is currently entering the implementation phase, and plans are to implement the system throughout the City of Los Angeles by 1998.(22,23,24)

In 1987 and in 1991, floating car studies were performed along portions of the ATSAC system. The total mileage of the routes tested is 21.2 miles. From this data, the LADOT estimated the city-wide travel characteristics for three different timing schemes: old timing; FETSIM timing, which represents coordination based on TRANSYT optimizations; and the ATSAC system. This data is now used to estimate the emission benefits of FETSIM and ATSAC timing.(25)

## Emissions Data Reduction

Although the Modified Winfrey Model has the potential of providing very accurate estimates of emission production along arterial streets, the model accuracy depends on the accuracy of the pollution cost factors. Unfortunately, these factors have not been maintained in recent years, and thus, a significant effort was required to produce estimates of these figures.

Currently, the emission factors are based on seven test runs of a 1984 Buick Century, performed in March 1991 by MES. (26) The test runs were conducted according to the Federal Test Procedure (FTP) with varied levels of temperature and humidity. (27) All seven tests were weighted equally in the averaging process.

### *Conservative Assumption List*

During the data reduction effort, a number of assumptions were required. These assumptions include the following:

- All cars have "warm engines," thus all data in the first five minutes and data from 33-35 minutes (which is after a 10 minute engine off period), are thrown out;
- There is a time delay between measured acceleration and resulting emissions due to exhaust flow that can be determined from the difference in time between the initial engine acceleration and the initial increase in tailpipe emission;(28)
- After the adjustment for the emission time delay, all emission data is reflective of the actual emissions for each given second;(28)
- Values measured by the various meters include background pollution levels. These levels are estimated by averaging pollution levels during the middle of the engine off period and subtracted from all other readings;(28)
- The low CO meter is accurate for all readings below 1000 ppm, and the high CO meter is accurate for all readings above or equal to 1000 ppm;(28)
- The data from the test is measured as a concentration in parts per million, or in percentage in the case of $CO_2$, and is converted to grams per second according to the following factors:

  1 ppm ROG = $1.649\ 10^{-4}$ gram/second ROG,
  1 ppm $NO_x$ = $2.188\ 10^{-4}$ gram/second $NO_x$,
  1 ppm CO = $3.329\ 10^{-4}$ gram/second CO, and
  1 percent $CO_2$ = 5.23 gram/second $CO_2$; (28) and

- The data from the Buick Century is representative of passenger cars with catalytic converters. The values obtained were multiplied by factors determined from the EMFAC7 sheet to represent the entire vehicle fleet. The primary reasons justifying this assumption are:
  * Most recent modeled passenger cars have emission systems similar to the 1984 Buick Century;
  * An eight year old vehicle is not unrepresentative of the average passenger car on the road;
  * Although emissions increase with the age of a vehicle, this vehicle would still produce only a small fraction of what a 1970's vehicle would emit.

*Methodology*

## FTP Data Format

The raw emissions data for each of the seven tests were obtained from MES, via the EPA, on computer diskettes and were formatted in ASCII text files. (*26*) These files were imported to the EXCEL spreadsheet program and parsed into separate columns. The files indicate second by second information on:

Temperature (C),
Relative humidity (%),
Speed (mph),
ROG concentration (ppm),
$NO_x$ concentration (ppm),
CO concentration (high and low meters in ppm), and
$CO_2$ concentration (%).

The first task was to add a time column to the database. This was performed by adding one additional column and numbering the rows consecutively.

## Trends in FTP Data

One file was then selected and analyzed to determine the speed trends during the test. A list was made of the times during the test that were found to be significant to this experiment. This list placed the relevant sections of the test into one of five categories.

As each test follows the FTP, all files should exhibit the same speed trends at approximately the same location. Thus, the compiled list serves as a guide as to where to look for significant data in the subsequent files. This list with categorized data is given in Table 2.

## Macro Creation

To aid in the analysis of the data, a set of macros was created to perform the repetitive tasks of searching for the relevant data. These macros were designed to

1. Organize the data into a standard format which included a time field,

2. Place field names at the top of each column,

3. Produce an additional field for the change in speed from the previous second,

4. Select the region containing the data and set it as the database,

5. Copy the field names to selected locations in the database based on the desired location of extracted data,

## Table 2
## Portions of the FTP Test Selected for Engine Emission Factor Estimation

| Category | Change in Speed | Speed Range | Time Range |
|---|---|---|---|
| Idle | - | < 0.1 mph | 250 < Time < 1350 |
| | - | < 0.1 mph | Time > 2050 |
| Cruise | -1.5 < Speed Diff < 1.5 | 16.5 < Speed < 26.5 | 570 < Time < 630 |
| | -1.5 < Speed Diff < 1.5 | 21.5 < Speed < 28.5 | 965 < Time < 1025 |
| | -1.5 < Speed Diff < 1.5 | 21.5 < Speed < 28.5 | 1095 < Time < 1145 |
| | -1.5 < Speed Diff < 1.5 | 21.5 < Speed < 28.5 | 1265 < Time < 1315 |
| | -1.5 < Speed Diff < 1.5 | 26.5 < Speed < 30.5 | 770 < Time < 850 |
| | -1.5 < Speed Diff < 1.5 | 33.5 < Speed < 36.5 | 355 < Time < 395 |
| | -1.5 < Speed Diff < 1.5 | 33.5 < Speed < 36.5 | 450 < Time < 510 |
| | -1.5 < Speed Diff < 1.5 | 33.5 < Speed < 36.5 | 2340 < Time < 2380 |
| | -1.5 < Speed Diff < 1.5 | 33.5 < Speed < 36.5 | 2430 < Time < 2480 |
| Acceleration | Speed Diff > 0.5 | - | 395 < Time < 425 |
| | Speed Diff > 0.5 | - | 440 < Time < 470 |
| | Speed Diff > 0.5 | - | 1045 < Time < 1075 |
| | Speed Diff > 0.5 | - | 1090 < Time < 1120 |
| | Speed Diff > 0.5 | - | 1160 < Time < 1190 |
| | Speed Diff > 0.5 | - | 1330 < Time < 1360 |
| | Speed Diff > 0.5 | - | 2135 < Time < 2165 |
| | Speed Diff > 0.5 | - | 2375 < Time < 2405 |
| | Speed Diff > 0.5 | - | 2420 < Time < 2450 |
| Deceleration | Speed Diff < -0.5 | - | 370 < Time < 410 |
| | Speed Diff < -0.5 | - | 485 < Time < 515 |
| | Speed Diff < -0.5 | - | 535 < Time < 565 |
| | Speed Diff < -0.5 | - | 660 < Time < 690 |
| | Speed Diff < -0.5 | - | 940 < Time < 970 |
| | Speed Diff < -0.5 | - | 1135 < Time < 1165 |
| | Speed Diff < -0.5 | - | 2350 < Time < 2390 |
| | Speed Diff < -0.5 | - | 2390 < Time < 2420 |
| | Speed Diff < -0.5 | - | 2460 < Time < 2500 |
| Background | - | Speed < 0.1 | 1651 < Time < 1749 |

6. Specify the criteria on which to base the selection of idling data. The criteria specified is indicated in Table 2.
7. Select the criteria range,
8. Select the extract range,
9. Extract the idle data and title the area in the spreadsheet,
10. Specify the criteria on which to base the selection of cruise data. The criteria specified is indicated in Table 2.
11. Select the criteria ranges,
12. Select the extract ranges,
13. Extract the cruise data sets and title the areas in the spreadsheet,
14. Specify the criteria on which to base the selection of acceleration data. The criteria specified is indicated in Table 2.
15. Select the criteria ranges,
16. Select the extract ranges,
17. Extract the acceleration data sets and title the areas in the spreadsheet,
18. Specify the criteria on which to base the selection of deceleration data. The criteria specified is indicated in Table 2.
19. Select the criteria ranges,
20. Select the extract ranges,
21. Extract the acceleration data sets and title the areas in the spreadsheet,
22. Specify the criteria on which to base the selection of background pollution data. The criteria specified is indicated in Table 2.
23. Select the criteria range,
24. Select the extract range,
25. Extract the background pollution data sets and title the area in the spreadsheet,

## Summary Block

Finally, a block of cells was formatted to summarize the data that was extracted from the database. This summary block includes the following:

- The average and maximum values of the various pollutants for each extraction set;
- The average emission rates for each extraction set converted to grams per second;
- The number of records (and thus the time covered) within each extraction set;
- Final averages for idle, cruise, acceleration and deceleration emission rates;
- The average time of acceleration;
- The average time of deceleration;
- Warning fields to indicate if the low CO meter recorded a reading above 1000 ppm during a second which was extracted. High CO meter readings should be used for all seconds found having such readings;
- Average temperature; and
- Average relative humidity.

