# EVALUATION OF DRIVING PATTERN MEASUREMENT TECHNIQUES

## TECHNICAL NOTE

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## TECHNICAL NOTE

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# 1.0 EXECUTIVE SUMMARY

Evaluations have been made of various measurement techniques to collect data on the driving patterns of light-duty vehicles in the population. This data would be used to evaluate the current certification test procedure, and revise, update, or replace it if necessary. To better evaluate the techniques, consideration has been given to the broader issues of the development of a certification test procedure: selection of measurement parameters, selection of measurement techniques, measurement of driving parameters, analysis of driving pattern data, and certification test procedure development.

A new certification test procedure could be made in various formats, but all candidate procedures would probably specify dynamometer speed versus time. A new procedure could be representative of either population driving patterns or population emissions patterns. A clear recommendation on which approach to take is difficult; each has strong advantages and disadvantages. The following compares the attributes of certification test procedures which are based on either driving patterns or emissions patterns:

- Vehicles tested using a driving pattern based certification test procedure would spend dynamometer time for various driving features in proportion to the occurrence of the same driving features in the vehicle population. This would produce emissions representative of the vehicle population. Emissions characterization would be good for today's emission control technology, fuel composition, and emission types and also for future technologies, fuels, and emission types. However, because the certification test procedure would be representative of driving patterns, this type of certification test procedure would be inefficient. That is, most dynamometer time would be spent on driving features that produce very low emissions; a small fraction of the dynamometer time would be spent on high emitting features.

- Vehicles tested using an emissions based certification test procedure would spend dynamometer time for various driving features in proportion to the mass emissions of the same driving features in the vehicle population. Because this new certification test procedure would be representative of emissions patterns, the procedure would be efficient. That is, all dynamometer time would be spent measuring the emissions of driving features in proportion to the importance of the driving feature emissions to the total emissions of the vehicle population. However, as vehicle manufacturers improve vehicle emission control technology in response to the new certification test procedure, as new fuels and fuel compositions are introduced into the marketplace, and as different pollutants become of concern (for example, perhaps formaldehyde), the new certification test procedure will become less relevant for measuring the emissions of new vehicles. At some point, a need for a new certification test procedure will become apparent. Still, an emissions pattern based procedure may be better than a driving pattern based procedure for some time.

Both the driving pattern based and the emissions pattern based certification test procedures will require driving pattern data for their development. In addition, an emissions based procedure would require the relationship between emissions and driving. However, Radian suggests that even if the emissions based procedure is desired, the emissions versus driving study would best be performed separately from the driving pattern study. This separate approach benefits the driving pattern study in several ways:

- Since fewer parameters need to be collected for the pure driving pattern study, simpler instrumentation of private cars is required.
- Fewer parameters means that early, as well as late model, cars can be used in the study to get a picture of driving pattern over the useful lifetime of cars.
- Simpler instrumentation means that more cars can be instrumented for the same funds and therefore more driving pattern data will be collected.
- Simpler instrumentation means that fewer refusals to participate will be encountered because the equipment installation is simpler, faster, less intrusive, and less inconvenient for the owner.

- Fewer refusals to participate means that the results of instrumented vehicles would potentially be less biased and representative sampling efforts to overcome bias would need to be implemented less often.

- Requiring fewer parameters means that the chase car technique will produce data which is more similar to the data from the instrumented private vehicle technique.

Radian recommends that the driving patterns be measured with a program that contains two data collection studies:

- Private vehicles instrumented for clock time (seconds), vehicle speed, ignition on/off, and manifold vacuum or manifold absolute pressure (MAP). In addition, information about the vehicle should be recorded: Vehicle Identification Number (VIN), power/weight ratio, and transmission type.

- Instrumented chase car with differential speed ranging device for clock time (seconds), vehicle speed, and ignition on/off. In addition, information about the vehicle should be recorded: license number, VIN, power/weight ratio, and transmission type.

Because the instrumented private car technique and the chase car technique are complementary, Radian recommends that both techniques be used so that the advantages of each are present in the program. For both studies considerable attention and effort needs to be used to attempt to minimize the effects of vehicle and driver sampling biases.

The instrumented private car technique provides continuous detailed information about vehicle speed wherever the vehicle is driven; however, potential biases exist in the collection of data because not all owners will want their vehicles instrumented and drivers may drive differently if they know the vehicle is instrumented. It seems that the most attractive procurement location for instrumented private cars is at centralized inspection/maintenance (I/M) lanes.

The chase car technique provides detailed speed information for more vehicles at a lower cost per vehicle than can be obtained from instrumented vehicles. However, since it is not practical to chase a single car for a complete trip, chase cars are more effectively used to monitor behavior over selected links in the road system. Since the driver of a vehicle being chased will probably not be aware that he is being followed, the driving behavior will probably not be biased. However, to avoid other kinds of bias, the chase car technique must also use appropriate sampling techniques for the selection of links to monitor and specific vehicles to chase. Urban Transportation Systems Planning can be used to help make link selections, but all possible driving paths are not covered by these models.

Radian also recommends that at each survey site, both techniques should collect data at the same time. This will eliminate the possibility of differences between the two study results caused by city or date. The following guidelines can be used to chose the survey sites:

- The site should be a non-attainment area but should not be dependent on whether it is an ozone or CO non-attainment area.
- The site should be at low altitude, be relatively flat, and have low precipitation during the survey period.
- The typical traffic should be neither congested nor light.
- A site using centralized I/M and having a good Urban Transportation Planning System is highly desired to reduce bias in the instrumented private car study and in the chase car study, respectively.
- A site which has an air quality staff which is willing and able to assist with various aspects of the studies is desirable.

# 2.0 INTRODUCTION

The Clean Air Act Amendments of 1990 require EPA to evaluate the Federal Test Procedure (FTP) and revise it as necessary to ensure that vehicles are tested under circumstances which reflect actual current driving conditions. These conditions include fuel, temperature, acceleration, and altitude. EPA currently is making appropriate changes in the procedure to address concerns over the representativeness of the fuel, temperature, and altitude provisions. However, the current driving cycle used in the FTP has not been evaluated to determine if it is representative of vehicles in actual use.

EPA's Certification Division (CD) of the Office of Mobile Source Air Pollution Control has been given the lead responsibility to analyze and modify, if necessary, the FTP. CD issued a work assignment to Radian Corporation to collect information on in-use driving patterns and define the most appropriate method to proceed with the task of modifying the FTP.

Characterizing in-use driving conditions is a complex problem that must consider several interrelated factors. Of key importance is how driving pattern data should be collected. The data collection method must be straightforward and be representative of the population.

The choice of measurement techniques (to) characterize driving patterns in real world fleets depends on the data that must be collected, how the data will be analyzed, and the desired certification test procedure to be developed. This report will cover the five stages which are used to develop a certification test procedure:

- select driving parameters;
- select measurement techniques;
- measure driving parameters;

- analyze driving pattern data; and
- develop certification test procedure.

Each of these stages of development will be discussed in the following sections so that the needs of the measurement program can be put in perspective. Evaluation of candidate driving pattern measurement techniques will be presented in greater detail.

## 3.0 APPROACH TO CERTIFICATION TEST PROCEDURE DEVELOPMENT

The ultimate goal of the driving pattern test program will be to evaluate the current certification test procedure, the FTP. This data will be used to determine whether the FTP is adequate, needs to be updated, or needs to be replaced. The current test procedure specifies the speed of the vehicle versus time, and it is anticipated that any new procedure which may replace it would use a similar approach.

### 3.1 Two Possible Bases for A Certification Test Procedure

A new certification test procedure can be developed using one of two bases. The cycles can be representative of today's:

- driving patterns; or
- emissions patterns.

Each basis has advantages and disadvantages as discussed below.

