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Additional Study of Preconditioning Effects and Other IM240 Testing Issues

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Prepared for:

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1. SUMMARY

Under Work Assignment 2-04 of EPA contract #68-C4-0056, Sierra Research, Inc. (Sierra) has performed several tasks related to improving the accuracy and efficiency of the tests conducted under motor vehicle inspection and maintenance (I/M) programs As described below, some of the work performed also resulted in the development of proposed revisions to the test procedures used during the new vehicle certification process

Revised IM240 Preconditioning Procedure - Additional analysis of IM240 preconditioning requirements reinforces the preliminary conclusions of work performed during 1996, which indicated that IM240 testing done in accordance with the current EPA guidance results in the failure of many vehicles that would pass the test with further preconditioning The test data collected during the performance of this Work Assignment also demonstrate that the first 93 second-long "hill" of the IM240 driving cycle is relatively ineffective for preconditioning. To ensure adequate preconditioning in the most efficient manner, the most effective change to the IM240 test procedure would be as follows.

1 The first hill of the IM240 driving cycle should be deleted, and

2 An algorithm should be implemented that determines when the second hill should be repeated based on emissions occurring during certain portions of the driving trace

Detailed criteria for determining when to extend the duration of the test have been developed on a pollutant-specific basis for the full IM240 test. Additional analysis is required to develop an algorithm for the second hill only

Revised Fast-Pass Cutpoints - Under current EPA guidance, a vehicle may pass the IM240 test without having the test run to completion if its emissions are sufficiently low, however, all vehicles are required to run the first 30 seconds of the test The current "fast-pass" cutpoints that apply between second 31 and second 239 are based on an analysis of data collected during the tests of a large sample of vehicles in an IM240 pilot lane The cutpoint at each second is based on the emissions of vehicles that were marginal failures at the end of the full test

Under this Work Assignment, a set of fast-pass cutpoints have been developed using a more rigorous statistical approach Rather than basing the cutpoints on cumulative emissions, consideration has been given to the rate of change in emissions that is occurring by predicting full-cycle emissions from emissions during specific segments of the test. This allows vehicles to be identified and passed that were not adequately preconditioned at the beginning of the test. This new approach, combined with more focus on eliminating false passes, has reduced the frequency of false passes occurring under the current fast-pass cutpoints by 50% while simultaneously reducing the average test time Additional analysis is needed to develop fast-pass cutpoints for testing performed using a shortened version of the IM240 (e g , with the first hill removed)

Speed-Variation/Excursion Criteria - Under the current IM240 test procedures, drivers are required to meet certain criteria specifying the accuracy with which the target speed-time trace is followed A *speed-excursion* criterion controls the deviation from the target trace allowed at any point along the trace, a *speed-variation* criterion limits the cumulative amount of deviation from the target trace over the entire test Under the current speed-excursion criterion, the vehicle speed may vary from the target trace by as much as 5 mph (The speed-excursion criterion requires that the vehicle be within 2 0 mph of the driving trace, but deviations from the trace of ±1 second are also allowed. As a result, when the trace specifies an acceleration rate of 3 mph/s, the allowable speed-variation increases to 5 0 mph) Although the allowable speed-excursion is significant itself, there is no limit to the difference between the target acceleration rate and the actual acceleration rate A limited laboratory testing program indicates that variations in the way a vehicle is driven within the allowable speed range may affect emissions by more than 100%

The current limit on the total amount of speed-variation allowed over the entire IM240 cycle limits the frequency of the instantaneous speed-excursions that occur during the course of the full test, however, the cumulative speed-variation criterion does not apply to fast-pass or fast-fail testing. In addition, our analysis indicates that enormous variations in emissions are still possible within the current speed-variation criterion

We are not recommending a change in the ±2 mph/±1 second speed-excursion criteria that currently apply Practical experience indicates that this range of excursion is necessary for many vehicles However, we are recommending a fundamental change in the speed-variation criterion. First, we are recommending that the cumulative variation allowed during the entire test be changed from a simple statistical measure of speed-variation to the variation in positive kinetic energy (PKE) change Because the power required to drive a vehicle increases exponentially with speed, a speed-variation that occurs at high speed requires more power than the same variation at low speed. Because of this, exhaust emissions are better correlated with PKE variation than speed-variation Second, we are recommending a modified PKE variation criterion be established for tests involving a fast-pass or fast-fail Specific recommendations have been developed for the full IM240 test Further analysis is required to develop speed-variation criteria for shortened versions of the test (e.g , with the removal of the first hill).

Because of the significant variation in exhaust emissions that is possible under the current speed-excursion criteria, we are also recommending that a PKE-based speed-variation criterion be added to the Federal Test Procedure (FTP). This would be effective in eliminating what we believe to be a common practice of driving vehicles on the official test more smoothly than the target trace for the purpose of minimizing emissions It would also be effective in eliminating the concern that poor drivers could cause unrepresentatively high emissions to occur during compliance testing

NOx/Humidity Correction Factor Revisions - Since the early days of the motor vehicle emissions control program, it has been observed that NOx emissions from internal combustion engines are dependent on the temperature and humidity Higher ambient temperatures and/or lower humidity raises the peak combustion temperature, which, in turn, increases NOx formation To account for variations in humidity, the FTP specifies a humidity correction factor Because of the relatively narrow temperature range (68-86°F) over which the official certification test is performed, there is no correction specified for temperature.

Current EPA I/M guidance requires that the humidity correction factor specified in the FTP be applied during I/M testing However, the current guidance states that the maximum ambient temperature used in calculating the correction factor should be 86°F, the maximum temperature allowed during the FTP This limitation was imposed to avoid going outside the temperature range of data set used to develop the humidity correction factor in the first place However, field experience indicates that the 86°F cap on the temperature used to calculate the humidity correction factor is resulting in significant under-estimation of NOx emissions during tests that occur when the actual ambient temperature exceeds 86°F For example, NOx emissions failure rates are lower during the summer in Phoenix, Arizona

Under this Work Assignment, Sierra was required to review the derivation of the currently-specified humidity correction factor and recommend an approach for developing an improved correction factor. Because of the potential significance of the problems we identified with the current correction factor, the level of effort invested in this portion of the Work Assignment went beyond our original plans. Our analysis shows that the current practice of doing NOx corrections based only on humidity differences should be changed Over the wide range of conditions experienced in I/M testing, both temperature and humidity need to be accounted for As an interim solution, we derived a new temperature and humidity correction factor that better matches the original data used to develop the current correction factor Immediate implementation of this new correction factor would significantly reduce the false passes now occurring during high temperature testing. As specified in the Work Plan, we have also developed a proposed approach for developing a more representative correction factor using the large amount of data available from programs using IM240 testing

As in the case of speed-excursions/variations, we recommend that similar changes be made to the correction factor currently contained in the FTP Although a less extreme range of temperature and humidity occur during certification, surveillance, and in-use compliance testing, our analysis indicates that the current NOx correction factor does not represent the best fit to the data from which it was developed More importantly, the current correction factor is based on the tests of vehicles with absolutely no NOx controls. There is serious question as to whether the relationship between NOx, temperature, and humidity for those vehicles is representative of present generation vehicles