The averages for idle and cruise data were determined by computing the mean of each idle and cruise second, respectively. Because the average emissions produced during acceleration and deceleration may be lower for longer speed change periods, these were averaged by a different process. The average emission, in grams per second, was determined for each speed change period. These average emission rates were then averaged to produce the appropriate factors.

## Analysis of Files

After the design of the spreadsheet was completed, each file was analyzed to determine the emission time lag for each of the chemicals. The column for each chemical was shifted upwards by the appropriate amount to associate the emission data with the correct second. After the columns were appropriately adjusted, the macros were performed for each data file, and the extracted data was manually reviewed to verify the elimination of all unnecessary data.

A handful of records would typically be found spread throughout the extracted data that did not meet the desired qualifications. Although the FTP was followed in each of the files, the actual time at which certain stages would occur would vary by a few seconds. Thus, the time criteria specified provided roughly ten seconds of leeway on either side of the expected location of data. In cases, this allowed the selection of an undesired record (second). These were easily identified because their time did not follow in consecutive order with other extracted records.

After the extracted data was verified, the summary block was copied into the appropriate location on the spreadsheet. This immediately initiated the calculation of all summary data.

Summary Data Files

Finally, a summary file was created to combine the results from each independent FTP test file. This file records the results of each file and averages these to produce the emission factors to be used for the Modified Winfrey Model.

Finally, a file was created which recorded all of the floating car data and combined it with emission and cost factors to produce the various tables and figures presented in this report.

# ANALYSIS OF RESULTS

The results obtained from the above methodology indicate significant emissions reductions through the coordination of signals.

## Estimated Emission Rates

The emission rates used for the EMFAC7 method are given in Appendix A. The estimated emission rates for the Modified Winfrey Model are given in Table 3 for the various speed profiles.

With additional research, a more extensive table of factors could be produced indicating factors for different cruise conditions and different end (start) speeds for the acceleration (deceleration) factors. However, this was not attempted with the limited database currently available.

In contrast, the MOBILE4 values for idle emissions are significantly higher, as indicated in Table 4. If these trends hold true for all of the factors, then the current estimates of the Modified Winfrey Model may be quite conservative.

## Valley Boulevard System

A summary of the floating car data for the Valley Boulevard project is given in 5Appendix B. Estimates of net emission benefits produced by the EMFAC7 method and the Modified Winfrey Model are given for Valley Boulevard in Tables 5 and 6, respectively.

Estimates of total emission costs for the two different timing schemes are given for both models in Appendix C. Table 7 indicates an estimate of the Swinton Index benefits of the operational improvement. The design and construction costs of the Valley Boulevard System totalled $370,000, and the maintenance costs are estimated at $2,755 per year. This translates into a total present value of $398,790 for all costs. Thus, using the Modified Winfrey Method, the benefit-to-cost ratio for this project is 132.48 to one. In other words, for every dollar spent, there is an estimated $132.48 worth of benefits gained.

Finally, Figure 7 depicts the savings provided by the system. The savings for the emissions are based on the Modified Winfrey Method.

## City of Los Angeles System

A summary of the floating car data for the ATSAC System is given in Appendix B. Estimates of net emission benefits of the various timing schemes produced by the EMFAC7 method and the Modified Winfrey Method are given for the Los Angeles system in Tables 8, 9 and 10.

## Table 3
## Engine Emission Factors for Modified Winfrey Method

| | CO *(gr/sec)* | ROG *(gr/sec)* | NOx *(gr/sec)* | CO2 *(gr/sec)* | Time *(sec/ event)* |
|---|---|---|---|---|---|
| Idle | 0.00191 | 0.00120 | 0.00124 | 1.76016 | |
| Cruise | 0.00488 | 0.00334 | 0.00945 | 4.63989 | |
| Accel | 0.06781 | 0.01155 | 0.02178 | 7.50627 | 11.62 |
| Decel | 0.00177 | 0.00119 | 0.00256 | 2.29564 | 12.25 |

## Table 4:
## Idle Emission Factor Comparison

| *Model* | *CO* | *ROG* | *NOx* |
|---|---|---|---|
| MOBILE4 | 0.08247 | 0.00756 | 0.00106 |
| Modified Winfrey | 0.00191 | 0.00120 | 0.00124 |
| % Difference | 4218 % | 530 % | - 15 % |

### Table 5
### EMFAC7 Method Results for Valley Boulevard: WWV vs. Old Timing

| *Valley Bl.*<br>*W W V vs Old* | *Total*<br>*CO (tons/yr)* | *Total*<br>*ROG (tons/yr)* | *Total*<br>*NOx (tons/yr)* | ***Total*** |
|---|---|---|---|---|
| (AM Peak) | 7.09 | 0.64 | 0.22 | |
| 4 hrs. | 11.19 | 1.00 | 0.34 | |
| (Off Peak) | 21.66 | 1.94 | 0.68 | |
| 9 hrs. | 22.75 | 2.04 | 0.71 | |
| (PM Peak) | 29.16 | 2.70 | 0.77 | |
| 4 hrs. | 0.22 | 0.02 | 0.01 | |
| Side Street | (3.89) | (0.36) | (0.05) | |
| **Total** | 88.17 | 7.99 | 2.69 | |
| **LA Cost** | $88,172 | $199,759 | $167,357 | $455,287 |
| **Nat'l Cost** | $26,452 | $24,371 | $7,399 | $58,221 |

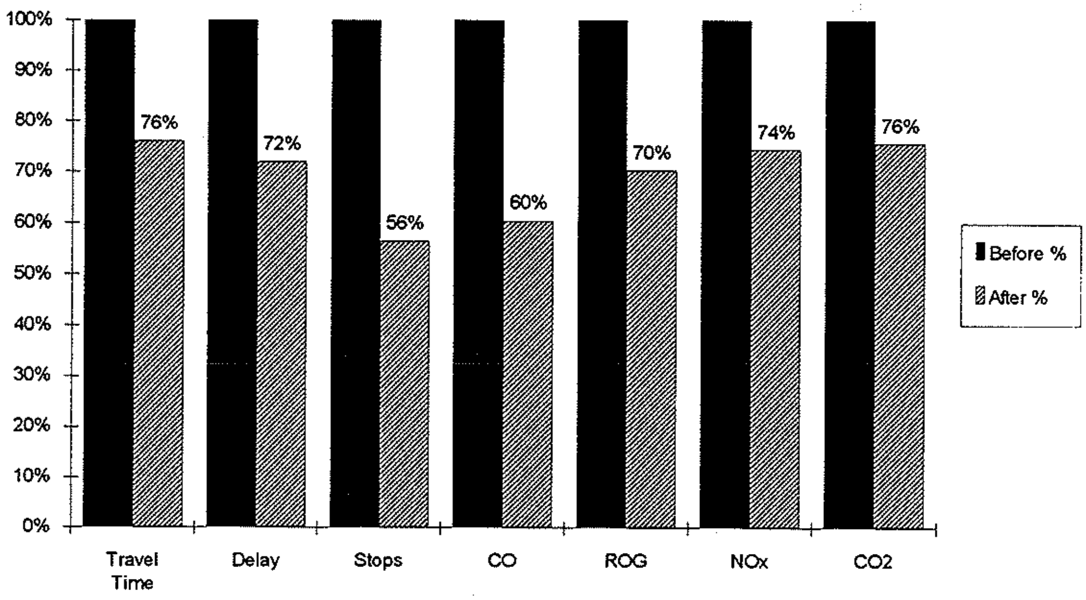
### Table 6
### Modified Winfrey Model Results for Valley Boulevard: WWV vs. Old Timing