A driving cycle which is based purely on driving patterns would be representative of the driving pattern of the vehicle population. Emission measurements taken while vehicles are driven in traffic indicates that such a cycle would spend most time testing driving features which produce low emissions and a small amount of time testing high emission driving features. During certain episodes, for example, during cold start operation or during heavy acceleration, HC and CO emissions are high. However, these high emission events occur during a small fraction of the total driving time. This means that a driving cycle which is representative of vehicle population driving patterns will be inefficient at measuring the performance of the vehicle emission control systems during high emissions episodes, even though it is accurately measuring the emissions performance of the vehicle in a cycle which is representative of real world driving.

Alternatively, a certification test procedure which is based on the emissions pattern of the vehicle population will reflect the range of driving in the real world but will be weighted by the response of the vehicle emissions to those driving features. Because of this, the emissions based driving cycle would contain more high emission driving features and fewer low emission driving features. Thus, the procedure would be efficient at measuring the high emissions behavior of vehicles.

An example will help clarify the important distinction between a driving pattern based certification test procedure and an emissions pattern based certification test procedure. Suppose that analysis of the driving pattern data and a separate study of the relationship between emissions and driving indicated that the emissions rate of hydrocarbon could be explained by just two kinds of driving modes: Type A and Type B. Suppose that it were found that vehicles spend 95% of their driving time in Type A driving but generate only 20% of the total fleet hydrocarbon emissions in this mode. Suppose that vehicles spend only 5% of their driving time in Type B driving but generate 80% of the total fleet hydrocarbons in this mode.

The driving based certification test procedure based on this hypothetical information would be a cycle with 95% of the time in the A mode and 5% of the time in the B mode. The emissions based certification test procedure would be a cycle with 20% of the time in the A mode and 80% of the time in the B mode. This second procedure emphasizes the time spent on high emissions features.

A driving cycle which is based purely on driving patterns will need to be updated only when the driving patterns of the vehicle population change. Changes may occur relatively slowly over perhaps twenty years. A driving pattern based test procedure will also continue to representatively measure the emissions of vehicles even though the vehicle emission control technology and fuel types may change dramatically in the next several years.

A driving cycle based on emissions patterns depends on the emissions behavior of current vehicles, which in turn depends on the type of fuel and emission control technology used when the current vehicles were being certified. Thus, for example, a new driving procedure developed in the next few years would be based on the emission characteristics of 1992 vehicles. These vehicles are, of course, creatures of the current federal test procedure, since they have been designed to pass that procedure. As vehicle manufacturers continue to develop more advanced control technologies and as new types of fuels become available in the market place, a driving cycle based on emission behavior of 1992 vehicles may become a poor measure of the emission behavior of the latest vehicles. Consequently, the new driving cycle may become obsolete in a short time. A continually revised certification test procedure in response to changes in vehicle technology and fuels will mean that the rules for manufacturing a new vehicle would be continually changing. Manufacturers would find such procedural changes difficult to quickly respond to, given the long lead times needed to integrate a new control system with a future model year vehicle. Also, the EPA would need to update the certification test procedure on a regular basis. In addition, there is no guarantee that this circular process would converge toward lower vehicle emissions and a simpler certification test procedure.

Another disadvantage of the emissions based test procedure is that the desired weighting of the high and low emitting driving features may not be the same for HC, CO, and $NO_x$ emissions. Road emissions data indicates that HC and CO emissions increase greatly during cold start operations and heavy accelerations, but the response of $NO_x$ emissions to driving may be different.

The choice of whether to use a driving pattern based or an emissions pattern based test procedure is difficult because which will be more effective depends to a large extent on the speed and degree of changes which may occur in emission control systems, fuel composition, and emissions of concern. If changes are slow and small, and if the new procedure can be implemented rapidly, then the emissions based procedure will be more effective for a long time by concentrating on the high emitting driving features of today's vehicles and vehicle population. If changes are fast and large, then the driving pattern based procedure will remain effective for a long time.

## 3.2 Studies Needed to Support Certification Test Procedure Development

The data needed to develop a certification test procedure depends on which of the bases discussed above is desired. If a new driving cycle is to be based purely on driving patterns of the population, then only the driving pattern of the vehicle population needs to be measured. However, if a new cycle is to be based on the emissions pattern of the vehicle population, then another study must be performed to measure the emissions response of 1992 vehicles to driving. This study could be either a dynamometer or a road study. It could be conducted at the same time that the driving pattern measurement of the vehicle population is being measured. The emissions response of the vehicles would be used to weight the occurrence of corresponding driving features in the new procedure.

Thus, it is clear, that regardless of whether the new test procedure will be based on driving patterns alone or the emissions patterns of the vehicle population, characterization of the driving patterns is needed. Therefore, the study on driving patterns can proceed before a decision is made on how to develop the certification test procedure.

## 3.3 Selection of Driving Parameters to be Measured

Since both approaches to develop the certification test procedure need measurement of the population driving patterns, parameters related to driving behavior must be measured; parameters related strictly to emissions behavior do not need to be collected. In this section, the parameters that affect vehicle driving characteristics will be examined, and then those parameters which are the minimum required to define the driving patterns will be identified.

### 3.3.1 Parameters that Affect Vehicle Driving Characteristics

The parameters that affect vehicle driving characteristics can be broken down into four groups:

- Driving pattern parameters;
- Vehicle environment parameters;
- Vehicle characteristics; and
- Engine operating parameters.

Table 3-1 shows a list of the parameters in these four categories.

Driving pattern parameters include those which are determined by the operator of the vehicle and the environment in which the vehicle finds itself. The most important driving pattern parameter is the speed of the vehicle as a function of time. If speed is known on a frequent basis, for example second-by-second, then the trip length and acceleration of the vehicle can be determined. The engine-on period is also an important driving parameter, since this helps determine trip length and periods of cold and warm start operation.

## Table 3-1

## PARAMETERS THAT AFFECT DRIVING CHARACTERISTICS

- Driving Pattern
  - Speed (t)
  - Engine On/Off (t)
- Vehicle Environment
  - Altitude
  - Terrain
  - A/C Status
  - Fuel Characteristics
- Vehicle Characteristics
  - Drive Train Characteristics
  - Power/Weight
- Engine Operation
  - Engine Load (t)
  - Engine RPM (t)

Vehicle and environmental parameters also may affect vehicle operation. Altitude, for example, may affect the emissions of the vehicle and also the way a vehicle is driven, since internal combustion engines produce less power at high altitudes. The demands on the performance of a vehicle will be affected differently in flat and hilly terrains. The performance of vehicles with small engines can be greatly affected by the operation of air conditioning. Finally, the fuel characteristics used in vehicles can affect driving patterns - especially if low octane fuel is used and the driver backs off on the throttle when engine knock is encountered.

Driving characteristics are also affected by vehicle design. The characteristics of the transmission and other drive train components will affect the speed of the engine with respect to the vehicle. Finally, the power/weight ratio and the weight of the vehicle may have an influence on how the vehicle is driven.

While measures of engine operation are not directly relevant to vehicle driving patterns, they can be used to estimate the vehicle emissions by knowing the response of engine emissions in different modes of operation. Two parameters which can be used to approximately define engine operation are manifold vacuum (or manifold absolute pressure) and engine speed (rpm). In addition to engine operation, manifold vacuum can provide some indication of terrain, cargo, and air conditioning loads, although it cannot distinguish among them. Comparison of engine speed with vehicle speed can be used to determine which transmission gear is being used at any given time.

### 3.3.2 Important Driving Parameters to Measure

From the list of parameters reviewed in Section 3.3.1, a subset should be chosen to be used in the driving pattern study. These parameters should be ones which can be used to define a new certification test procedure or ones which could be used to understand population driving patterns. Based on our review of the literature, interviews with experts, our judgment, and discussions which occurred at the June 6, 1991 meeting in Atlanta, we recommend that the parameters given in Table 3-2 be used to determine the driving patterns of the vehicle population.