2. INTRODUCTION

Background

Under the Clean Air Act Amendments of 1990, metropolitan areas with the most serious air quality problems are required to implement so-called "enhanced" I/M programs. One element of an enhanced program is a more effective test procedure than the simple idle tests used in "basic" I/M programs Two different test procedures for exhaust emissions testing in enhanced programs have been approved by EPA the "IM240" test, and the "Acceleration Simulation Mode" (ASM) test. Both of these procedures have been shown to be capable of separating vehicles with excessive exhaust emissions from other vehicles, however, the accuracy of the test depends on whether tested vehicles have been adequately preconditioned and whether the speed-time profile associated with each test procedure is closely followed With either procedure, the efficiency of the testing process depends on how quickly accurate decisions can be made as to whether a vehicle should pass or fail

Inadequate preconditioning of vehicles prior to testing is a potential cause of inaccurate or inconsistent test results because exhaust emission levels depend on how thoroughly a vehicle has been warmed up Before the vehicle is thoroughly warmed up, high emissions can be caused by air-fuel ratio enrichment or an inactive catalytic converter In addition, increased emissions due to purging of loaded evaporative emissions canisters may also be an issue associated with inadequate preconditioning prior to I/M testing

Inadequate vehicle preconditioning has previously been identified as a cause of false failures in I/M programs Under the current EPA "high-tech" test guidance[1*], IM240 preconditioning procedures are woven into the "two-ways-to-pass" standards. Vehicles that exceed the emissions standards established for the entire 239-second test are passed or failed based on emissions occurring during the last 146 seconds of the test (Phase 2) The separate set of standards that apply to Phase 2 are slightly more stringent For vehicles that initially demonstrate high emissions, the first 93 seconds (Phase 1) of the test are used to precondition the vehicle for the second phase of the test In addition, EPA calls for a "second-chance" test whenever a vehicle fails the initial test by less than 50% of the standard and was in a queue for more than 20 minutes before being tested

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[*] Superscripts denote references listed in Section 9 of this report

Considerable data have already been collected regarding the preconditioning requirements for IM240 testing. During 1996, Sierra conducted an evaluation of this issue using data obtained from a sample of vehicles recruited from IM240 lanes in Phoenix, Arizona, and a laboratory test program at Sierra's facilities in Sacramento [2] Preliminary conclusions from the evaluation are summarized below

1 Most vehicles that have been waiting in a queue for 15-30 minutes prior to testing are not thoroughly warmed up by running Phase 1 of the IM240 test

2 Phase 2 of the IM240 test procedure is more effective for preconditioning than Phase 1

3 Using the current IM240 test procedures, it is estimated that 25% of the vehicles failing the final IM240 standards would pass with further preconditioning.

4 Vehicles that would benefit from further preconditioning can be identified through modal analysis of the emissions recorded during the IM240 test

Based on the above conclusions, two options (A and B) were recommended for changing the current preconditioning procedures·

<u>Option A</u>

1 Retain existing IM240 test procedure and two-ways-to-pass standards.

2 Repeat entire IM240 if.

- Phase 2 emissions failure is marginal, or
- emissions near end of Phase 2 are relatively low; or
- emissions during Phase 2 are significantly lower than during Phase 1.

<u>Option B</u>

1 Eliminate Phase 1 and make initial pass/fail decision based on running only Phase 2

2. Give second-chance test (another Phase 2) for all vehicles that initially fail

3 Give third-chance test if emissions during second-chance test are significantly lower than emissions during initial test

In addition to the false failures caused by inadequate preconditioning, inadequate control over vehicle operation during the IM240 test procedure can contribute to inaccurate results The ability of a driver to follow the IM240 speed-time trace has a significant effect on the emissions recorded during the test To limit this variation in test results, tolerances are applied to driver performance However, measured test-to-test variability indicates that the tolerances specified by EPA are not adequate These tolerances include speed excursion limits within ±2 mph of the target speed within 1 second of any given test time, and a standard error (speed variation tolerance) of ±2 0 mph over the entire drive cycle for all full IM240 tests Within the specified tolerances, it is possible for less skilled drivers to introduce more severe throttle variation by overshooting the target trace while staying within the specified tolerances The variation in emissions can exceed 100% compared to a drive that more precisely conforms with the target trace

More stringent speed *excursion* tolerances on the IM240 driving cycle are not considered practical, but more effective speed *variation* tolerances can be employed, especially for "fast pass" and "fast fail" testing. Currently, there is *no* speed variation tolerance applied to anything other than the full IM240 test. Developing speed variation criteria for variable driving distance is clearly needed to identify when unacceptable speed variability occurs during shortened versions of the IM240 cycle

There are also alternative speed variation criteria that may minimize the variation in emissions while still being feasible for use by minimally trained drivers with a reasonable aptitude for dynamometer driving One alternative criterion is the total Positive Kinetic Energy (PKE) change per mile traveled during the IM240 cycle This criterion proved to be well correlated with throttle variation during previous work performed by Sierra for the EPA Certification Division It may also be possible to adjust actual emissions results based on PKE results or another vehicle power-related parameter to explicitly account for the effect of driver variation on vehicle emissions.

Two other IM240 issues that need to be investigated are the fast-pass phase-in standards and the humidity correction factor formula for NOx emissions contained in EPA's high-tech test guidance The fast-pass standards were developed in 1993 based on emissions data from roughly 3,700 IM240 tests The selected standards represent the tenth-lowest cumulative emissions at each second of the test for all vehicles in the dataset that failed the IM240 using the two-ways-to-pass criteria. These standards need to be reevaluated using additional IM240 test data that have been collected to date to improve the robustness of the analysis, with the objective being to reduce average test times and false passes It also appears that a re-examination of the analytical approach used to set the current fast-pass standards would be of benefit, to determine if an alternate approach could be developed to further minimize both false-pass rates and average test times

Changes in atmospheric humidity can significantly affect vehicle NOx emissions Increased humidity leads to a decrease in the maximum flame temperature in the engine cylinder, which in turn results in a reduction in NOx emissions As part of the Federal Test Procedure (FTP), all NOx emission results are corrected to standard humidity using a correction formula based on Ferrel's Equation The same formula is incorporated into the high-tech test guidance to correct IM240 test results to standard conditions

Because the nonlinearity of the correction formula results in anomalous results at higher temperatures, the test guidance specifies that a temperature of 86°F should be used in the formula whenever the ambient temperature is 86°F or above This temperature cap has, however, resulted in the undercorrecting of test results at high temperatures, such as those experienced in Arizona during the summer months For example, the correction factor for ambient conditions of 85°F and 85% relative humidity is roughly the same as for 95°F and 65% humidity In the latter case, however, the test guidance caps the temperature at 86°F The resulting use of 86°F and 65% humidity produces an incorrect reduction in the correction factor, which in turn improperly lowers reported NOx emission readings This computational error appears to be reflected in the Arizona NOx emissions data, which show a decreased summertime fail rate and lower average emissions The derivation of this formula therefore needs to be reevaluated and improved for temperature above 86°F

Project Scope

Under Work Assignment 2-04 of contract #68-C4-0056, EPA directed Sierra to perform the following tasks

1 Analyze and evaluate procedures to address IM240 false failures due to insufficient preconditioning,

2 Develop optimized speed variation criteria to minimize emission variations due to driver variability;

3 Examine the feasibility of adjusting emission results due to speed variations using a vehicle power-related parameter such as PKE,

4 Reevaluate the fast-pass phase-in cutpoints using existing Arizona data in order to minimize test time, false failures and false passes, and

5. Evaluate the sensitivity and accuracy of the NOx correction factor formula.

To accomplish the above tasks, Sierra undertook and completed several analysis efforts, the results of which are documented in this report. A separate project element involved the design and implementation of an emissions test program at IM240 inspection lanes operated by Gordon-Darby in Phoenix, Arizona. The test program was designed to collect additional emissions data for analysis related to the evaluation of alternate IM240 preconditioning procedures

Organization of the Report

Immediately following this introduction, Section 3 summarizes the previous preconditioning test program conducted for EPA in 1996, and provides details regarding the 1997 Arizona test program and the data collected in that program. Section 4 presents the results of the vehicle preconditioning analysis, while Section 5 discusses the development of revised IM240 fast-pass cutpoints Section 6 details the impact of changes in preconditioning procedures and cutpoints on projected IM240 test times. Section 7 summarizes the results of the assessment of IM240 speed variation criteria, and Section 8 presents an evaluation of the current NOx correction factor formula. Section 9 lists the references that were cited in the report.