| *Valley Bl.*<br>*W W V vs Old* | *Time*<br>*(veh-hrs./day)* | *Total*<br>*CO (tons/yr)* | *Total*<br>*ROG (tons/yr)* | *Total*<br>*NOx (tons/yr)* | *Total*<br>*CO2 (tons/yr)* | ***Total*** |
|---|---|---|---|---|---|---|
| Idle | 593 | 1.13 | 0.71 | 0.73 | 1,036 | |
| Cruise | (9) | (0.04) | (0.03) | (0.09) | (43) | |
| Accel | 377 | 25.36 | 4.32 | 8.14 | 2,807 | |
| Decel | 397 | 0.70 | 0.47 | 1.01 | 905 | |
| **Total** | 1,358 | 27.14 | 5.47 | 9.80 | 4,705 | |
| **LA Cost** | | $27,137 | $136,683 | $609,439 | | $773,259 |
| **Nat'l Cost** | | $8,141 | $16,675 | $26,945 | | $51,761 |

### Table 7:
### Swinton Index Results for Valley Boulevard: WWV vs. Old Timing

| *Valley Bl.*<br>*W W V vs Old* | *Unit* | *Unit*<br>*Value* | *Savings*<br>*( units / yr )* | *Savings*<br>*( $ / yr )* | *Present Value*<br>*( $ )* |
|---|---|---|---|---|---|
| Value of Vehicle Time | hour | $7.20 | 339,581 | $2,444,984 | $25,550,507 |
| Vehicle Costs | hour | $2.00 | 339,581 | $679,162 | $7,097,363 |
| Cost per Stop | stop | $0.04 | 29,197,275 | $1,167,891 | $12,204,666 |
| Price of Gas (no taxes) | gallon | $0.80 | 247,090 | $197,672 | $2,065,707 |
| Cost of CO in LA | ton | $1,000 | 27.14 | $27,137 | $207,588 |
| Cost of ROG in LA | ton | $25,000 | 5.47 | $136,683 | $1,045,585 |
| Cost of NOx in LA | ton | $62,200 | 9.80 | $609,439 | $4,662,022 |
| **Total** | | | | $5,262,968 | $52,833,438 |

## Figure 7:
## Comparison of Costs for WWV Timing vs. Old Timing



## Table 8:
## EMFAC7 Method Results for Los Angeles City-wide System

|  | *Total CO (tons/yr)* | *Total ROG (tons/yr)* | *Total NOx (tons/yr)* | *LA Cost* | *Nat'l Cost* |
|---|---|---|---|---|---|
| **FETSIM vs. Old** | 8,646 | 772 | 266 | $44,522,949 | $5,681,346 |
| **ATSAC vs. Old** | 22,779 | 2,056 | 737 | $119,992,894 | $15,129,348 |

## Table 9:
## Modified Winfrey Method Results for Los Angeles City-wide System: FETSIM vs. Old Timing

| *FETSIM vs OLD* | *Time hrs./day* | *Total CO (tons / yr)* | *Total ROG (tons / yr)* | *Total NOx (tons / yr)* | *Total CO2 (tons / yr)* | *Total* |
|---|---|---|---|---|---|---|
| Idle | 66,395 | 126 | 79 | 82 | 115,940 |  |
| Cruise | (39,856) | (193) | (132) | (374) | (183,464) |  |
| Accel | 34,448 | 2,317 | 395 | 744 | 256,530 |  |
| Decel | 36,319 | 64 | 43 | 92 | 82,715 |  |
| **Total** | 97,306 | 2,314 | 385 | 545 | 271,721 |  |
| **LA Cost** |  | $2,314,269 | $9,618,911 | $33,874,465 |  | $45,807,645 |
| **Nat'l Cost** |  | $694,281 | $1,173,507 | $1,497,665 |  | $3,365,453 |

## Table 10:
## Modified Winfrey Method Results for Los Angeles City-wide System: ATSAC vs. Old Timing

| *ATSAC vs OLD* | *Time hrs./day* | *Total CO (tons / yr)* | *Total ROG (tons / yr)* | *Total NOx (tons / yr)* | *Total CO2 (tons / yr)* | *Total* |
|---|---|---|---|---|---|---|
| Idle | 245,536 | 466 | 293 | 302 | 428,761 |  |
| Cruise | (150,566) | (729) | (500) | (1,412) | (693,078) |  |
| Accel | 128,938 | 8,674 | 1,478 | 2,786 | 960,181 |  |
| Decel | 135,940 | 239 | 161 | 345 | 309,598 |  |
| **Total** | 359,848 | 8,650 | 1,432 | 2,022 | 1,005,461 |  |
| **LA Cost** |  | $8,649,847 | $35,799,228 | $125,754,025 |  | $170,203,101 |
| **Nat'l Cost** |  | $2,594,954 | $4,367,506 | $5,559,864 |  | $12.522,325 |

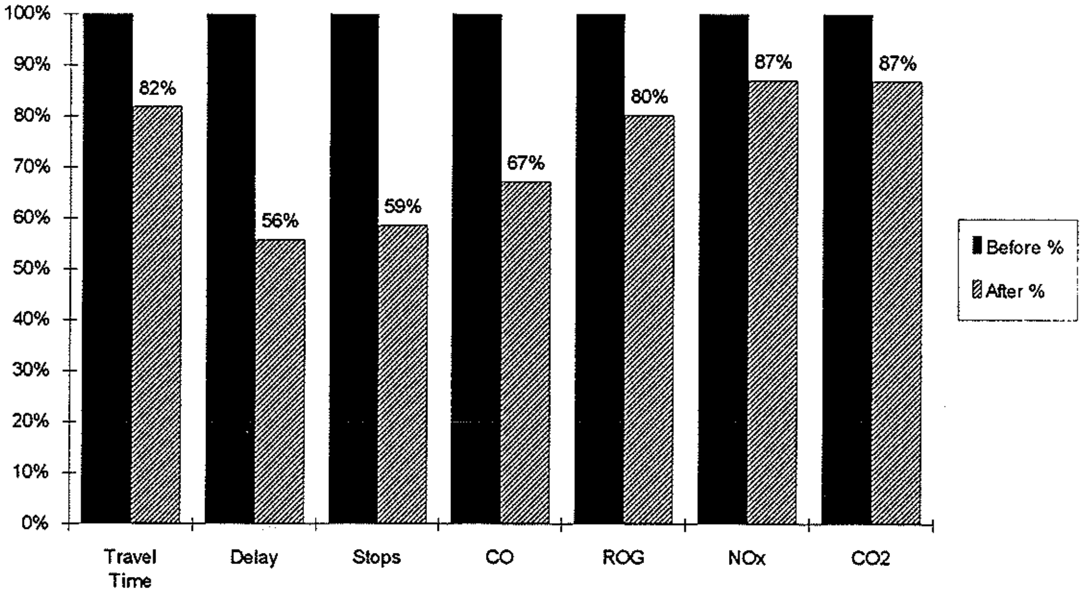
Estimates of total emission costs for the different timing schemes are given in Appendix C for both models. Table 11 indicates an estimate of the Swinton Index benefits for the ATSAC upgrade. Using historical prices, the design and construction costs of the city-wide ATSAC system are estimated at $304 million. However, these costs should decrease with the use of spread-spectrum communications technology. The marginal maintenance costs are estimated at $5,029,852 per year for all 3800 signals. This translates into a total present value of $356,562,835 for all costs. Thus, the Modified Winfrey benefit-to-cost ratio for this project is 41.74 to one.