The identity of each vehicle should be documented. This would include the vehicle identification number (VIN), the vehicle power/weight ratio, and whether the vehicle has a manual or automatic transmission. The VIN could be derived from the vehicle license number, and the power/weight ratio and transmission type could be derived from the VIN. Specific second-by-second driving data should include vehicle speed and engine on/off period.

We feel that this relatively short list of data to be obtained in the study will result in a study which has more vehicles being monitored and will result in less potential bias for data obtained from instrumented vehicles.

The above parameters are the minimum ones required to define vehicle driving patterns and can be effectively used to evaluate the current FTP or develop a new certification procedure. Manifold absolute pressure and engine speed are two additional, but optional, parameters that would be useful to define engine operation and to understand how drivers and drive trains achieve the speeds that make up driving patterns. Also, through the use of an engine map and emissions model such as VEHSIME, these two parameters can be used to better estimate vehicle emissions if engine maps for the specific vehicle drive train configurations are available. The collection of these two optional parameters is attractive for future analysis of the data if the incremental cost of collecting them is not too great.

## Table 3-2

## Parameters to be Recorded in Driving Pattern Study

Vehicle Identification Number (VIN)

Power/Weight

Transmission: Automatic or Manual

Vehicle Speed (sec)

Ignition On/Off (sec)

Optional

Engine Speed (rpm)

Manifold Absolute Pressure

## 4.0 ASSESSMENT OF DATA COLLECTION TECHNIQUES

The following approaches have been identified to collect data for the purpose of evaluating and revising the FTP:

- Method #1--Instrument private vehicles to obtain continuous data;
- Method #2--Instrument private vehicles to obtain summarized data;
- Method #3--Perform chase car surveys of individual vehicles;
- Method #4--Use vehicle diaries to collect information about driving;
- Method #5--Make external observations with stationary observers.

Each of the above methods is described below. Each technique has advantages and disadvantages. In each discussion, measures which could be used to mitigate disadvantages are summarized.

### 4.1 Method #1--Instrument Private Vehicles To Obtain Continuous Data

A popular approach toward characterizing in-use driving is to instrument private vehicles to obtain continuous data on parameters important to characterization of driving cycles. Instrumentation is available to collect at least the following parameters on a second-by-second basis:

- Engine speed;
- Vehicle speed;
- Clock time;
- Demand air/fuel ratio;
- Actual air/fuel ratio;

- Air flow;
- Manifold absolute pressure;
- Throttle position; and
- Coolant temperature.

The Motor Vehicle Manufacturers Association (MVMA) and the Association of Imported Automobiles (AIA) have proposed to provide at least 20 sets of instruments to record the above data. Initially, it is proposed that a pilot study be performed whereby at least three vehicles would be instrumented to measure the above parameters. Based on the analysis of the pilot program data, recommendations will be made on parameters, frequency of data collection, and equipment needed for an in-depth study of driving cycles.

Based on the specific goals of the driving pattern measurement study, the list of parameters which need to be monitored may be reduced. A minimum list would contain clock time, vehicle speed, and manifold absolute pressure, as discussed in the previous section.

Instrumentation of loaner vehicles is a related approach that could be used. The use of loaner vehicles introduces a bias in the data caused by people who do not want to give up their vehicle or who would drive a loaner differently from their own vehicle.

**Advantages**

The primary advantage of instrumenting vehicles and recording continuous data is that a complete history of the operation for the particular vehicle is obtained. Unlike the situation with external observations or chase cars, the data recorded by instruments on the target vehicle precisely measures the parameters for that vehicle. As a result, this method accurately monitors cold-, warm-, and hot-start operation, as well as trip beginnings and ends. In addition, this method provides accurate data on engine load. With other data collection methods, engine load can be inferred from acceleration and information on the vehicle, but it cannot be accurately measured.

Other advantages of this approach are listed below:

- **Provides high-frequency information on parameters.** Information can be provided on a second-by-second basis or even more frequent intervals.
- **This method is able to detect small variations in speed and load which may have significant impact on emissions.** For example, the classic "foot-pumper" that is constantly changing throttle while maintaining a relatively constant speed could be detected by this method.
- **Has capabilities of maintaining average (summarized) as well as instantaneous data.**
- **Data are recorded in machine-readable form, and therefore no key punching or data entry is needed.**
- **Provides an accurate measure of the distance travelled by the vehicle.**
- **Data analysis technique can be changed without the need to collect additional data.** When several key engine parameters are monitored on a continuous basis, versus being logged into bins, the data analysis technique can be revised as more knowledge is gained about driving cycles and emissions.

Another possible advantage of this method is that air/fuel ratio also can be continuously recorded. This may simplify data analysis by allowing the analysis to concentrate on open-loop rather than closed-loop operation. Based on discussions, manufacturers apparently attempt to maintain closed-loop operation through most of the FTP. During closed-loop operation, emissions are minimized. However, open-loop or closed-loop operation may not be an appropriate measure of driving pattern, since the mode of operation depends on vehicle technology.

**Disadvantages**

The primary disadvantage of instrumenting vehicles is the representativeness of the data collected. As vehicle procurement programs have discovered, a majority of vehicle owners do not positively respond to procurement requests. Rejection rates often exceed 70 percent. This raises concerns over the representativeness of the vehicle owners that do respond. Vehicles in EPA's emission factor program typically show much less tampering than the overall vehicle population, which implies that these people tend to be "do-gooders." Accordingly, the same people may be easier on the vehicles than the average vehicle owner or the more aggressive vehicle owner. Note that the issue is fleet emissions, which often are determined by a small percentage of the overall vehicle population. Therefore, if motorists with aggressive driving behavior are not included in the study, the results may fail to indicate a significant cause of excess emissions due to off-FTP driving conditions. To reduce the impact of participation refusals, considerable effort would need to be made to sample representatively and replace refusals with the same type of driver but who is willing to participate.

Another related issue concerns the representativeness of the vehicles that are procured for the program. The many-parameter type of monitoring discussed above would best be performed on late-model vehicles, where most of the parameters can be pulled off the on-board computer. Owners of late-model vehicles may have significantly different driving behaviors than owners of older vehicles. It is likely they may be easier on their vehicles and, accordingly, may encounter less off-FTP operation. To avoid measurements on only late-model vehicles, we favor the measurement of just a few parameters (speed, manifold vacuum) which can be monitored easily on any technology vehicle. Another advantage of the few-parameter approach is that the data collection equipment can be installed quickly. The relationship between emissions and driving can more appropriately and be better measured in a study separate from this driving pattern study.

The above concerns with instrumented vehicles most likely apply more to driving on moderate or uncongested roads rather than to congested roads. On congested roads and in parking lots, driving patterns more likely are influenced by the driving behavior of nearby motorists and less by individual preference.

Other disadvantages of obtaining continuous data from instrumented vehicles are listed below:

- **The estimated cost to procure and instrument vehicles is high;**
- **Large quantities of data are generated by this method, which makes data analysis complex;**
- **This method requires a high-capacity storage medium and/or frequent off-loading of data; and**
- **Data recovery requires personnel involved in the study.**

Note that there are alternatives to the traditional use of an onboard data acquisition device with hard disk drive. Datalinks by radio or mobile telephone to a central computer are also possibilities that may be attractive.

## 4.2 Method #2--Instrument Vehicles to Obtain Summarized Data

This method is similar to Method #1, except that it involves recording summarized data rather than continuous data. In this case, key observables such as acceleration rates, speed, load, coolant temperature, etc., are logged into pre-defined bins. For example, a data logger may create histograms of different acceleration rates. The histograms are continuously updated as the vehicle is being driven, but the memory requirements of the data recording system usually do not grow.