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3. DESCRIPTION OF IM240 TEST PROGRAMS

Previous Test Programs

The previous 1996 preconditioning study made use of IM240 data that were collected in a number of different test programs conducted both in Gordon-Darby's I/M lanes in Arizona and in Sierra's emissions laboratory The primary elements of that testing are summarized below.

- *Replicate IM240 Testing* - To better determine whether the full IM240 provides adequate preconditioning, Gordon-Darby ran back-to-back IM240 tests on over 300 vehicles. The vehicles selected for testing were those that passed the start-up emissions standards but failed the final emissions standards, i.e., they would be considered marginal failures under the final emissions standards The selection criteria for this series of tests resulted in vehicles waiting in a queue for 15 to 20 minutes prior to IM240 testing The purpose of this testing was to determine (1) if a single IM240 test adequately preconditioned a vehicle that had been waiting in a queue, and (2) if the information gained in the initial IM240 test could be used to predict whether the vehicle was adequately preconditioned

  To supplement Gordon-Darby's testing, Sierra also conducted replicate IM240 tests on a smaller sample of vehicles under more controlled laboratory conditions. Sierra tested nine different employee-owned 1989 and later model passenger cars and light trucks that were selected to span a wide range of manufacturers, engine sizes, and catalyst locations In Sierra's testing, vehicles were given three back-to-back tests following a more precisely controlled hot soak

- *Replicate Phase 2 Testing* - The results of the replicate IM240 testing indicated that a full IM240 cycle appeared to be adequate for preconditioning purposes Based on these results, another sample of vehicles was recruited and subjected to further testing After the vehicles were tested using the full IM240 cycle, they were soaked for a minimum of 30 minutes and then tested using two Phase 2 portions of the IM240 cycle run back-to-back The purpose of this testing was to determine whether the Phase 2 portion of the IM240 test would be adequate to fully precondition a vehicle that had been soaked while waiting in an I/M lane queue (A positive finding would indicate that reversing the order of the phases in the IM240 test might be a relatively easy way to provide adequate preconditioning during the test) Vehicles for this test program were again selected based on whether they would have failed the final EPA-recommended emission standards during the initial IM240

To supplement Gordon-Darby's testing, Sierra also conducted replicate Phase 2 tests on the same sample of vehicles used for replicate IM240 testing in the laboratory The test sequence involved warming-up each vehicle with an IM240, hot soaking the vehicle for 30 minutes, and then running three Phase 2s in a row

Based on the results of these test programs, Sierra proposed two options to ensure adequate preconditioning for the IM240 test (a) analyze the modal emissions of the initial test to determine if another IM240 is necessary, or (b) eliminate Phase 1 of the test entirely and give a second-chance test to all vehicles that fail the initial Phase 2; a third Phase 2 would be given if emissions during the second test are significantly lower than the first

During the summer of 1997, Gordon-Darby collected additional data to enhance the database needed to evaluate and refine the preconditioning procedures proposed in the 1996 study. The new test programs are described below

New Test Programs

Replicate IM240 Testing - Similar to the replicate IM240 testing conducted for the previous study, this program tested failing vehicles over back-to-back IM240s Vehicles selected for this program were chosen at random, and they had failed the EPA IM240 start-up cutpoints. This is an important distinction between this test program and the previous replicate IM240 testing, which had been based on vehicles failing the final cutpoints but passing the start-up cutpoints (i e , the sample used for the 1996 preconditioning study had been "marginal" failures under the final cutpoints). The test sequence used in this program is shown in Figure 1

A total of 336 vehicles were included in the replicate IM240 testing for this study; the model year distribution of those vehicles is given in Figure 2 As seen in the figure, the sample peaks in the 1984 to 1988 model year range, which is consistent with the failures observed in the state program. Although the failure rate is higher for the older model years, there are fewer of them in the fleet due to normal attrition. Thus, a maximum number of failures is observed in model years that have a moderately high failure rate coupled with a large total number of vehicles In addition, the large increase in the number of failures in the 1984 model year is partially a result of a change in HC cutpoints for light-duty trucks from 7 5 g/mi to 3 2 g/mi

Replicate Phase 2 Testing - The replicate Phase 2 testing performed for this study made use of a slightly revised test protocol compared to the 1996 study The test sequence used