Finally, Figure 8 depicts the savings provided by the system. The savings for the emissions are based on the Modified Winfrey Method.

## Table 11:
## Swinton Index Results for Los Angeles: ATSAC vs. Old Timing

| *Los Angeles ATSAC vs Old* | *Unit* | *Unit Value* | *Savings ( units / yr )* | *Savings ( $ / yr )* | *Present Value ( $ )* |
|---|---|---|---|---|---|
| Value of Vehicle Time | hour | $7.20 | 89,962,093 | $647,727,071 | $6,768,861,436 |
| Vehicle Costs | hour | $2.00 | 89,962,093 | $179,924,186 | $1,880,239,288 |
| Cost per Stop | stop | $0.04 | 9,987,436,557 | $399,497,462 | $4,174,818,513 |
| Price of Gas (no taxes) | gallon | $0.80 | 89,600,000.00 | $71,680,000 | $749,068,566 |
| Cost of CO in LA | ton | $1,000 | 8649.85 | $8,649,847 | $66,168,681 |
| Cost of ROG in LA | ton | $25,000 | 1431.97 | $35,799,228 | $273,853,122 |
| Cost of NOx in LA | ton | $62,200 | 2021.77 | $125,754,025 | $961,979,737 |
| **Total** | | | | $1,469,031,820 | $14,874,989,342 |

## Figure 8:
## Comparison of Costs for ATSAC vs. Old Timing



# CONCLUSIONS

## EMFAC7/MOBILE4.1

Perhaps the most important conclusion of this research is that no documentation was discovered indicating that the EMFAC7 or MOBILE4.1 methods are designed, recommended, or even suggested for this type of study. These methods were suggested by a few of the people contacted over the phone as the "recognized" methodology. However, most of those contacted agreed that there were deficiencies in applying this method to arterial streets, especially when estimating benefits from the coordination of traffic signals.

Thus, even with its current deficiencies, the Modified Winfrey Method may be more desirable than the other existing models due to its direct calculation of emissions.

## Modified Winfrey Model

The original design of this project was to compare the results of the various methods to determine their accuracy. While the Modified Winfrey Model has the more precise methodology, the lack of an extensive database makes it impossible to indicate which of the two methods currently produce more accurate results.

Results indicate the EMFAC7 method, and thus similar methods such as the MOBILE4.1 method, produce somewhat lower benefit estimates than a more detailed method. This supports the original hypothesis that macroscopic methods underestimate emission benefits related to improved traffic management.

The data for the Modified Winfrey Model is still limited; however, the results obtained seem quite realistic. The results are in the same order of magnitude as those predicted by the EMFAC7 model. In addition, they seem reasonable as compared to area-wide figures supplied by SCAQMD. If the factors for the Modified Winfrey Model are inaccurate, they are likely underestimating actual emissions, as suggested by the MOBILE4 idle emission data.

## ATSAC System Impacts

Based on the current data, a city-wide implementation of the ATSAC system will reduce area-wide emissions by roughly 1% in each category. (1) Although this may seem to be a small amount, the "area" covers much more than the City of Los Angeles, and the emissions on arterial streets are is only a fraction of total mobile source emissions. Figure 8 presents the estimated savings as a percentage improvement over the current system. This is likely a better perspective of the true benefits because both the before and after emissions are calculated in the same manner. Any error in the factors would have little impact on the relative improvement, but the absolute magnitude may vary considerably.

## Coordinated System Benefits

One result, which is clearly shown in this report, is that the coordination of signals provides an excellent benefit-to-cost ratio. Previous analyses of advanced signal coordination projects have indicated benefit-to-cost ratios in the range of 20:1 to 58:1 without including any value for emission reductions.(29) The results presented here strongly support such a claim and even suggest that the true benefit cost ratio may even be *higher*.

Even with the current conservative estimation of emission reductions, the two coordinated systems pay for themselves in emission benefits alone when SCAQMD values are used. However, cost effectiveness is not the only factor considered in implementing an emission control strategy. The SCAQMD also considers: (1)

Efficiency -- The positive effects of a control measure compared to its negative effects;

Emission Reduction Potential -- The total amount of pollution that a control measure can actually reduce;

Enforceability -- The ability to force polluters to comply with a control measure;

Equity -- The fairness of the distribution of all the positive and negative effects among the various socioeconomic groups;

Legal Authority -- The possibility that local governments and agencies will cooperate to approve a control measure;

Public Acceptability -- The support the public gives to a control measure;

Rate of Emission Reduction -- The time it will take for a control measure to reduce air pollution; and

Technological Feasibility -- The likelihood that the technology for a control measure will be available when anticipated.

The coordination of signals would be ranked high in each of these categories. In addition, the emission reductions occur primarily at or near intersections. Intersections are often the pollution "hot spots" of an area and, thus, the reductions have the greatest impact at the critical locations within the area.

These facts would suggest that the coordination of signals may be justified for any jurisdiction not meeting the federal air standards.

**Relative Performance of Systems**

The results should not be used to compare ATSAC operation to WWV operation because

- The analyses only consider before and after comparisons. The before condition may have been significantly different at the two separate study sites;
- The Valley Boulevard System did not have any major crossing systems at the time of the study. Effectively, the ATSAC system is presenting network benefits while the WWV system is presenting an arterial system;
- The Valley Boulevard system only covers 2.8 miles and thus may not be representative of the average benefits to be gained through WWV coordination. Even the ATSAC study only covered 21.2 miles, which is a fraction of the 1421.3 miles that a city-wide system would cover;
- A centralized system provides other benefits that can not be addressed by the current Valley WWV system; and
- A diminishing return on investment would be expected for any higher cost project. Thus, the more expensive ATSAC system may provide a lower benefit-to-cost ratio while providing a larger benefit potential due to the increased investment.

## POTENTIAL ERRORS

As mentioned above, some of the original assumptions will be modified to improve the accuracy of the estimates. However, there are some other assumptions that are made within this report which will not be modified.

### Driver Characteristics

*Acceleration Rate*

The data obtained from the EPA is an evaluation of emissions from a vehicle during the FTP test. A number of agencies have mentioned that the acceleration and deceleration rates used within this test may be different from what occurs in the field. The maximum rate of acceleration in the FTP is less than 4 mph/s. This figure is supported by studies conducted in 1971 as a part of NCHRP project 2-5A.(30) However, this may not be reflective of current acceleration characteristics.

Ideally, data should be obtained for field acceleration rates and then for emission characteristics at this rate. However, the present data should serve as a conservative assumption as to the amount of pollution emitted, and thus, for the estimated benefits of signal coordination.

*Inter-vehicle Interactions*

Due to the data available, the cruise emission factor is designed to be used for the average cruise speed. This data considers some speed fluctuations due to inter-vehicle interference, such as when a lead vehicle slows to negotiate a turn. However, this methodology assumes that the impact of such maneuvers stays constant between the different timing schemes.

This assumption may not be completely true in all cases. For example, if two closely spaced intersections are not coordinated, congestion may result. Thus, when queue discharge commences from the upstream signal, the mean free speed may never be reached due to immediate slowing caused by the next queue. After coordination, this congestion may disappear, and thus when vehicles accelerate, they will achieve the mean free flow speed.