Data loggers are currently available to continuously update histograms describing different parameters. Some of these data loggers can maintain both continuous records of data as well as histograms. Data loggers can be programmed to maintain histograms describing the overall driving and continuous records of certain episodes, such as times the vehicle is operating open-loop. The cost for a data logger that only maintains histograms is much less than one that maintains both continuous and histogram data.

**Advantages**

Method #2 has many of the same advantages as Method #1. Most notably, Method #2 accurately represents the vehicle being studied; is able to monitor all vehicle operation including cold starts, hot starts, and trip end; provides good information on engine load if manifold pressure and throttle position are recorded; provides good information on percent of time in off-FTP operation if air/fuel is being monitored; and records data in machine-readable form (i.e., no key punching is necessary).

Method #2 has some inherent advantages over Method #1. The most significant advantage is that data analysis is greatly simplified, because the data are essentially processed on board the vehicle. In addition, data does not need to be retrieved as frequently as Method #1. In fact, it is conceivable that data recovery can be done by the vehicle owner. In addition, as mentioned earlier, histogram data loggers generally are less expensive than continuous data loggers.

**Disadvantages**

Method #2 shares many of the same disadvantages with Method #1. In particular, concerns are raised over the representativeness of the owners and/or the vehicles being procured for testing. Some of these concerns are partially alleviated if the equipment can be installed quickly and is not too obtrusive. However, it is still likely that certain segments of the population will refuse to have their vehicles instrumented. Appropriate selection of study participants can be used to minimize the bias produced.

In addition to the problems shared with Method #1 over vehicle procurement, Method #2 has some additional disadvantages. The most significant problem with recording summarized data versus continuous data is that there is no chance to reanalyze the data. This means that correct observables must be chosen before the study. Therefore, the key parameters affecting emissions must be identified before the instruments can be installed on the vehicles.

An example will illustrate potential problems with this approach. Suppose that engine load is recorded onto histograms and the analysis of the data indicates that full-throttle engine operation is important. Suppose, however, that the duration of full-throttle accelerations are not recorded. Thus it would be difficult to describe how long full-throttle operation must be monitored during the revised emission test procedure. Requiring that full-throttle acceleration be monitored for an excessively long period of time creates problems for the vehicle manufacturers in control system design, because methods must be developed to prevent catalysts from overheating and/or excessive engine wear during full-throttle operation. However, if it is determined that these episodes generally are very short, EPA can devise a test procedure involving full-throttle operation that does not greatly limit design options or increase emission control system cost for the automobile manufacturers.

Identifying cases of the classic "foot-pumper" would be another example of the difficulties associated with the using histogram data loggers. Unless the data logger is programmed in advance to recognize patterns of frequent on and off throttle operation, these cases will not be identified with this approach. The data logger might pick-up a foot-pumper from the vehicle speed data. However, usually bin widths would be set too wide to detect such small changes in speed. This may be a significant problem if these types of driving are important contributors to off-FTP emissions.

## 4.3 Method #3--Perform Chase Car Surveys

As opposed to instrumenting vehicles, driving characteristics can be determined by using chase cars to follow motorists over pre-determined paths. The chase car is instrumented so that it can keep continuous traces of speed versus time of the vehicle being followed. Transportation models typically are used to estimate the traffic intensity between zones in the city. A variety of chase car routes are chosen so that most driving conditions are encountered. The chase car tends to follow only one vehicle on the route, changing to other vehicles only if that particular vehicle exits the route.

Sierra Research is in the process of developing significant enhancements to the chase car technique to help overcome some of its shortcomings. In particular, they are funding the development of an infrared laser device that will accurately measure the differential between the speeds of the chase car and the vehicle being followed. This eliminates the need to exactly mimic the speed of the target vehicle. Other enhancements include using multi-channel recorders to allow the occupants of the chase vehicle to record parameters describing the type of vehicle being chased, road conditions, and other factors that will be useful in analyzing the data.

**Advantages**

The primary advantage of using chase cars is that motorists are participating in a study without being aware of it. Consequently, the driving of all types of drivers, not just a subset of the drivers that might be willing to participate in a study, can be characterized. In addition, chase cars are able to follow all types of vehicles, so any interaction between vehicle type and driving pattern can be identified.

Chase cars also are able to track the driving characteristics of a larger number of vehicles, although day-to-day variations in individual vehicle characteristics are not possible to determine.

Other significant advantages of using chase cars are listed below:

- **Provides instantaneous speeds on a second-by-second basis;**
- **Is able to monitor most accelerations on the target vehicle;**
- **Time to begin data collection is short once the chase car has been instrumented;**
- **Data recovery is simpler than in instrumented vehicles, because it is concentrated on one vehicle; and**
- **Like instrumented vehicles with continuous recording, the data can be analyzed in several ways, and the data analysis technique can be changed as new information is generated about important parameters.**

**Disadvantages**

The infrared speed tracking system being developed by Sierra Research will eliminate one of the major disadvantages of chase cars, that is, the inability to accurately determine the speeds and accelerations of the target vehicle. However, other disadvantages remain.

The most significant disadvantage of chase cars is that they are unable to monitor manifold pressure, and throttle position. Consequently, engine load and off-FTP operation cannot be directly determined. Engine load can be inferred based on the type of vehicle and the observed acceleration, but there is uncertainty on the actual load. For example, a manual transmission car, operating under full load in a high gear, could experience the same acceleration as the same vehicle under part load in a lower gear. Certainly the emission characteristics would be different under these two conditions.

Another significant disadvantage of chase cars is that they are probably are unable to detect cycling of vehicle speed due to driving characteristics such a pumping of the accelerator. As previously mentioned, these types of driving behavior may affect emissions.

Other disadvantages of chase cars are listed below:

- **The chase car is unable to determine soak times, being able to follow the vehicle only when it is moving.**

- **The chase car does not provide an accurate indication of vehicle operation in the cold-start or warm-start mode.**

- **The chase car generates large quantities of data that may be difficult to process, particularly if the chase vehicle has to switch target vehicles several times during a trip.**

- **Selection of the chase car routes may result in certain routes being neglected that may have a disproportionate impact on emissions.** For example, a road system that has a lot of stop-and-go driving due to stop signs and/or traffic could generate more emissions than an equal length system more conducive to steady-state operation. If the former road system is not included in the survey, then this type of driving pattern may be under-represented.

- **There may be an unintentional bias in selecting the target vehicles, which may influence study results.** This concern can be partially alleviated by well-defined methods of selecting the vehicles and/or data analysis techniques to normalize the data based upon expected vehicle population.

## 4.4 Method #4--Use Vehicle Diaries

Vehicle diaries have been used in the past to generate statistics about average trip length, miles travelled per day, number of trips performed per day, when trips occur, and lengths of soak periods. Currently, several surveys of this type are in progress to collect more data on trip characteristics.

### Advantages

In addition to providing the statistics discussed above (average trip length, miles travelled per day, number of trips per day, soak times, etc.), diaries can provide information on average speeds. Other advantages of diaries are listed below:

- Does not require installation of data logging equipment.
- Permits different data analysis techniques.
- Does not require high capacity storage medium.
- Data recovery does not require personnel at the vehicle.

### Disadvantages

The primary disadvantage of diaries is that they do not provide specific data on maximum speeds, accelerations, load, and other parameters important in the characterization of driving patterns. Other disadvantages are listed below:

- This method generates large quantities of data that must be keypunched or manually entered into a computer system.
- Procurement of participants may introduce bias into the sample.
- Drivers may neglect to accurately record data on all trips.