Figure 1

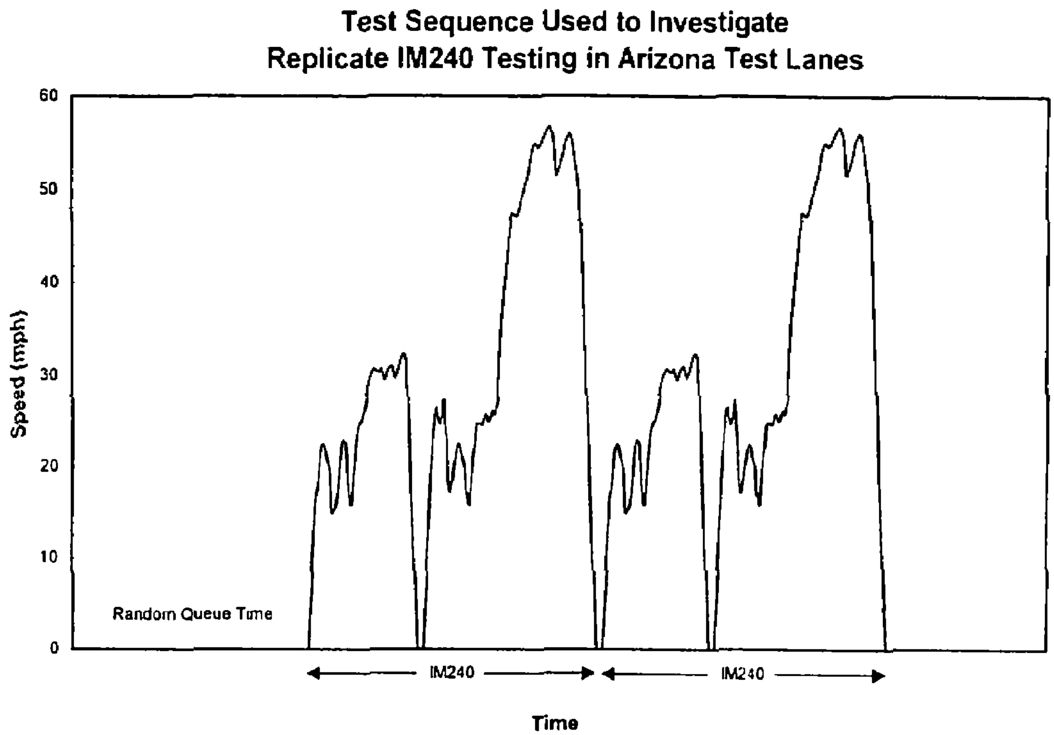
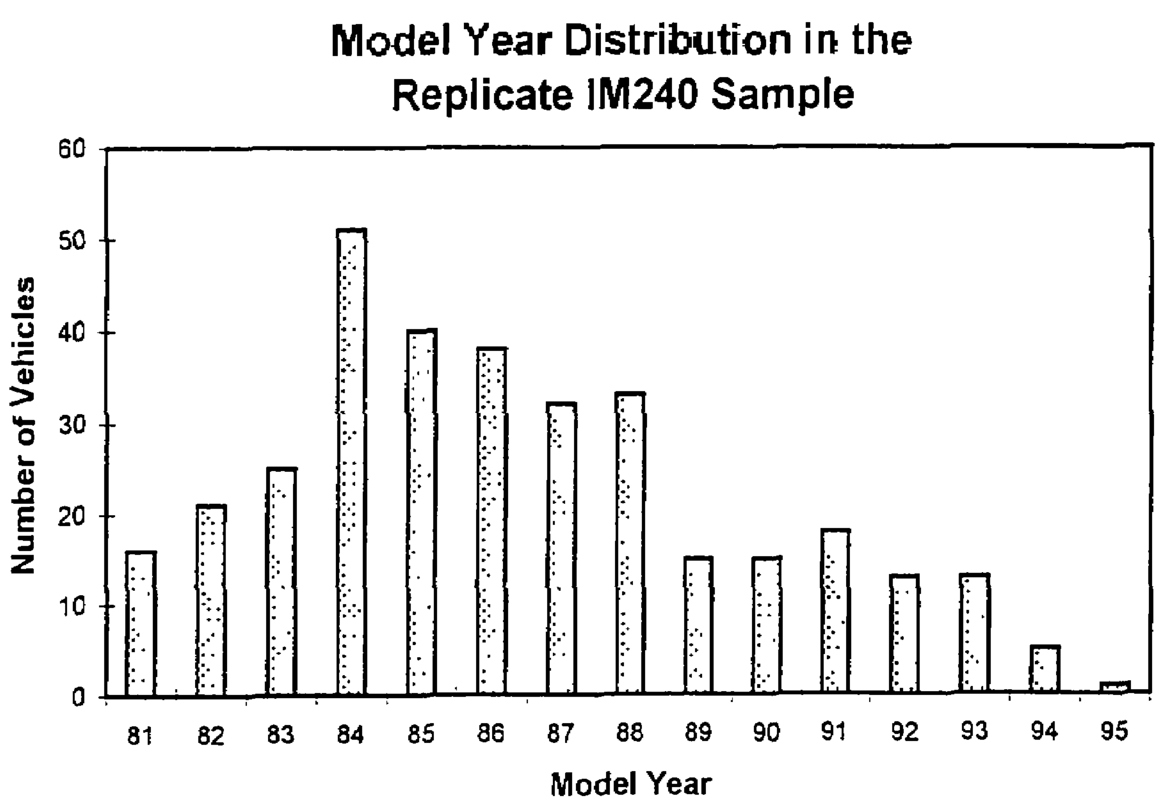


Figure 2



for this subfleet is illustrated in Figure 3, which shows that the vehicles tested in this program were subjected to the following procedure

- 30-minute idle,
- two full IM240 tests,
- 30-minute idle, and
- three Phase 2 IM240 tests

(The Phase 2 portions of the initial IM240s are herein referred to as Phase 2A and Phase 2B; the three Phase 2 tests following the last idle period are referred to as Phase 2C, Phase 2D, and Phase 2E)

The vehicles in this program were selected at random, and both passing and failing vehicles were included in the sample Vehicles were given their official state I/M inspection prior to starting the initial 30-minute idle period Motorists participating in the program received a monetary incentive of $100

A total of 101 vehicles participated in this part of the study, and the model year distribution is illustrated in Figure 4 As observed in that figure, there are more newer vehicles in this sample than in the replicate IM240 sample, which is consistent with the test protocol that called for a completely random sample to be procured.

Figure 3
Test Sequence Used to Investigate Replicate Phase 2 Tests in Arizona Test Lanes

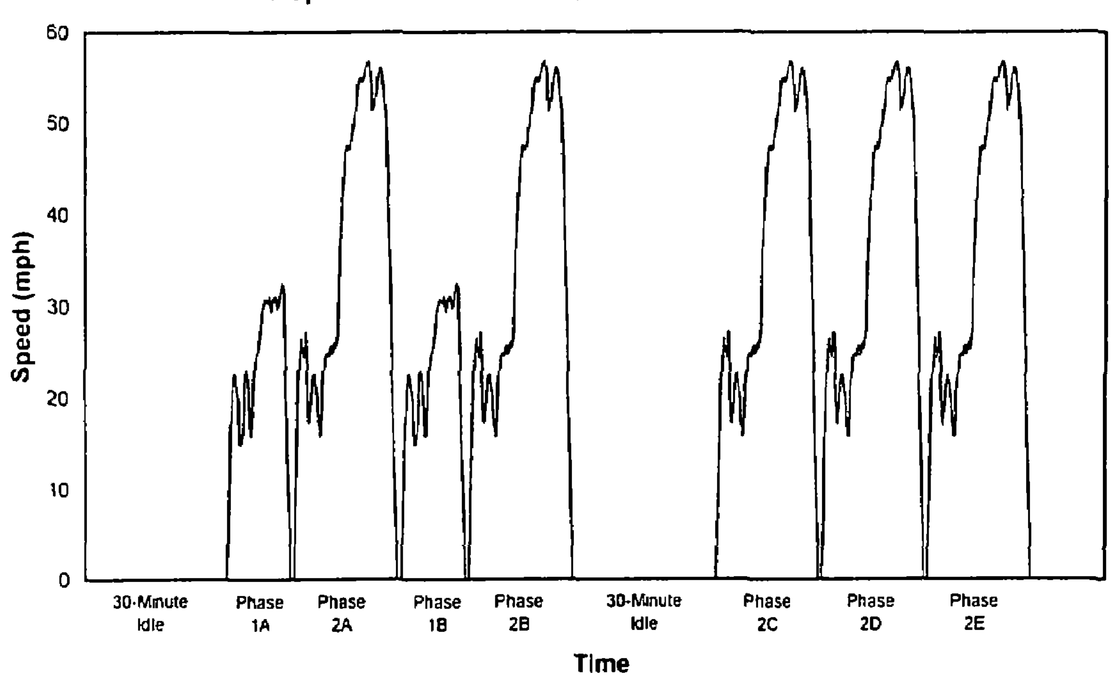
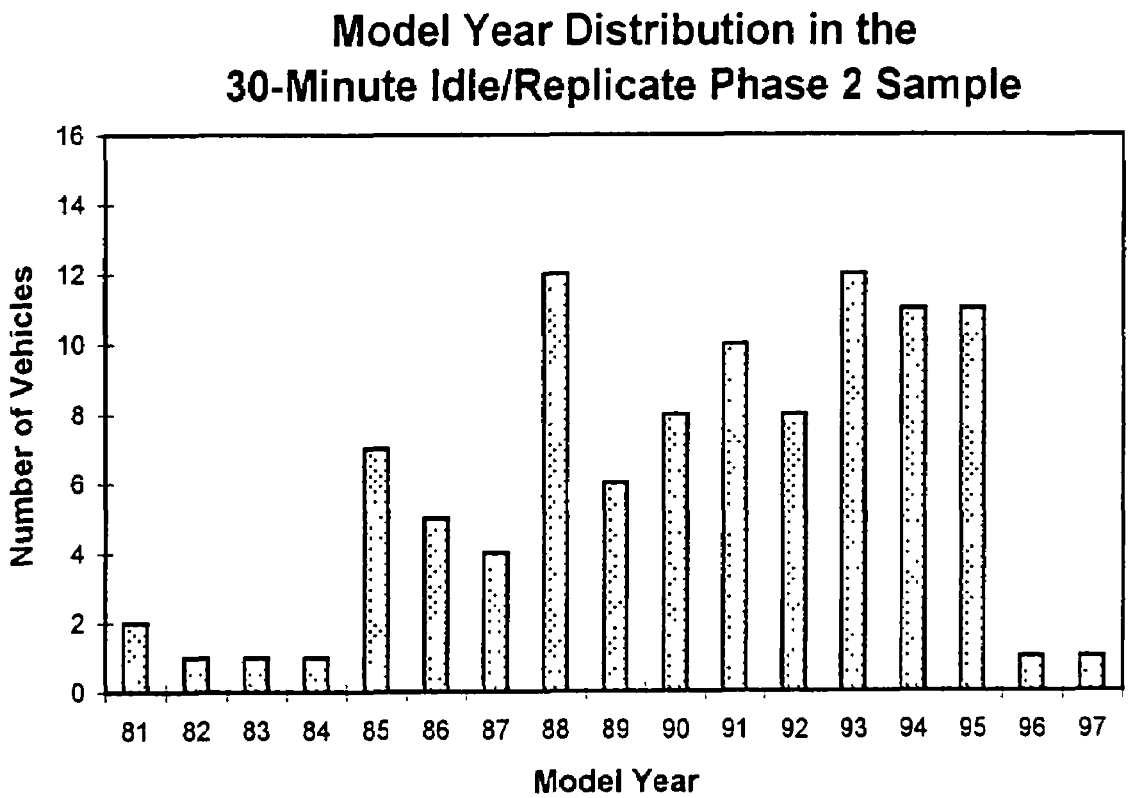