### Vehicle Characteristics

The EMFAC7 data is designed to be representative of the 1990 Los Angeles County vehicle fleet. This may not be a completely accurate representation of arterial street traffic. Some trucks will drive through the city on the freeways, and thus, never impact the arterial street system. As trucks emit considerably more pollution than passenger cars, this may result in a distortion in the emission statistics. Likewise, the data produced by EMFAC7 and MOBILE4.1 are designed for the average condition. As "cold" cars are more likely to be on the arterial street system than on the freeways, an additional distortion of the emission statistics may take place. However, these two factors have opposite effects, and the estimates given reflect the best guess at the true statistics.

The data for the Modified Winfrey Model is based on a single 1984 Buick Century. As this car is equipped with the standard emissions equipment, it is likely a very conservative estimate of the vehicle fleet. Trucks and pre-1980 vehicles emit a disproportionately large amount of the pollution in the traffic stream today. To adjust for this conservative estimate, the ratios comparing catalytic equipped passenger cars' emissions to the overall vehicle fleet emissions were determined. Each emission factor was then multiplied by the appropriate ratio.

One indicator that suggests the derived Modified Winfrey Model factors are conservative is the MOBILE4 idle emission rates. These rates suggest significantly higher emissions for CO and ROG during idle. The $NO_x$ emission estimates appeared to be within 15%. However, until further research is done in this area, it is impossible to know the appropriate factors.

## RECOMMENDATIONS

### Coordinate Signals

From the results presented in this report, as well as previous documentation, it is evident that signal coordination projects are *extremely* cost efficient. For cities with severe air quality problems, coordinated signals provide additional benefits that should not be overlooked.

### Update Data and Improve Models

Although EMFAC7 and MOBILE4.1 are widely used, many appear to question the results obtained when using them to estimate emissions on arterial streets. As the CAAA are becoming increasingly important, it is highly recommended that the transportation and air quality professionals adopt a more accurate method for this specialized application as well as other similar traffic management improvements. The FHWA is currently sponsoring research in such a project with an expected completion date of October 1993. In the meantime, the Modified Winfrey Method appears to be the best suited for such an application.

Regardless of the method eventually selected, it is important that the data be continuously updated. The data used in this paper for the Modified Winfrey Method is only based on a 1984 Buick Century with adjustments made to represent the vehicle fleet. While this may provide a reasonable representation of the vehicle fleet, it is far from being an accurate database.

### Initiate New Research

In addition to developing models, it is desirable to obtain at least a limited database of real-life, real-time, arterial emission measurements. Such a data collection effort may be possible through a joint effort by the CARB and the LADPW. The CARB has recently obtained equipment that measures real-time emissions in the field, and the LADPW is conducting numerous floating car studies in conjunction with the Traffic Signal Synchronization Project. If implemented, this project could provide extensive insight into the benefits of such a project.

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Additional information on air quality and emissions were gathered from a number of individuals as cited in the references below. Finally, the author would like to recognize Don Capelle, Randy Kier, Joe McDermott and Dave Roper for providing insight and direction on topics not covered in the scope of this paper.

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10. Telephone interview with George Dresser, Texas Transportation Institute, Texas A&M University System.

11. Telephone interview with Jerry Bullin, Texas Transportation Institute, Texas A&M University System.

12. Telephone interview with Dick Zimmer, Texas Transportation Institute, Texas A&M University System.

13. Telephone interview with Frank MacFarland, Texas Transportation Institute, Texas A&M University System.

14. Telephone interview with Steve Kadle, General Motors.

15. Telephone interview with Larry Erwin, Southern California Air Quality Management District.
16. Telephone interview with John Myan, Federal Highway Administration.

17. Telephone interview with Ed Rowe, Los Angeles Department of Transportation.

18. Telephone interview with John Squiuer, Los Angeles County Department of Public Works.

19. Telephone interview with Ajay Rathi, Oak Ridge National Laboratories.

20. Telephone interview with Michael Morris, North Central Texas Council of Governments.

21. Telephone interview with Everett Bacon, North Central Texas Council of Governments.

Kenneth L. Vaughn received his B.S. in Civil Engineering in May 1989 from Tulane University. Upon graduation he was employed by the Traffic and Lighting Division of the Los Angeles County Department of Public Works as a Civil Engineering Assistant. In the Fall of 1991, he enrolled in Texas A&M University and started employment at the Texas Transportation Institute as a Graduate Research Assistant. University activities involved in including: Institute of Transportation Engineers, American Society of Civil Engineers and Tau Beta Pi. His areas of interest include: traffic management systems, traffic signal operations and environmental impacts of transportation.

Averages of EMFAC7 Emission Factors
Year: 1990

| Veh. Type | Light Duty Passenger | | | | Light Duty Trucks | | | | Med. Trucks | | | Heavy Duty Trucks | | | | Urban | Motor- | **All** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-cat | Cat | Diesel | Total | Non-cat | Cat | Diesel | Total | Non-cat | Cat | Total | Non-cat | Cat | Diesel | Total | Diesel | cycle | **Vehicles** |
| Make-up of Car Population in Los Angeles County | | | | | | | | | | | | | | | | | | |
| # of Veh. in use | 371867 | 3368629 | 89233 | 3829729 | 84719 | 699700 | 22430 | 806849 | 52092 | 204646 | 256738 | 107590 | 34913 | 48137 | 190640 | 2214 | 172617 | **5258787** |
| Daily VMT | 6543 | 109815 | 3045 | 119403 | 1361 | 23139 | 657 | 25157 | 746 | 7259 | 8005 | 2919 | 1769 | 3952 | 8640 | 308 | 981 | **162494** |
| % of Total VMT | 4.03 | 67.58 | 1.87 | 73.48 | 0.84 | 14.24 | 0.40 | 15.48 | 0.46 | 4.47 | 4.93 | 1.80 | 1.09 | 2.43 | 5.32 | 0.19 | 0.60 | **100.00** |
| Rate of Total Organic Gas Production (ROG) grams/mile | | | | | | | | | | | | | | | | | | |
| Speed | | | | | | | | | | | | | | | | | | |
| 5 | 17.53 | 2.45 | 0.83 | | 17.77 | 3.5 | 0.84 | | 18.54 | 4.23 | | 18.48 | 4.24 | 8.24 | | 10.84 | 10.95 | **3.97** |
| 10 | 9.63 | 1.21 | 0.65 | | 9.58 | 1.73 | 0.66 | | 10.25 | 2.07 | | 12.11 | 2.78 | 6.47 | | 8.51 | 5.78 | **2.14** |
| 15 | 6.96 | 0.8 | 0.52 | | 6.81 | 1.13 | 0.53 | | 7.45 | 1.35 | | 8.27 | 1.9 | 5.19 | | 6.83 | 4.07 | **1.48** |
| 20 | 5.69 | 0.6 | 0.43 | | 5.49 | 0.85 | 0.43 | | 6.11 | 1.01 | | 5.89 | 1.35 | 4.26 | | 5.6 | 3.3 | **1.14** |
| 25 | 4.86 | 0.48 | 0.36 | | 4.65 | 0.68 | 0.36 | | 5.23 | 0.81 | | 4.37 | 1 | 3.57 | | 4.7 | 2.83 | **0.93** |
| 30 | 4.21 | 0.4 | 0.31 | | 4.01 | 0.57 | 0.31 | | 4.52 | 0.67 | | 3.38 | 0.78 | 3.06 | | 4.03 | 2.46 | **0.78** |
| 35 | 3.7 | 0.34 | 0.27 | | 3.52 | 0.48 | 0.27 | | 3.97 | 0.58 | | 2.72 | 0.63 | 2.68 | | 3.53 | 2.18 | **0.67** |
| 40 | 3.35 | 0.3 | 0.24 | | 3.18 | 0.42 | 0.25 | | 3.59 | 0.5 | | 2.29 | 0.53 | 2.4 | | 3.16 | 1.97 | **0.59** |
| 45 | 3.16 | 0.27 | 0.22 | | 2.97 | 0.38 | 0.22 | | 3.38 | 0.45 | | 2.01 | 0.46 | 2.2 | | 2.9 | 1.86 | **0.54** |
| 50 | 3.06 | 0.24 | 0.21 | | 2.85 | 0.34 | 0.21 | | 3.28 | 0.4 | | 1.83 | 0.42 | 2.06 | | 2.71 | 1.8 | **0.50** |
| 55 | 2.89 | 0.22 | 0.2 | | 2.69 | 0.31 | 0.2 | | 3.1 | 0.37 | | 1.74 | 0.4 | 1.97 | | 2.59 | 1.74 | **0.47** |
| 60 | 3.66 | 0.28 | 0.19 | | 3.43 | 0.4 | 0.2 | | 3.9 | 0.48 | | 1.73 | 0.4 | 1.93 | | 2.54 | 1.53 | **0.56** |
| 65 | 6.17 | 0.48 | 0.19 | | 5.8 | 0.68 | 0.2 | | 6.59 | 0.81 | | 1.79 | 0.41 | 1.93 | | 2.54 | 1.05 | **0.88** |