## 4.5 Method #5--Make External Observations With Stationary Observers

Stationary observers can record data on vehicle driving patterns. Sierra Research is currently using this method to characterize trip ends and trip beginnings. Observers are being positioned in residential neighborhoods to record data on driving characteristics immediately following engine start-up. Observers also are being positioned in parking lots and other likely trip end locations to characterize vehicle driving at the end of the trip. Data collected in this manner can complement chase car and other data, and help characterize the complete spectrum of driving.

External observations also can be used to characterize driving behavior from points along a trip length. For example, observers with radar guns or with the infrared laser ranging device discussed previously under chase cars, could characterize speeds and accelerations as vehicles enter on-ramps.

Other methods of performing external observations include using helicopters or airplanes to make aerial observations. However, these methods probably are not feasible to characterize speeds and accelerations, although they could help characterize vehicle travel in the transportation system.

**Advantages**

The primary advantage of external observations is that they provide data on several different types of vehicles and drivers. As with the case of chase car surveys, this method is not constrained by possible procurement problems. All vehicles that are visible from the street can be surveyed.

**Disadvantages**

The primary disadvantage of external observations is that they are limited to characterizing vehicle operation within the line of sight of the observer. Another significant disadvantage is the inability to monitor engine loads, particularly during key modes, such as cold starts.

Other disadvantages of external observations are listed below:

- This method requires information on trip origins and trip ends, so that observers can be placed in representative sites;
- Positioning observers in residential neighborhoods triggers suspicion by residents and can possibly lead to police calls; and
- This method cannot be used to characterize vehicle travel throughout the whole trip.

## 4.6 Comparison of Different Approaches and Recommendations for the Approach to be Used in the Driving Pattern Study

Table 4-1 summarizes positive and negative features of each of the five methods to collect data for purposes of evaluating and revising the FTP. The features have been broken down into three general areas:

# Table 4-1

## Evaluation of Measurement Techniques

| | Instrumented Private Car | DataLogger on Private Car | Driving Diary | Chase Car | Stationary Observer |
|---|---|---|---|---|---|
| SOURCES OF BIAS | | | | | |
| Driver does not know he is being monitored | - | - | - | + | + |
| Representative of vehicle population | - | - | - | + | + |
| Representative of drivers | - | - | - | + | + |
| Nonintrusive installation of data logging equipment | - | - | + | + | + |
| Representative of all types of trip segments | + | + | + | - | - |
| TECHNICAL | | | | | |
| Follows each car all the time - moving or not | + | + | - | - | - |
| Contains high frequency information | + | P | - | + | - |
| Measures average speeds | + | P | + | + | - |
| Measures instantaneous speeds | + | P | - | + | - |
| Measures accelerations | + | P | - | + | - |
| Measures number of cold starts | + | P | + | - | + |
| Measures during cold starts | + | P | - | - | - |
| Measures number of warm starts | + | P | + | - | + |
| Measures during warm starts | + | P | - | - | - |
| Measures distance travelled | + | P | + | - | - |
| Contains load information | + | - | - | - | - |
| Permits various data analysis techniques | + | - | + | + | + |
| Correct observables not needed at beginning of study | + | - | + | + | + |
| Generates small quantity of data | - | + | - | - | - |
| Can measure drive train operation | + | - | - | - | - |
| COST | | | | | |
| Low procurement cost | - | - | - | + | + |
| Low installation cost per car | - | - | + | + | + |
| High capacity storage medium not required | - | + | + | - | + |
| Data recovery does not require personnel at vehicle | - | - | + | + | - |
| Does not require data keypunching | + | + | - | + | - |

P = Measureable if pre-processor is programmed appropriately

- Sources of bias
- The technical features of the method? (For example, frequency of data collection, parameters monitored, and quantity of data.)
- Cost of the technique (For example, installation cost, vehicle procurement cost, data recovery costs).

A review of Table 4-1 indicates that no single technique is without significant drawbacks. Instrumenting private vehicles has the advantage of being able to collect detailed data on different parameters important in driving pattern characterization, but there are significant concerns over the bias of the sample. Chase car surveys can collect much driving information without the knowledge of the target vehicle but still must deal with appropriate sampling techniques and are unable to record some of the significant parameters in driving pattern characterization, such as engine load. Chase cars are also not able to record data on vehicle operation during the cold start modes, hot start modes, and trip ends. Diary surveys provide good information on trip characteristics, but no information on acceleration, load, high frequency variables, and other key parameters important to vehicle emissions. External observations of trip beginnings and trip ends may provide information on an unbiased sample, but the type of data that can be collected is very limited.

No single approach appears capable of addressing all the needs of a driving pattern survey. The complete picture of driving behavior can be seen using data obtained from a combination study using three techniques. Radian recommends that:

- Private cars should be instrumented to collect continuous data on vehicle speed and engine load parameters;
- Chase cars should be used along representatively selected segments to characterize speed versus time history, including accelerations, of randomly selected vehicles; and

- Existing diary data should be analyzed to better characterize soak times, trip lengths, and possibly average speeds. (A recommendation is not being made to collect new diary data as part of this driving pattern study.)

# 5.0 SURVEY SITE SELECTION AND ELIMINATION OF BIAS

For the implementation of the instrumented private car and chase car studies, it is important to consider the elimination of bias and criteria for selection of survey site.

## 5.1 Elimination of Bias

There exists considerable potential for the collection of biased data in both the instrumented car survey and the chase car survey. Considerable effort needs to be spent trying to minimize the bias. The reason for this is at the conclusion of each of the studies, the results from the studies will be compared and combined to obtain the overall picture of driving patterns. If a considerable degree of bias is present in either or both of the studies, then the comparison will show that they do not agree. At that point it will be necessary to resolve the differences either by throwing out data or by altering data so that the characteristics of the driving patterns obtained from the two studies are consistent.

In the discussions below, the instrumented private car and chase car studies are considered for sources of bias and techniques which may be used to try to eliminate bias.

### 5.1.1 Instrumented Private Vehicles

For the instrumented private car study, bias may be introduced by two types of driver behavior: 1) some drivers will refuse to participate in the study; and 2) knowledge that their car is instrumented will affect their driving.

People who are willing to let their private cars be instrumented may be a subset of the driving public that has a significantly different driving behavior pattern than the entire driving population. For example, it could be expected that young drivers driving sporty vehicles would have a higher refusal rate than older drivers driving sedans. *Demonstration that the owners of instrumented vehicles have the same demographic* description as the population as a whole is not sufficient for guaranteeing that the driving behavior of the drivers of instrumented vehicles is the same as the driving behavior of the entire population.

Several statistical and operational techniques can be used to try to eliminate this bias. Either random sampling or stratified random sampling techniques can be used.

Stratified random sampling involves breaking the drivers into demographic descriptions which are perceived to be related to their driving behavior. Such demographic descriptors as driver's age, sex, marital status, and vehicle descriptors as power/weight ratio, sedan versus sport car, and type of transmission can be used to describe the different strata which need to be sampled. The strata would then be filled with the number of participants which is proportional to the entire population.

A random sampling technique may be most easily implemented by sampling on a centralized inspection and maintenance lane. With this technique, the driver of every hundredth car having his car inspected would be asked to participate in the test program. The I/M lanes to be sampled would be randomly chosen across the city so that different socio-economic strata could be covered. A strategy would be needed to deal with bias caused by drivers who refuse to participate. Demographic data of those who refuse may be used to identify other drivers from the same stratum. It may also be possible to use the description of the vehicle as a surrogate descriptor of the driver. For example, if a young driver who is driving a red sports car refuses to participate in the program, then another young driver who is driving a red sports car could be requested to participate even though he is not the hundredth person getting his car inspected.