Figure 4


Model Year Distribution in the
30-Minute Idle/Replicate Phase 2 Sample
16
14
12
10
8
6
4
2
0
Number of Vehicles
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
Model Year

4. VEHICLE PRECONDITIONING ANALYSIS

This section of the report presents the analysis of the replicate IM240 data and replicate Phase 2 data collected by Gordon-Darby in its Arizona I/M lanes For ease of comparison to the results from the 1996 preconditioning study, many of the tables and figures in this section follow the same format as the previous report When comparing results between the two studies, however, it must be kept in mind that different vehicle selection criteria were used For example, the replicate IM240 database for the 1996 study was based on vehicles that had failed the final IM240 cutpoints but passed the start-up cutpoints (i e., they were "marginal" failures under the final cutpoints), while the replicate IM240 tests conducted for this study were on vehicles that had failed the start-up standards only Similarly, the replicate Phase 2 testing performed for the 1996 study included only failing vehicles (based on the final cutpoints), whereas the replicate Phase 2 testing for this study was based on a random sample of vehicles (both passing and failing). In addition, the replicate Phase 2 testing in this study used a slightly different, more controlled test protocol than in the 1996 preconditioning study

Analysis of Data from the Replicate IM240 Testing

Table 1 summarizes Gordon-Darby's replicate IM240 results from the 1997 test program. As shown in the table, 19% of the 1981 and later model passenger cars and light trucks failing the initial IM240 test (based on the start-up cutpoints) passed when immediately retested; 6% passed the final cutpoints on the retest after failing the start-up cutpoints on the initial test. In terms of specific pollutants, the impact on NOx was most pronounced in that 27% of the NOx failures passed the start-up NOx standard on the second test, and 9% passed the final NOx standard on the retest The results for HC and CO were similar, with 23% and 20% of the failures going on to pass an immediate retest, and 5% passing the final standards on the retest

Based on the testing conducted for this study, the fraction of vehicles passing an immediate retest under the start-up standards is lower than that observed in the database constructed for the 1996 preconditioning study (19% versus 47%). However, the 1996 study results were based on "marginal" failures (i.e , vehicles passing the start-up standards but failing the final standards) Since the likelihood that a vehicle will pass a retest increases as emission levels get closer to the cutpoint, this is not an unexpected result In fact, in the 1996 study, Sierra estimated that approximately 25% of the final cutpoint failures would pass a retest This is reasonably consistent with the 19% retest

Table 1 Replicate IM240 Test Results in I/M Lanes All 1981 and Later Passenger Cars and Light Trucks Combined (336 Vehicle Sample)					
Pollutant	# Failing 1st IM240 (Start-up Stds)	# Passing 2nd IM240 (Start-up Stds)	% Passing 2nd IM240 (Start-up Stds)	# Passing 2nd IM240 (Final Stds)	% Passing 2nd IM240 (Final Stds)
Any	336	65	19%	20	6%
HC	185	42	23%	9	5%
CO	143	28	20%	7	5%
NOx	146	40	27%	13	9%

passing rate in Table 1 (A detailed analysis of false failure rates as a function of cutpoints is presented later in this section of the report)

<u>Differences Between Passenger Cars and Light Trucks</u> - The replicate IM240 tests in the Arizona I/M lanes were analyzed to determine whether there were any differences between passenger cars and light-duty trucks That evaluation, summarized in Table 2, shows that passenger cars appear to be more sensitive to preconditioning effects than light-duty trucks. This could partially be due to the difference in cutpoint stringency between cars and light trucks under the start-up standards (light-duty trucks have much less stringent IM240 cutpoints than passenger cars under the start-up standards) It is interesting to note, however, that there is a high percentage (34%) of LDT NOx failures that pass on a retest, with nearly 20% passing the final cutpoints after failing the start-up cutpoints

The results presented in Table 2 are slightly inconsistent compared to the 1996 preconditioning study, which showed that passenger cars and light trucks had nearly identical retest pass rates Again, however, this could be a result of differences in vehicle selection criteria between the 1996 and 1997 replicate IM240 test programs

<u>Model Year Range Differences</u> - Table 3 shows how the results for pre-1986 model year vehicles compare to 1986 and later model year vehicles Consistent with the results of the 1996 study, the newer vehicles in the 1997 database appear to be more sensitive to preconditioning than the older vehicles For example, 26% of the 1986 and newer model year vehicles failing the initial IM240 test for HC, CO, or NOx passed the second test. The percentage of failing vehicles passing the second test drops to 12% for the pre-1986 model year vehicles. In addition, the vast majority of vehicles that failed the start-up standards and went on to pass the final standards are from the 1986 and later model year group. This is likely related to the fact that vehicles in the newer model year group have emissions that are closer to the standard than the older vehicles.