# Appendix A

| Veh. Type | Light Duty Passenger | | | | Light Duty Trucks | | | | Med. Trucks | | | Heavy Duty Trucks | | | | Urban | Motor- | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-cat | Cat | Diesel | Total | Non-cat | Cat | Diesel | Total | Non-cat | Cat | Total | Non-cat | Cat | Diesel | Total | Diesel | cycle | **Vehicles** |
| Rate of Carbon Monoxide Production (CO) | | | | grams/mile | | | | | | | | | | | | | | |
| Speed | | | | | | | | | | | | | | | | | | |
| 5 | 177.66 | 27.51 | 3.82 | | 175.57 | 37.8 | 3.92 | | 183.32 | 23.9 | | 303.35 | 44.49 | 38.79 | | 63.12 | 63.32 | **41.97** |
| 10 | 88.66 | 14.25 | 2.63 | | 87.27 | 19.33 | 2.71 | | 94.28 | 12.78 | | 201.82 | 29.6 | 26.75 | | 43.52 | 30.43 | **22.61** |
| 15 | 59.82 | 9.83 | 1.9 | | 58.39 | 13.17 | 1.95 | | 65.73 | 9.07 | | 141.87 | 20.81 | 19.3 | | 31.41 | 19.96 | **15.59** |
| 20 | 46.21 | 7.42 | 1.43 | | 44.78 | 9.92 | 1.47 | | 52.01 | 6.89 | | 105.36 | 15.45 | 14.58 | | 23.72 | 15.29 | **11.79** |
| 25 | 37.5 | 5.94 | 1.13 | | 36.35 | 7.94 | 1.17 | | 42.84 | 5.51 | | 82.67 | 12.12 | 11.52 | | 18.75 | 12.5 | **9.44** |
| 30 | 31.01 | 4.95 | 0.94 | | 30.26 | 6.62 | 0.96 | | 35.75 | 4.59 | | 68.54 | 10.05 | 9.53 | | 15.51 | 10.49 | **7.85** |
| 35 | 26.23 | 4.24 | 0.81 | | 25.78 | 5.67 | 0.83 | | 30.48 | 3.94 | | 60.03 | 8.8 | 8.25 | | 13.42 | 8.97 | **6.73** |
| 40 | 23.01 | 3.71 | 0.74 | | 22.67 | 4.96 | 0.76 | | 27.04 | 3.44 | | 55.56 | 8.15 | 7.47 | | 12.16 | 7.91 | **5.96** |
| 45 | 21.12 | 3.3 | 0.7 | | 20.7 | 4.41 | 0.72 | | 25.21 | 3.06 | | 54.32 | 7.97 | 7.09 | | 11.53 | 7.28 | **5.45** |
| 50 | 19.98 | 2.97 | 0.69 | | 19.44 | 3.97 | 0.71 | | 24.21 | 2.75 | | 56.11 | 8.23 | 7.03 | | 11.44 | 6.98 | **5.12** |
| 55 | 18.34 | 2.7 | 0.72 | | 17.97 | 3.61 | 0.74 | | 22.31 | 2.5 | | 61.25 | 8.98 | 7.3 | | 11.88 | 6.74 | **4.90** |
| 60 | 33.9 | 5.27 | 0.78 | | 33.95 | 7.05 | 0.8 | | 40.81 | 4.89 | | 70.62 | 10.36 | 7.94 | | 12.91 | 6.02 | **8.27** |
| 65 | 77.52 | 12.05 | 0.89 | | 77.62 | 16.12 | 0.91 | | 93.31 | 11.18 | | 86.05 | 12.62 | 9.03 | | 14.69 | 4.31 | **17.12** |
| Rate of Oxides of Nitrogen Production (NOx) | | | | grams/mile | | | | | | | | | | | | | | |
| Speed | | | | | | | | | | | | | | | | | | |
| 5 | 2.03 | 1.14 | 2.12 | | 2.17 | 1.4 | 2.03 | | 2.14 | 2.05 | | 5.01 | 3.72 | 26.53 | | 37.91 | 0.69 | **2.07** |
| 10 | 2.08 | 1.02 | 1.76 | | 2.13 | 1.25 | 1.69 | | 2.12 | 1.83 | | 5.27 | 3.91 | 22.01 | | 31.45 | 0.62 | **1.84** |
| 15 | 2.12 | 0.93 | 1.51 | | 2.12 | 1.13 | 1.45 | | 2.13 | 1.66 | | 5.52 | 4.09 | 18.92 | | 27.04 | 0.64 | **1.67** |
| 20 | 2.16 | 0.86 | 1.35 | | 2.12 | 1.04 | 1.29 | | 2.17 | 1.52 | | 5.78 | 4.28 | 16.86 | | 24.08 | 0.67 | **1.55** |
| 25 | 2.2 | 0.81 | 1.24 | | 2.14 | 0.98 | 1.19 | | 2.21 | 1.4 | | 6.03 | 4.47 | 15.56 | | 22.23 | 0.77 | **1.48** |
| 30 | 2.23 | 0.77 | 1.19 | | 2.17 | 0.93 | 1.14 | | 2.25 | 1.32 | | 6.29 | 4.66 | 14.88 | | 21.25 | 0.85 | **1.43** |
| 35 | 2.27 | 0.75 | 1.18 | | 2.21 | 0.91 | 1.13 | | 2.29 | 1.25 | | 6.54 | 4.85 | 14.74 | | 21.06 | 0.91 | **1.41** |
| 40 | 2.32 | 0.75 | 1.21 | | 2.26 | 0.9 | 1.16 | | 2.33 | 1.2 | | 6.79 | 5.04 | 15.13 | | 21.62 | 0.96 | **1.43** |
| 45 | 2.39 | 0.76 | 1.29 | | 2.33 | 0.91 | 1.23 | | 2.39 | 1.17 | | 7.05 | 5.22 | 16.09 | | 22.99 | 0.99 | **1.48** |
| 50 | 2.79 | 0.88 | 1.42 | | 2.74 | 1.06 | 1.36 | | 2.79 | 1.33 | | 7.3 | 5.41 | 17.74 | | 25.34 | 1.05 | **1.66** |
| 55 | 3.67 | 1.15 | 1.62 | | 3.6 | 1.39 | 1.55 | | 3.67 | 1.74 | | 7.56 | 5.6 | 20.26 | | 28.94 | 1.16 | **2.04** |
| 60 | 4.55 | 1.43 | 1.92 | | 4.46 | 1.72 | 1.83 | | 4.54 | 2.16 | | 7.81 | 5.79 | 23.97 | | 34.24 | 1.43 | **2.45** |
| 65 | 5.43 | 1.71 | 2.35 | | 5.32 | 2.05 | 2.25 | | 5.42 | 2.58 | | 8.06 | 5.98 | 29.38 | | 41.98 | 2.1 | **2.92** |