It is possible that the knowledge that a vehicle is instrumented will affect the way the driver drives. One way to reduce the potential for this type of bias is to tell the participant that the study involves something other than driving patterns or to not tell the driver the complete story of the study. For example, the driver may be told that the study involves the characterization of the vehicle emissions. It may be advantageous to provide a dummy sensor which is placed in the tailpipe to confirm the driver's belief about what is being measured by the instrument on the vehicle. There is a possibility of legal complications in deliberately misleading the driver of the vehicle.

It may also be advantageous to use a follow-up interview after the data has been collected from each vehicle to determine if the driver has changed his driving habits during the study, if he went out of town on a long trip, or if he had mechanical problems with his car.

### 5.1.2 Chase Car Surveys

Biases can be encountered in the chase car driving pattern measurement technique. The vehicles which are difficult to follow will tend to be under-represented in the data that is obtained using a chase car. Thus, a vehicle which drives fast and changes lanes quickly, weaving in and out of traffic, may be under-represented simply because the chase car has difficulty following the vehicle.

An urban transportation planning system (UTPS) model will be used to determine where private vehicles should be chased. Apparently, these models describe primarily interzonal trips. Specifically, they count the trips between city zones.

However, the precise path which vehicles take to move from one zone to the other is not part of the UTPS. In addition, trips within a zone, so-called intrazonal trips, are not described at all by the UTPS models. Accordingly, random sampling techniques will need to be developed to choose the interzonal trip paths and intrazonal trip paths which will be monitored.

In the chase car technique, as it is proposed, target vehicles will be monitored until they turn off the trip path. At that point, the next target vehicle needs to randomly be chosen.

## 5.2 Definition of Most Appropriate Survey Site

Desirable characteristics of the survey sites should be considered when choosing the city which will be used for the measurement of driving patterns. These are discussed below.

It is appropriate to use an emissions non-attainment area for the study. However, the question arises whether ozone non-attainment areas, CO non-attainment areas, or areas in which both are not attained should be considered. We do not see any reason why either type of non-attainment area which is surveyed would affect the driving pattern behavior of the vehicle.

From a practical point of view, the survey site which has centralized I/M would make the procurement of instrumented vehicles easier. For the chase car study, a survey site with a good urban transportation planning system model is required.

The terrain and altitude of the survey site will have an affect on the way the vehicles are driven. Since most vehicles are at low altitude, it would seem appropriate that low altitude survey sites are most reasonable. Since the presence of many steep hills can affect vehicle driving patterns, and most large cities are relatively flat, it is appropriate to chose a city which is relatively flat.

The presence of precipitation on the road most likely affects driving patterns, so cities which are expected to have a large amount of precipitation during the period of the study, should be avoided.

The characteristics of the traffic and road systems of the survey site will greatly affect the results of this study. Driving characteristics of a city which has congested traffic will be significantly different from a city which has relatively open traffic. Trips in large, spread out cities will tend to be longer than those in small, compact cities. For example, downtown Boston would have different driving patterns than Los Angeles.

A list of the non-attainment areas within the continental United States that have centralized I/M programs is shown in Table 5-1. The table contains information about the I/M program, the altitude, and the precipitation in these 25 areas. This information along with other information specific to the collection of data by the chase car technique can be considered to select candidate cities for the measurement of vehicle driving patterns.

All 25 areas use centralized I/M programs; however, only 20 use centralized I/M exclusively. For example, in New Jersey vehicles may be inspected at the centralized state station, or for a higher fee they may be inspected at decentralized stations. While most vehicles go to the state stations, it is possible that the vehicles that are inspected at the decentralized stations are driven differently than those that are inspected at the centralized stations. Consequently, the five areas that have a combination of centralized and decentralized I/M (New Jersey, Washington DC, Jacksonville FL, Miami FL, Tampa FL) are less attractive than those that have only

# TABLE 5-1

Attributes of Non-Attainment Areas with Centralized I/M Programs
for OCT NOV DEC JAN FEB

| | Model Years of Light Duty Vehicles Tested for Emissions | I/M Program Type (C = Centralized) (D = Decentralized) | Altitude (feet) | Average Per Cent of Days With > 0.01 Inch Precipitation (%) | Average Monthly Precipitation (inches) | Average Number of Days With > 1 Inch Snow (days) (OCT NOV DEC JAN FEB) | Comments |
|---|---|---|---|---|---|---|---|
| **STATES** | | | | | | | |
| Connecticut (e.g. Hartford) | 68+ | C | 169 | 36 | 3.7 | 0 1 4 3 3 | Frequent snow |
| Delaware (e.g. Wilmington) | 68+ | C | 74 | 32 | 3.2 | 0 1 1 2 2 | * |
| New Jersey | All | C + D | 160 | 34 | 3.4 | 0 0 2 2 2 | Partly decentralized I/M |
| **METROPOLITAN AREAS** | | | | | | | |
| Baltimore MD | 79+ | C | 148 | 32 | 3.1 | 0 0 1 2 2 | * |
| Washington suburbs MD | 79+ | C | 10 | 32 | 2.9 | 0 0 1 2 1 | Suburbs |
| Washington DC | All | C + D | 10 | 32 | 2.9 | 0 0 1 2 1 | Partly decentralized I/M |
| Jacksonville FL | 75+ | C + D | 26 | 25 | 2.9 | 0 0 0 0 0 | Partly decentralized I/M |
| Miami FL | 75+ | C + D | 7 | 28 | 3.2 | 0 0 0 0 0 | Partly decentralized I/M |
| Tampa FL | 75+ | C + D | 19 | 20 | 2.3 | 0 0 0 0 0 | Partly decentralized I/M |
| Memphis TN | All | C | 258 | 30 | 4.1 | 0 0 1 1 1 | * |
| Nashville TN | 79+ | C | 590 | 34 | 3.8 | 0 0 1 1 1 | * |
| Cleveland OH | 75+ | C | 777 | 46 | 2.6 | 0 2 4 4 4 | Frequent precip, frequent snow |
| Louisville KY | All | C | 477 | 35 | 3.2 | 0 0 1 2 1 | * |
| Louisville suburbs IN | 76+ | C | 477 | 35 | 3.2 | 0 0 1 2 1 | Suburbs |
| Chicago suburbs IN | 76+ | C | 801 | 34 | 2.4 | 0 1 3 3 3 | Frequent snow |
| Chicago IL | 68+ | C | 658 | 32 | 1.9 | 0 1 3 3 3 | Frequent snow |
| E.St.Louis IL | 68+ | C | 535 | 30 | 2.2 | 0 1 1 2 2 | Suburbs |
| Milwaukee WI | 76+ | C | 672 | 33 | 1.8 | 0 1 3 4 3 | Frequent snow |
| Minneapolis MN | 76+ | C | 834 | 22 | 1.2 | 0 2 3 3 3 | Frequent snow |
| Phoenix AZ | 67+ | C | 1112 | 12 | 0.6 | 0 0 0 0 0 | * |
| Tucson AZ | 67+ | C | 2584 | 13 | 0.8 | 0 1 0 0 0 | Higher altitude |
| Medford OR | 71+ | C | 1298 | 53 | 2.7 | 0 1 1 1 1 | Frequent precip |
| Portland OR | 71+ | C | 21 | 59 | 5.0 | 0 0 1 1 1 | Frequent precip |
| Seattle WA | 68+ | C | 19 | 63 | 5.1 | 0 1 1 2 1 | Frequent precip |
| Spokane WA | 68+ | C | 2357 | 43 | 2.0 | 0 2 5 6 3 | Higher altitude, frequent precip, frequent snow |

centralized inspection. More detailed information about the specific I/M programs used in these five areas might allow some of these areas to remain under consideration.