Table 2 Replicate IM240 Test Results in I/M Lanes All 1981 and Later Passenger Cars vs. Light Trucks (336 Vehicle Sample)						
Vehicle Type	Pollutant	# Failing 1st IM240 (Start-up Stds)	# Passing 2nd IM240 (Start-up Stds)	% Passing 2nd IM240 (Start-up Stds)	# Passing 2nd IM240 (Final Stds)	% Passing 2nd IM240 (Final Stds)
Passenger Car	Any	253	52	21%	13	5%
	HC	134	35	26%	7	5%
	CO	119	25	21%	7	6%
	NOx	114	29	25%	7	6%
Light-Duty Truck	Any	83	13	16%	7	8%
	HC	51	7	14%	2	4%
	CO	24	3	13%	0	--
	NOx	32	11	34%	6	19%

Table 3 Replicate IM240 Test Results in I/M Lanes Pre-1986 vs. 1986 and Later Model Year (336 Vehicle Sample)						
Model Year	Pollutant	# Failing 1st IM240 (Start-up Stds)	# Passing 2nd IM240 (Start-up Stds)	% Passing 2nd IM240 (Start-up Stds)	# Passing 2nd IM240 (Final Stds)	% Passing 2nd IM240 (Final Stds)
Pre-1986	Any	153	18	12%	0	--
	HC	98	13	13%	0	--
	CO	77	11	14%	2	3%
	NOx	55	11	20%	0	--
1986 and later	Any	183	47	26%	20	11%
	HC	87	29	33%	9	10%
	CO	66	17	26%	5	8%
	NOx	91	29	32%	13	14%

Analysis of Data from the Replicate Phase 2 Testing

As described in Section 3 of this report, vehicles in the replicate Phase 2 sample were subjected to the following test sequence protocol·

- 30-minute idle,
- two full IM240 tests (the Phase 2 portions of these tests will be referred to as Phase 2A and Phase 2B);
- 30-minute idle; and
- three Phase 2 IM240 tests (referred to as Phase 2C, 2D, and 2E)

Vehicles tested in this portion of the study were selected at random and include both passing and failing vehicles A total of 101 vehicles were included in this program, and the results of their replicate IM240 tests are given in Table 4 by vehicle type

Table 4
Number of IM240 Failures for Vehicles Included in the Multiple Phase 2 Testing
Passenger Cars vs. Light-Duty Trucks
(101 Vehicle Sample)

Vehicle Type	Sample Size	Pollutant	Start-Up Standard Failures		Final Standard Failures	
			1st Test	2nd Test	1st Test	2nd Test
Passenger Cars	67	Any	5	4	15	12
		HC	2	1	10	5
		CO	2	2	3	4[a]
		NOx	3	2	9	6
Light-Duty Trucks	34	Any	2	0	9	5
		HC	1	0	7	3
		CO	0	0	2	2
		NOx	1	0	3	2

[a] The increase in CO failures on the second test is a result of two vehicles that failed the second test after passing the first One failing vehicle passed the second test, and two vehicles failed both

Mean Phase 2 Scores - One of the pnmary motivations for this series of tests was to determine the relative effectiveness of the full IM240 versus Phase 2 of the IM240 at preconditioning vehicles that had been waiting in a queue. A simple evaluation that can be performed is to review the mean Phase 2 scores during the replicate IM240s (i e , Phase 2A and 2B) to the mean Phase 2 scores during the replicate Phase 2 testing (i.e., Phase 2C, 2D, and 2E). Similar mean emission rates for Phase 2B and Phase 2D would indicate that a single Phase 2 (i.e , Phase 2C in this case) is as effective as a full IM240 plus a Phase 1 (i.e , the total amount of testing leading up to Phase 2B) at preconditioning a vehicle.

Comparisons of means were made using a t-test for the difference between two means.[3] The null hypothesis in this test is that the two means are identical. From the usual test statistic, the probability that the null hypothesis was correct was found These probabilities are reported below as "p-values" to indicate the statistical strength of the conclusions presented

The mean Phase 2 emission rates of the 101-vehicle sample in the replicate Phase 2 database are summarized in Table 5 Based on the results presented in that table, the following observations are made

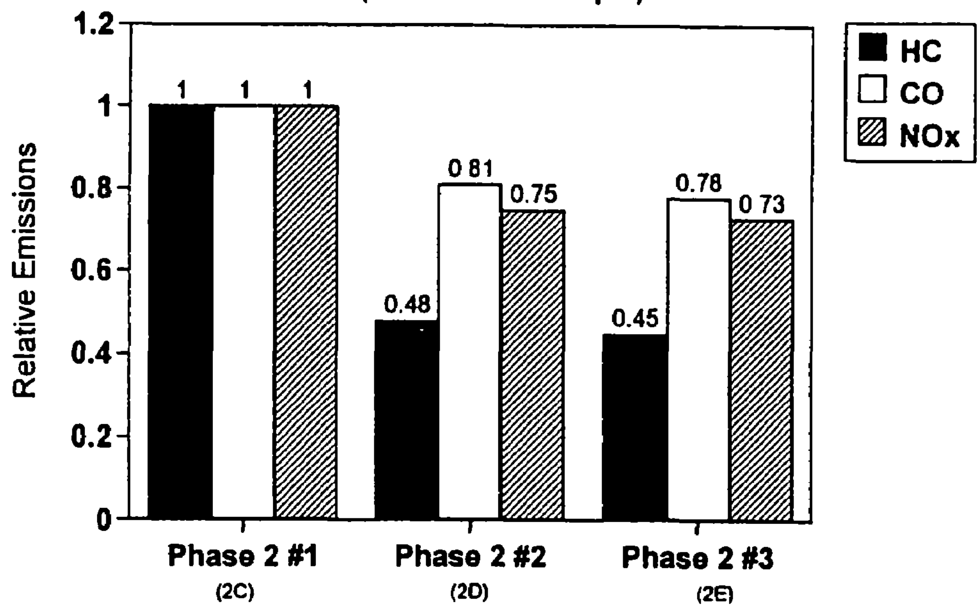
- The results of Phase 2A (which follows the first Phase 1 of the IM240 test) and of Phase 2C (which immediately follows a 30-minute idle period) are significantly different for HC (p-value = 0.014), from this difference, it is clear that Phase 1 of the IM240 provides some degree of preconditioning. However, the HC results in the Phase 2B test are significantly different from the results in the Phase 2A test (p-value = 0 097), this shows that a single Phase 1 is inadequate to fully precondition a vehicle for the sample used here

- The mean emissions from Phase 2B and Phase 2D are nearly identical (The p-values that the 2B and 2D means are the same are 0 994, 0 963, and 0 988 for HC, CO, and NOx, respectively) This leads to the conclusion that a single Phase 2 (i e , Phase 2C in this series of tests), is as effective as a full IM240 plus a Phase 1 (i.e , Phase 1A, Phase 2A, and Phase 1B) at preconditioning a vehicle that has been idling in a queue for 30 minutes. This represents a significant difference in overall preconditioning time – 146 seconds versus 334 seconds

- Based on the results of Phase 2C, 2D, and 2E, only a small degree of additional preconditioning occurs by running a second Phase 2 prior to the final test This additional preconditioning is not statistically significant for the means, the p-values that the 2D and 2E means are the same are 0 712, 0 853, and 0 851 for HC, CO and NOx, respectively This is illustrated in Figure 5, which shows the relative HC, CO, and NOx emissions for the three Phase 2 tests following a 30-minute idle However, as discussed below, some vehicles may need a second Phase 2 preconditioning cycle if there has been a significant engine-off or idle period prior to testing.