MOBILE4 Idle Factors

| CO | | ROG | | NOx | |
|---|---|---|---|---|---|
| CO | 296.9 | ROG | 27.2 | NOx | 3.8 |

# APPENDIX B: FLOATING CAR STUDY SUMMARIES

## Valley Boulevard

### Table B-1
### Summary Data for
### Valley Boulevard :Cabrillo Av./Westminster Av. - New Av.

| (Dial) Length of Operation | Dir | Before Study | | | | After Study | | | | Volume during Dial per Day |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Avg. Speed (mph) | Total Travel Time (veh-sec/veh) | Stopped Delay Time (veh-sec/veh) | Number of Stops (per veh) | Avg. Speed (mph) | Total Travel Time (veh-sec/veh) | Stopped Delay Time (veh-sec/veh) | Number of Stops (per veh) | |
| (AM Peak) | EB | 18.4 | 549.0 | 208.3 | 8.5 | 29.8 | 338.5 | 42.0 | 1.5 | 1794 |
| 4 hrs. | WB | 15.0 | 671.5 | 288.8 | 7.5 | 19.8 | 508.8 | 180.0 | 2.3 | 3978 |
| (Off Peak) | EB | 17.7 | 571.0 | 177.3 | 8.8 | 23.7 | 425.0 | 153.0 | 4.0 | 7938 |
| 9 hrs. | WB | 16.9 | 594.8 | 236.3 | 7.8 | 23.0 | 438.3 | 122.5 | 4.8 | 7900 |
| (PM Peak) | EB | 11.9 | 846.3 | 386.0 | 11.0 | 18.4 | 547.5 | 234.3 | 6.3 | 5454 |
| 4 hrs. | WB | 18.3 | 551.8 | 166.0 | 7.5 | 18.4 | 549.0 | 249.5 | 7.0 | 4113 |

### Table B-2
### Additional Data for Valley Boulevard System

| | |
|---|---|
| **Arterial Street** | |
| Fuel Consumption (gal/day) | (1,023) |
| **Side Street** | |
| Stopped Delay (veh-hrs./day) | 48 |
| Stops (stops/day) | 5,947 |
| Fuel Consumption (gal/day) | 35 |

Positive numbers indicate an increase

## Los Angeles City

### Table B-3
### Summary Data for ATSAC Test Area for 1991 Evaluation Study

| Method of Signal Operation | Area Milage | Avg. Speed (mph) | Total Travel Time (veh-min/veh) | Stopped Delay Time (veh-min/veh) | Number of Stops (per veh area trip) |
|---|---|---|---|---|---|
| Old Timing | 21.2 | 20.1 | 63.3 | 17.7 | 51.2 |
| Fetsim | 21.2 | 21.1 | 60.2 | 15.6 | 45.6 |
| ATSAC | 21.2 | 24.6 | 51.8 | 9.9 | 30.0 |

## Table B-4
## Estimated Data for Los Angeles Area from 1991 Evaluation Study

| Method of Signal Operation | VMT | Avg. Speed (mph) | Total Travel Time (veh-hrs/day) | Stopped Delay Time (veh-hrs/day) | Number of Stops (total/day) |
|---|---|---|---|---|---|
| Old Timing | 39,837,000 | 20.1 | 1,982,454 | 555,588 | 96,285,277 |
| Fetsim | 39,837,000 | 21.1 | 1,885,149 | 489,193 | 85,611,968 |
| ATSAC | 39,837,000 | 24.6 | 1,622,606 | 310,052 | 56,335,531 |

## Valley Boulevard

### Table C-1
### EMFAC7 CO Results for Valley Boulevard: Old Timing

| *Valley Bl. Old* | *Avg. Speed (mph)* | *EMFAC7 CO Emission Factor (gr/mi)* | *Veh-Mi Travelled (veh-mi/day)* | ***CO Generated (tons/year)*** |
|---|---|---|---|---|
| (AM Peak) | 18.4 | 13.0 | 5,023 | 18.1 |
| 4 hrs. | 15.0 | 15.6 | 11,138 | 47.8 |
| (Off Peak) | 17.7 | 13.6 | 22,226 | 83.2 |
| 9 hrs. | 16.9 | 14.1 | 22,120 | 86.0 |
| (PM Peak) | 11.9 | 19.9 | 15,271 | 83.9 |
| 4 hrs. | 18.3 | 13.1 | 11,516 | 41.6 |
| **Total** | | | 87,296 | 360.5 |

### Table C-2
### EMFAC7 CO Results for Valley Boulevard: WWV Timing

| *Valley Bl. W W V* | *Avg. Speed (mph)* | *EMFAC7 CO Emission Factor (gr/mi)* | *Veh-Mi Travelled (veh-mi/day)* | ***CO Generated (tons/year)*** |
|---|---|---|---|---|
| (AM Peak) | 29.8 | 7.9 | 5,023 | 11.0 |
| 4 hrs. | 19.8 | 11.9 | 11,138 | 36.6 |
| (Off Peak) | 23.7 | 10.0 | 22,226 | 61.5 |
| 9 hrs. | 23.0 | 10.4 | 22,120 | 63.3 |
| (PM Peak) | 18.4 | 13.0 | 15,271 | 54.7 |
| 4 hrs. | 18.4 | 13.0 | 11,516 | 41.4 |
| **Total** | | | 87,296 | 268.5 |

### Table C-3
### EMFAC7 ROG Results for Valley Boulevard: Old Timing

| *Valley Bl. Old* | *Avg. Speed (mph)* | *EMFAC7 ROG Emission Factor (gr/mi)* | *Veh-Mi Travelled (veh-mi/day)* | ***ROG Generated (tons/year)*** |
|---|---|---|---|---|
| (AM Peak) | 18.4 | 1.25 | 5,023 | 1.7 |
| 4 hrs. | 15.0 | 1.48 | 11,138 | 4.5 |
| (Off Peak) | 17.7 | 1.30 | 22,226 | 8.0 |
| 9 hrs. | 16.9 | 1.35 | 22,120 | 8.2 |
| (PM Peak) | 11.9 | 1.89 | 15,271 | 7.9 |
| 4 hrs. | 18.3 | 1.26 | 11,516 | 4.0 |
| **Total** | | | 87,296 | 34.4 |

## Table C-4
## EMFAC7 ROG Results for Valley Boulevard: WWV Timing

| *Valley Bl. W W V* | *Avg. Speed (mph)* | *EMFAC7 ROG Emission Factor (gr/mi)* | *Veh-Mi Travelled (veh-mi/day)* | ***ROG Generated (tons/year)*** |
|---|---|---|---|---|
| (AM Peak) | 29.8 | 0.79 | 5,023 | 1.09 |
| 4 hrs. | 19.8 | 1.15 | 11,138 | 3.54 |
| (Off Peak) | 23.7 | 0.98 | 22,226 | 6.01 |
| 9 hrs. | 23.0 | 1.01 | 22,120 | 6.17 |
| (PM Peak) | 18.4 | 1.25 | 15,271 | 5.25 |
| 4 hrs. | 18.4 | 1.25 | 11,516 | 3.97 |
| **Total** | | | 87,296 | 26.0 |