All of the sites except Tucson AZ and Spokane WA have altitudes below 1300 feet. The higher altitudes of these two cities may cause different driving behavior because vehicles will not respond to driver demands as do the majority of vehicles which are operated at lower altitudes. Also, the terrain of the 25 areas needs to be considered in the final selection of survey sites.

Precipitation can produce differences in measured driving patterns by allowing wheel spin and by inducing drivers to drive more carefully than they would on dry pavement. On the other hand, since wet or snowy roads are part of the environment in which most vehicles are occasionally driven, it is reasonable to measure driving behavior under wet conditions during part of the study. However, because the data in this study will likely be collected in autumn and winter, but the results must be relevant to year-round driving, an excessive number of wet days should be avoided.

Data collection is expected to occur sometime between October 1991 and February 1992. The average precipitation for the months of October through February at each of the 25 areas is given in Table 5-1 in terms of the average percentage of days that have measureable precipitation, the average monthly precipitation in equivalent inches of water, and the monthly average number of days that snowfall is greater than one inch.

Consideration of the percentage of days with precipitation shows that the 18 areas that remain on the list can be broken into three groups: 12-22%, 30-36%, and 43-63%. Those areas with 43-63% of the days which are wet (Cleveland OH, Medford OR, Portland OR, Spokane WA, Seattle WA) should be thrown out.

The amount of precipitation is also shown in the table. Large amounts of rainfall in comparison with small amounts are not expected to be a problem because roads will drain and dry; however, days with snow can be a problem, especially in cold climates, because roads may remain slippery for days after the snowfall. Accordingly, the table also shows the average number of days with snowfall by month. In general, days with snowfall are low in October and November, but are high in December, January, and February. Thus any of the remaining 14 sites could be used if measurements are completed by the end of November; however, if the measurements cannot be completed before December, then the sites with greater than 9 snow days (Connecticut, Chicago suburbs IN, Chicago IL, Milwaukee WI, Spokane WA, Minneapolis MN) are less attractive.

Nine areas remain that are characterized by strictly centralized I/M programs, lower altitudes, less than 36% of the days with precipitation, and less than 7 days snowfall for the five month test period:

Delaware (e.g. Wilmington)
Baltimore MD
Washington suburbs MD
Memphis TN
Nashville TN
Louisville KY
Louisville suburbs IN
E.St.Louis IL
Phoenix AZ

Any of these areas appear to be acceptable for an instrumented private car study. Considerations will be imposed by the chase car study requirements and especially by the need for the existence of an Urban Transportation Planning System.

An additional, although perhaps minor, consideration to be made for either type of study might be the presence of a nearby large city which could attract vehicles from the area of interest and thus increase the amount of interstate driving that would otherwise not be present. Areas with nearby large cities include the suburbs: Washington suburbs MD, Louisville suburbs IN, and E.St.Louis IL. Wilmington DE and Baltimore MD might be expected to be large enough to have driving patterns like cities rather than suburbs even though other large cities are nearby. This would leave in the list:

Wilmington DE
Baltimore MD
Memphis TN
Nashville TN
Louisville KY
Phoenix AZ

Finally, to assist in this study, a city with a local air quality staff which is available and willing to assist is desirable. Several areas of assistance could be used to improve the efficiency of the survey program, and as a result reduce the cost of the measurements. Because they are familiar with the area in which the study will be made, local air quality staff can help coordinate activities with the local I/M authorities, help procure private vehicles for instrumentation, tabulate meteorological data during the measurement program, assist with data handling at the I/M lanes, and help get information from the Urban Tansportation Planning System.

The cost of an instrumented private vehicle measurement program depends on many factors: the driving parameters which are to be recorded, the cost of instrumentation, the number of vehicles to be surveyed, the number of cities to be surveyed, the participation rate of drivers who are solicited, the time required to instrument each car, the amount of time each car will be monitored, losses incurred from instrument breakdown, claims by drivers that their cars were damaged by the instrument, and the extent to which local air quality staff can assist the measurement program. We have estimated to instrument from 50 to 250 private vehicles at each of two cities including data analysis and reporting could cost between $315,000 and $600,000 depending on the makeup of the survey. In most cases, the largest expenses in the different scenarios are the labor and travel costs associated with staff installing and retrieving vehicle data logging equipment.

# 6.0 DRIVING PATTERN DATA ANALYSIS

The analysis of the data obtained in the two driving pattern studies will be used to evaluate the current FTP and potentially be used to develop a new certification test procedure. The analysis of the driving pattern data can be made with a variety of techniques. The two discussed here are summary statistics and signal processing techniques.

## 6.1 Summary Statistics

Summary statistics can be calculated for the data obtained in each of the surveys. This would include the distribution of specific statistics as well as average values. The distribution is important because extreme values of a given statistic may describe the high emission behavior which the FTP currently does not now describe. Distributions of statistics for the survey data can be compared with the statistics for the FTP to get an idea of where the FTP fails to represent the driving of the vehicle population.

The statistics for the same driving mode between the chase car and the instrumented private car studies should be similar. If they are not similar, this is an indication that either of the studies may have bias, in which case, appropriate resolution of the data would need to be made. This would mean that either the data which is considered unusual should be discarded or data should be adjusted so that the results of the two studies will be consistent.

## 6.2 Signal Processing Techniques

All vehicles are driven differently, and yet many similarities exist in the way different vehicles are driven. For example, a vehicle with a large power to weight ratio may be driven differently from one with a small power to weight ratio; a young driver may drive differently than a retired person; and vehicles may be driven differently in congested traffic and in open traffic. On the other hand, all vehicles stop at stoplights, accelerate up to a speed limit, and then stop at the next stoplight; they are usually not driven in the early morning hours and therefore cool down overnight; and during cruises a small amount of speed variation is present.

A more descriptive and more detailed analysis of the driving pattern data can be used to describe these differences and similarities present in the driving pattern data by using signal processing techniques. These techniques use advanced, but standard mathematical tools applied with the guidance of engineering experience to find and describe the speed versus time profiles of vehicle driving patterns in terms of driving pattern descriptors. Thus, the driving patterns of the entire study would be characterized by several descriptors and a distribution of values for each descriptor. The goal of the signal processing analysis would be to seek a set of descriptors which along with appropriate values of each descriptor could completely describe any trip. Thus, a value chosen for each descriptor would be sufficient to define a specific driving cycle which is consistent with the driving patterns measured in the field.

Because signal processing may not be familiar to the reader, it is described briefly below. A small list of books which may introduce the interested to signal processing is included in the references.

Signal processing is the study of sequences of numbers. The driving speed history for an individual vehicle is an example of a signal. Here the numbers represent speed, and the sequence represents equally spaced samples in time. A sequence often also represents sampling in space, for example, in meteorology a pressure field is often represented as a 4-dimensional signal in space and time. The signal processing field has developed tools and techniques for manipulating signals, to better understand the sampling process, noise in the measurements, to extract useful parameters from signals, and to display results.

Signal processing has been applied to many technical areas, such as speech, biomedical engineering, acoustics, radar, sonar, seismology, telecommunications, vibration, and process control. Because of the deep technical interest in these applications, signal processing is a mature field with a solid mathematical foundation, theoretical and applied journals, textbooks, and commercial software and hardware products. The signal processing aspects of vehicle driving pattern analysis are simple and straightforward compared to some of these other applications listed above, and quite a bit could be gained just from applying the basic tools of the field to the driving pattern problem.

To demonstrate one method of applying signal processing analysis to the driving pattern problem, some parallels can be drawn between speech processing and driving pattern analysis. To use speech recognition, a voice waveform is captured as a temporal sequence of sound pressure level samples, signal processing procedures convert the waveform signal to phonemes, words, and eventually to the meaning of the utterance, and then some action is based on this meaning.

Speech recognition is usually accomplished by dividing the low level signal into distinct sections in time, representing the separate phonemes. Then each phoneme is analyzed, and the sequence of phonemes are appended together to form words.