Table 5 Mean Emissions Results from Replicate Phase 2 Testing of 101 Vehicles (g/mi)			
Phase	HC	CO	NOx
~~ 30-Minute Idle ~~~~~~~~~~~~~~			
2A	0 51	7 72	1.34
2B	0 36	7.35	1 20
~~ 30-Minute Idle ~~~~~~~~~~~~~~			
2C	0 75	9.16	1.61
2D	0 36	7.43	1 20
2E	0 34	7 11	1.17

Figure 5
Replicate Phase 2-Only Emissions Following a 30-Minute Idle (101 Vehicle Sample)



Comparison of IM240 and Phase 2 Results for IM240 Failing Vehicles - Of considerable interest in this program were the vehicles that failed the first IM240 test following the 30-minute idle period and went on to pass the second test In addition to those vehicles, there were 2 vehicles that passed the final CO cutpoints on the first IM240 test, but failed on the second A summary of the vehicles in the replicate Phase 2 sample that had inconsistent pass/fail results between the first IM240 and the second IM240 (based on the final cutpoints) is shown in Table 6

Table 6

Replicate Phase 2 Test Results for Vehicles with Inconsistent Pass/Fail Scores Between the First IM240 and the Second IM240 Based on EPA's Final IM240 Standards

Hydrocarbon Emission Results

VIN	Test Date	Vehicle Class	Model Year	1st IM240 P/F	2nd IM240 P/F	Composite IM240 (g/mi)			Phase 2 Scores (g/mi)					
						Cutpoint	1st Test	2nd Test	Cutpoint	P2A	P2B	P2C	P2D	P2E
1FABP4034GG124849	970821	LDV	1986	F	P	0 8	1 49	0 61	0 50	0 82	0 61	1 80	0 55	0 49
1FABP62F4JH136083	970812	LDV	1988	F	P	0 8	0 87	0 43	0 50	0 66	0 44	0 85	0 48	0 37
1G1JF31W4K7162806	970819	LDV	1989	F	P	0 8	1 23	0 50	0 50	0 54	0 38	1 29	0 51	0 38
1G6DW51Y3KR704759	970813	LDV	1989	F	P	0 8	1 28	0 42	0 50	0 86	0 46	1 35	0 48	0 47
1GNCS13Z8M2316674	970813	LDT	1991	F	P	1 6	1 63	0 18	1 00	1 06	0 13	1 23	0 13	0 06
1GNER16K2MF110830	970814	LDT	1991	F	P	1 6	2 85	1 48	1 00	2 63	1 35	3 12	1 83	1 21
2P4FH41G6FR354315	970812	LDT	1985	F	P	1 6	1 87	1 49	1 00	1 84	1 56	2 14	1 70	1 87
3GCCW80H1FS916333	970819	LDT	1985	F	P	1 6	1 87	1 32	1 00	1 70	1 33	1 91	1 32	1 34
JHMSZ5327CC134515	970815	LDV	1982	F	P	0 8	0 88	0 69	0 50	0 72	0 63	0 88	0 66	0 64

Carbon Monoxide Emission Results

VIN	Test Date	Vehicle Class	Model Year	1st IM240 P/F	2nd IM240 P/F	Composite IM240 (g/mi)			Phase 2 Scores (g/mi)					
						Cutpoint	1st Test	2nd Test	Cutpoint	P2A	P2B	P2C	P2D	P2E
1G6DW51Y3KR704759	970813	LDV	1989	F	P	15 0	16 87	14 06	12 0	17 40	17 16	18 56	14 99	18 20
JT2MX73E3F0011461	970813	LDV	1985	P	F	15 0	12 02	15 21	12 0	10 39	14 79	10 56	10 14	17 05
1G1BU51H8HX219475	970820	LDV	1987	P	F	15 0	27 42	16 02	12 0	3 62	14 91	30 91	19 04	13 84

NOx Emission Results

VIN	Test Date	Vehicle Class	Model Year	1st IM240 P/F	2nd IM240 P/F	Composite IM240 (g/mi)			Phase 2 Scores (g/mi)					
						Cutpoint	1st Test	2nd Test	Cutpoint	P2A	P2B	P2C	P2D	P2E
4T1SV21EXMU417927	970812	LDV	1991	F	P	2 0	2 05	1 46	2 0	2 22	1 68	2 41	1 52	1 64
JT2MX73E3F0011461	970813	LDV	1985	F	P	2 0	4 73	1 84	2 0	3 88	2 01	5 67	2 00	2 47
1FABP4034GG124849	970821	LDV	1986	F	P	2 0	2 41	1 40	2 0	2 36	1 58	2 03	1 50	1 41
1GNER16K2MF110830	970814	LDT	1991	F	P	2 5	3 89	1 49	2 5	4 21	1 68	5 18	2 35	1 61

For vehicles failing the first IM240 and passing the second, the results presented in Table 6 show a significant decrease in Phase 2D emissions relative to Phase 2C (recall that Phase 2C follows the 30-minute idle period) In some cases, emissions continue to decrease through Phase 2E, which may be needed if a vehicle has been soaked or idled for an extensive length of time Although the Phase 2D scores are not always below the Phase 2 cutpoints established by EPA for the IM240 "two-ways-to-pass" algorithm, in general they are relatively close In some cases, even the third replicate Phase 2 (i e , 2E) has higher emissions than the Phase 2 cutpoint However, the Phase 2 cutpoints developed by EPA can be thought of as "secondary" standards in that the pass/fail decision is also based on the full IM240 score If an I/M program were to adopt the Phase 2 test as the official I/M test, a new set of cutpoints would have to be developed based solely on Phase 2 testing

Two vehicles listed in Table 6 failed the second IM240 for CO after passing the first On one of the vehicles, this appears simply to be a result of test-to-test variability. That vehicle had composite and Phase 2 scores of 12 0/10 4 g/mi on the first IM240 and 15 2/14 8 g/mi on the second (The composite and Phase 2 CO cutpoints for this vehicle are 15.0 g/mi and 12 0 g/mi, respectively) Thus, although the vehicle failed the second test, it was very close to the cutpoint, and the results on the first IM240 were not significantly below the cutpoint. The second vehicle that passed the first IM240 and failed the second had relatively high emissions for the composite IM240 on the first test (27 4 g/mi), but its Phase 2 score was very low (3.6 g/mi) and it passed based on the "two-ways-to-pass" criterion The vehicle failed the second IM240, but its composite score was fairly close to the cutpoint (i e., 16.0 g/mi versus 15 0 g/mi) The Phase 2B, 2C, 2D, and 2E CO emissions for this vehicle were much higher than the Phase 2A results. It is unclear what caused this apparent anomaly

Based on the results of this test program, it is clear that Phase 2 of the IM240 is a much more effective preconditioning cycle than Phase 1 of the IM240 However, from a practical perspective, it is unclear that I/M program managers would be receptive to eliminating the current IM240 in favor of Phase 2. One of the primary concerns related to the current version of the IM240 test is the high-speed operation conducted in Phase 2. (This concern is related to the public's perception that the noisier operation during this part of the test is somehow detrimental to the vehicle.) By maintaining Phase 1, and making use of fast-pass cutpoints, many vehicles pass before Phase 2 is reached, particularly the high-speed portion of that phase