## Table C-5
## EMFAC7 $NO_X$ Results for Valley Boulevard: Old Timing

| *Valley Bl. Old* | *Avg. Speed (mph)* | *EMFAC7 NOx Emission Factor (gr/mi)* | *Veh-Mi Travelled (veh-mi/day)* | ***NOx Generated (tons/year)*** |
|---|---|---|---|---|
| (AM Peak) | 18.4 | 1.59 | 5,023 | 2.2 |
| 4 hrs. | 15.0 | 1.67 | 11,138 | 5.1 |
| (Off Peak) | 17.7 | 1.61 | 22,226 | 9.8 |
| 9 hrs. | 16.9 | 1.62 | 22,120 | 9.9 |
| (PM Peak) | 11.9 | 1.77 | 15,271 | 7.5 |
| 4 hrs. | 18.3 | 1.59 | 11,516 | 5.1 |
| **Total** | | | 87,296 | 39.6 |

## Table C-6
## EMFAC7 $NO_X$ Results for Valley Boulevard: WWV Timing

| *Valley Bl. W W V* | *Avg. Speed (mph)* | *EMFAC7 NOx Emission Factor (gr/mi)* | *Veh-Mi Travelled (veh-mi/day)* | ***NOx Generated (tons/year)*** |
|---|---|---|---|---|
| (AM Peak) | 29.8 | 1.43 | 5,023 | 1.98 |
| 4 hrs. | 19.8 | 1.56 | 11,138 | 4.78 |
| (Off Peak) | 23.7 | 1.50 | 22,226 | 9.16 |
| 9 hrs. | 23.0 | 1.51 | 22,120 | 9.19 |
| (PM Peak) | 18.4 | 1.59 | 15,271 | 6.69 |
| 4 hrs. | 18.4 | 1.59 | 11,516 | 5.05 |
| **Total** | | | 87,296 | 36.8 |

## Table C-7
## Modified Winfrey Model Results for Valley Boulevard: Old Timing

| *Valley Bl. Old Timing* | *Time (veh-hrs./day)* | *Total CO (tons/yr)* | *Total ROG (tons/yr)* | *Total NOx (tons/yr)* | *Total CO2 (tons/yr)* | *Total* |
|---|---|---|---|---|---|---|
| Idle | 2,107 | 4.00 | 2.52 | 2.59 | 3,679 | |
| Cruise | 1,613 | 7.81 | 5.35 | 15.12 | 7,423 | |
| Accel | 863 | 58.06 | 9.89 | 18.65 | 6,427 | |
| Decel | 910 | 1.60 | 1.07 | 2.31 | 2,072 | |
| **Total** | 5,492 | 71.46 | 18.83 | 38.68 | 19,602 | |
| **LA Cost** | | $71,464 | $470,861 | $2,405,759 | | $2,948,084 |
| **Nat'l Cost** | | $21,439 | $57,445 | $106,364 | | $185,248 |

## Table C-8
## Modified Winfrey Model Results for Valley Boulevard: WWV Timing

| *Valley Bl. W W V Timing* | *Time (veh-hrs./day)* | *Total CO (tons/yr)* | *Total ROG (tons/yr)* | *Total NOx (tons/yr)* | *Total CO2 (tons/yr)* | *Total* |
|---|---|---|---|---|---|---|
| Idle | 1,466 | 2.78 | 1.75 | 1.81 | 2,560 | |
| Cruise | 1,661 | 8.04 | 5.51 | 15.58 | 7,647 | |
| Accel | 467 | 31.41 | 5.35 | 10.09 | 3,477 | |
| Decel | 492 | 0.86 | 0.58 | 1.25 | 1,121 | |
| **Total** | 4,087 | 43.10 | 13.20 | 28.72 | 14,806 | |
| **LA Cost** | | $43,101 | $329,931 | $1,786,679 | | $2,159,711 |
| **Nat'l Cost** | | $12,930 | $40,252 | $78,993 | | $132,175 |

## Los Angeles City

## Table C-9
## EMFAC7 Results for Los Angeles

| | *Speed (mph)* | *VMT (per day)* | *Total CO (tons/yr)* | *Total ROG (tons/yr)* | *Total NOx (tons/yr)* | *LA Cost* | *Nat'l Cost* |
|---|---|---|---|---|---|---|---|
| Old | 20.1 | 39,837,000 | 128,697 | 12,436 | 17,020 | $775,013,500 | $123,344,331 |
| FETSIM | 21.1 | 39,837,000 | 120,051 | 11,664 | 16,753 | $746,456,434 | $117,662,985 |
| ATSAC | 24.6 | 39,837,000 | 105,918 | 10,381 | 16,283 | $698,371,204 | $108,214,983 |

## Table C-10
## Modified Winfrey Model Results for Los Angeles: Old Timing

| *OLD* | *Time hrs./day* | *Total CO (tons/yr)* | *Total ROG (tons/yr)* | *Total NOx (tons/yr)* | *Total CO2 (tons/yr)* | *Total* |
|---|---|---|---|---|---|---|
| Idle | 555,588 | 1,054.70 | 663.91 | 684.29 | 970,180 | |
| Cruise | 788,467 | 3,817.43 | 2,616.50 | 7,394.16 | 3,629,424 | |
| Accel | 310,762 | 20,905.64 | 3,561.50 | 6,714.54 | 2,314,190 | |
| Decel | 327,637 | 575.43 | 386.86 | 832.51 | 746,180 | |
| **Total** | 1,982,454 | 26353.20 | 7228.77 | 15625.50 | 7,659,974 | |
| **LA Cost** | | $26,353,197 | $180,719,138 | $971,905,977 | | $1,178,978,313 |
| **Nat'l Cost** | | $7,905,959 | $22,047,735 | $42,970,120 | | $72,923,814 |

## Table C-11
## Modified Winfrey Model Results for Los Angeles: FETSIM Timing

| *FETSIM* | *Time hrs./day* | *Total CO (tons/yr)* | *Total ROG (tons/yr)* | *Total NOx (tons/yr)* | *Total CO2 (tons/yr)* | *Total* |
|---|---|---|---|---|---|---|
| Idle | 489,193 | 928.66 | 584.57 | 602.51 | 854,240 | |
| Cruise | 828,323 | 4,010.40 | 2,748.77 | 7,767.92 | 3,812,888 | |
| Accel | 276,314 | 18,588.23 | 3,166.70 | 5,970.23 | 2,057,660 | |
| Decel | 291,319 | 511.64 | 343.98 | 740.23 | 663,465 | |
| **Total** | 1,885,149 | 24038.93 | 6844.01 | 15080.89 | 7,388,253 | |
| **LA Cost** | | $24,038,928 | $171,100,227 | $938,031,512 | | $1,133,170,668 |
| **Nat'l Cost** | | $7,211,679 | $20,874,228 | $41,472,454 | | $69,558,361 |

## Table C-12
## Modified Winfrey Model Results for Los Angeles: ATSAC Timing

| *ATSAC* | *Time hrs./day* | *Total CO (tons/yr)* | *Total ROG (tons/yr)* | *Total NOx (tons/yr)* | *Total CO2 (tons/yr)* | *Total* |
|---|---|---|---|---|---|---|
| Idle | 310,052 | 588.59 | 370.50 | 381.87 | 541,420 | |
| Cruise | 939,033 | 4,546.41 | 3,116.15 | 8,806.15 | 4,322,502 | |
| Accel | 181,824 | 12,231.68 | 2,083.79 | 3,928.61 | 1,354,009 | |
| Decel | 191,697 | 336.68 | 226.35 | 487.09 | 436,582 | |
| **Total** | 1,622,606 | 17703.35 | 5796.80 | 13603.73 | 6,654,513 | |
| **LA Cost** | | $17,703,350 | $144,919,910 | $846,151,952 | | $1,008,775,212 |
| **Nat'l Cost** | | $5,311,005 | $17,680,229 | $37,410,255 | | $60,401,489 |