This analysis is very difficult, and the most successful recognition systems use a hybrid approach. Detailed models of the speaking processing and the physics of the vocal chords/mouth cavity are used to help in the dividing into separate phonemes. More basic and general techniques, such as Fourier analysis, Markov processes, adaptive filtering, and artificial neural networks are used to analyze each phoneme.

Just as a speech signal naturally consists of a sequence of phonemes, a driving history consists of a sequence of trip segments, where each segment starts and stops with the vehicle at rest. Different kinds of trip segments (between city blocks, a stretch on an interstate, etc.) correspond to the different phonemes.

So a natural representation for a driving pattern might be as a sequence of segments, with a few parameters (max speed, duration, speed fluctuations, accelerations, etc.) required to describe each one. The signal processing analysis for driving patterns should be much simpler than for speech, but a similar approach should work well.

The model of the speech system is a slowly varying linear system, with just a few parameters required to represent the differences between speakers. In a similar manner, a driving pattern model should be a simple system, requiring few parameters.

Speech synthesis (e.g. automatic reading from text) is an inversion of the analysis task above. The analogous driving pattern task would be generation of typical random driving patterns.

An example of the process used in speech recognition and synthesis is the telephone communications application now being used by AT&T. For essentially all long distance communications, the voice signal is sampled, compressed using digital algorithms and special high-speed dedicated signal processing hardware, and then transmitted. At the receiving end, the compressed digital signal is decoded (again using special hardware) and the analog signal is generated and sent to the telephone receiver. The compression achieved is a factor of 10 to 50, and yet the telephone users can easily recognize the familiar voices of acquaintences.

A variation on this is secure communications, where the compressed digital signals are scrambled before transmission and unscrambled at the receiving end.

Because of the short time between the end of the field testing and the due date of the report, it would be helpful to develop signal processing data analysis procedures using an existing set of data while the new driving pattern data is being collected. This could be performed on the OCS Columbus, Ohio data which contains vehicle speed and temperature data on many vehicle/driver combinations or on the MVMA instrumented car pilot data which will have vehicle speed and several engine operation parameters on a few vehicles. Then, when the data in the driving pattern field studies becomes available in November 1991, the data analysis techniques could be applied to it in a reasonably short period of time. It is expected that the driving descriptors for the OCS data set and the new data set would be the same; the distribution of values for each descriptor will be different.

## 7.0 CERTIFICATION TEST PROCEDURE DEVELOPMENT

The final development of the new certification test procedure or updating of the current FTP will depend on the basis of the new procedure and the format which the new procedure might have. (As discussed in Section 3.1, the certification test procedure may be focused on driving patterns or emission patterns. The test procedure could be developed in a straightforward manner as a direct consequence of the signal processing data analysis technique.) In the discussion below, options for the revised test procedure are discussed.

Several different certification test procedure formats can be envisioned for an updated or new procedure. These might include procedures which are based either on driving patterns or emission patterns. These formats include:

- Current FTP;
- Revised FTP (Bag 4);
- New deterministic cycle;
- Multiple deterministic cycles; and
- Multiple stochastic cycles.

After analysis of the driving pattern data, it may be found that the current FTP is a good representation of today's driving and therefore does not need to be revised. However, the current FTP is believed not to cover the full range of accelerations which are present in the vehicle population. Since in today's technology vehicles, heavy accelerations are known to produce emissions, the FTP may be underestimating the emission potential of today's new vehicles. One approach to correct this situation is to add a Bag 4 to the end of the current FTP. This fourth bag would contain the higher accelerations and other emission features which need to be added to the FTP to make it more representative of actual emission patterns. The driving features which would be included in Bag 4 can not include all of the driving pattern features which would make the FTP representative of driving patterns in the population. If this were done, most of the driving features in Bag 4 would not contribute significantly to emissions produced by the FTP cycle. Since the features which should be included in Bag 4 are based on emissions, it is imperative that the relationship between emissions and driving be known. This would have to be determined in a separate study or be based on existing information.

If the signal processing approach is used to analyze the data, and if the driving pattern descriptors are evaluated for their contributions to emissions, then the current FTP can be evaluated to determine the types of driving features that need to be added to make it more representative of emissions pattern of the vehicle population.

Another approach is to replace the current FTP with a new deterministic cycle. A most likely deterministic cycle could be produced by using a Monte Carlo simulation of the most likely values for each of the descriptors developed in the signal processing analysis of the data. If this new cycle is based on emission patterns, then the most likely cycle will emphasize the high emission driving features of the vehicle population. However, if this cycle is based on driving patterns, then the most likely cycle will not include very much high emission feature content since the test procedure would be representative of population driving.

An alternative approach is to use multiple deterministic cycles. Such a battery of cycles could be used to test the vehicles near the extremes of driving behavior which were measured in the driving pattern study.

Rather than deterministic cycles, which are fixed, multiple stochastic (randomly generated) cycles could be used to certify new vehicles. Such cycles could be generated using a Monte Carlo simulation based on the distribution of values and the descriptors developed from the signal processing analysis of the driving pattern data.

Earlier, this technical note made an anology between driving patterns and speech patterns. Signal processing techniques have successfully been used to recognize speech patterns and to perform the reverse, that is, to synthesize speech from printed text. For the signal processing analysis of driving patterns, the reverse of determining the structure of the underlying random and non-random features of driving patterns is the synthesis of driving cycles which are consistent with the structure of the driving pattern data collected in the field study.

A general example of the driving pattern analysis and the stochastic driving cycle synthesis processes might help clarify this discussion. The goal of the signal processing analysis would be to find an algorithm to break each driving pattern down into a set of functions (descriptors) which is common to all driving and a set of values (e.g. coefficients) for each function that describes the random differences present in driving caused by the many random influences that cause vehicles to be driven differently. At least several functions can be expected in the real set of functions that describe real-world driving patterns. But for the purposes of the example, suppose there are two, A and B. Also, suppose that each of these descriptor functions has only one value, a and b, that is required for each function to make it specific so that a driving pattern can be described. The result of the signal processing analysis might be that each vehicle speed versus time driving pattern, v(t), could be described by:

$$v(t) = A(a) + B(b)$$

In this simple example, the algorithm is simply the sum of the two functions, A and B, when appropriate values of a and b are used. Since the functions are independent of vehicle and driver, it is the a and b which describe the differences in driving behavior. For the driving measured in the driving pattern study, distributions of a and b will be observed. A stochastic cycle could be generated by randomly selecting values of a and b from the distributions and then applying the algorithm discovered in values of a and b from the distributions and then applying the algorithm discovered in the signal processing analysis, in this example, A(a) + B(b).

Randomly generated cycles would have a variety of driving features; the severity of each feature would be randomly selected from the range of severities found in the driving pattern study. For a new vehicle to pass certification, it would have to pass a certain fraction of a certain number of randomly generated driving cycles. A computer program which generates the cycles would be made available to anyone for testing purposes. The fraction of stochastic cycles which must be passed and what determines a pass would have to be decided using statistical and probablistic techniques.

The advantage of using the stochastic approach to develop a driving pattern based test procedure is that the approach would work regardless of the emission control technology, the fuels being used by the vehicles, or the emissions of concern. In addition, the stochastic approach would be effective because the procedure would encourage manufacturers to develop emission control systems which could pass most randomly generated cycles. EPA's testing of vehicles to be certified would be inefficient, but the development of an emission control system would not require the testing of numerous stochastic cycles. In the development of a vehicle emission control system the manufacturer might choose to test the vehicle for only those features where emissions were high. Such a certification test procedure would be good as long as the driving pattern data used to develop the driving pattern descriptors and their distribution of values are good.

Signal Processing Bibliography


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