Impact of Cutpoints on False Failures Due to Preconditioning

The scope of work for this work assignment also called for an assessment of how much the current cutpoints could be tightened below the phase-in cutpoints without resulting in an excessive failure rate. In addition, the false failure rate (at various cutpoints) due to preconditioning was to be determined as part of this task

Using the 2% random IM240 sample from the Arizona program, failure rates for 1981 and later model year light-duty vehicles (i.e., passenger cars) were generated under four sets of composite IM240 cutpoints·*

- 0 8 g/mi HC, 15 0 g/mi CO, 2 0 g/mi NOx,
- 1 2 g/mi HC, 20 0 g/mi CO, 2 3 g/mi NOx;
- 1 6 g/mi HC, 25 0 g/mi CO, 2.6 g/mi NOx, and
- 2 0 g/mi HC, 30 0 g/mi CO, 3.0 g/mi NOx.

The first set of cutpoints represents the final IM240 standards for 1983 to 1995 model year light-duty vehicles, and the last set of cutpoints reflects the start-up IM240 standards for 1983 to 1990 model year light-duty vehicles The two sets of standards between the final and start-up standards were chosen to reflect varying levels of stringency. For this analysis, only light-duty vehicles were considered (i e , light-duty trucks were removed from the analysis), and the same standards were applied to all 1981 and later model year vehicles This approach avoided the complications of applying different IM240 standards to vehicles that were certified to essentially the same numerical emission standards The failure rates under the current preconditioning approach are given in Table 7 for the fleet as a whole and for the following model year groups

- 1981 to 1984,
- 1985 to 1990, and
- 1991 and later

As observed in Table 7, going from the 2 0/30/3 0 HC/CO/NOx cutpoints to the 0 8/15/2.0 HC/CO/NOx cutpoints doubles the fleet-wide failure rate, and the difference (in terms of relative differences) is most pronounced for newer model year cars. Table 7 also shows that the impact of tighter cutpoints on failure rates is not linear For example, there is a more pronounced effect in going from 1 2 g/mi HC to 0 8 g/mi HC than any of the other HC cutpoint increments This indicates that it might be worthwhile to consider limiting the HC cutpoints to 1 2 g/mi for older vehicles (i.e., pre-1991) as a trade-off between cutpoint stringency (and resulting failure rates) and emission benefits

* Phase 2 cutpoints were also developed for each set of composite cutpoints, and the "two-ways-to-pass" algorithm was employed in determining pass/fail rates

Table 7
IM240 Failure Rates as a Function of Cutpoint for 1981 and Later Passenger Cars Based on the 2% Random Sample Database (17,000 Vehicle Sample)

Pollutant	Cutpoint (g/mi)	All Vehicles	1981 - 1984 Model Year	1985 - 1990 Model Year	1991+ Model Year
HC/CO/NOx	0.8/15/2 0	32%	80%	41%	6%
	1 2/20/2 3	24%	69%	29%	3%
	1 6/25/2 6	19%	60%	22%	2%
	2 0/30/3 0	15%	51%	16%	1%
HC	0 8	23%	63%	29%	4%
	1 2	15%	48%	18%	2%
	1.6	11%	37%	12%	1%
	2.0	8%	30%	8%	<1%
CO	15	15%	47%	17%	2%
	20	11%	37%	12%	1%
	25	8%	31%	9%	1%
	30	7%	26%	7%	<1%
NOx	2 0	17%	47%	21%	2%
	2.3	13%	39%	15%	1%
	2.6	10%	32%	12%	1%
	3 0	7%	25%	8%	1%

The false failure rates as a result of inadequate preconditioning were also estimated for the cutpoints analyzed above. This was done by first determining the percentage of vehicles in the replicate IM240 databases that passed an immediate retest based on these different cutpoint scenarios.[*] (This is similar to the results presented in Tables 1 to 3) The results

[*] The 1996 and 1997 replicate IM240 databases were combined for this analysis Overall, there were 328 vehicles (that passed the start-up IM240 cutpoints but failed the final IM240 cutpoints) in the 1996 database and 336 vehicles (that failed the start-up standards only) in the 1997 database The failure rate in the current program is expected to double when the final standards are implemented This implies that roughly half of the failures would fail the start-up standards, while the other half would pass the start-up standards and fail the final standards Thus, simply combining the 1996 and 1997 databases (which contain approximately the same number of vehicles) should give a good representation of failing vehicles in the fleet under the final standards

from this analysis were then applied to the overall failure rates in Table 7 to arrive at a false failure rate as a fraction of the fleet, which is given in Table 8

Table 8
Replicate IM240 Results and Estimated False Failure Rate as a Function of IM240 Cutpoints
(664 Vehicle Sample)

Pollutant	Cutpoint (g/mi)	# Failing 1st IM240	# Passing 2nd IM240	% Passing 2nd IM240	False Failures as a Fraction of the Fleet[a]
HC/CO/NOx	0 8/15/2 0	487	120	25%	8%
	1 2/20/2 3	391	106	27%	6%
	1 6/25/2 6	319	82	26%	5%
	2 0/30/3 0	246	52	21%	3%
HC	0.8	375	140	37%	9%
	1 2	267	95	36%	5%
	1 6	184	64	35%	4%
	2.0	126	32	25%	2%
CO	15	255	63	25%	4%
	20	188	47	25%	3%
	25	154	36	29%	2%
	30	130	30	23%	2%
NOx	2 0	228	49	21%	4%
	2 3	175	42	24%	3%
	2 6	146	37	25%	3%
	3 0	99	22	22%	2%

[a] False failures as a fraction of the fleet were derived by multiplying the fleet failure rate under each set of cutpoints by the fraction of failing vehicles passing an immediate retest

Of note in Table 8 is that the percentage of failing vehicles that passed an immediate retest is relatively constant across the cutpoint scenarios analyzed here, with the more stringent cutpoints generally having a larger fraction of vehicles passing the second IM240 However, because of the difference in fleet failure rates among the cutpoint scenarios, the false failures as a fraction of the fleet are much lower for the less stringent cutpoints.

Modal Analysis of Replicate IM240 Testing

The emission results from the 336 failing vehicles tested in the replicate IM240 phase of this study were also analyzed on a modal, or second-by-second, basis In addition, the IM240 data from the replicate Phase 2 testing were evaluated on a modal basis. This evaluation was motivated by the results of the 1996 preconditioning study that indicated it was possible to successfully predict whether a vehicle was adequately preconditioned by analyzing its second-by-second IM240 emission results

Mean Concentration Estimates - One of the parameters investigated in the 1996 study was IM240 second-by-second emissions concentrations Although the IM240 is a mass-based emissions test, it is possible to estimate tailpipe concentration from measurements of dilute exhaust by calculating the dilution factor using equations contained in the high-tech guidance. This technique provides an acceptable approximation for cars running near stoichiometric * By comparing tailpipe concentrations near the end of Phase 1 to concentrations near the end of Phase 2, it is possible to determine if a car was adequately warmed up at the start of the test

The mean second-by-second HC concentration (in ppm C) for the 336 vehicles in the replicate IM240 sample is illustrated in Figure 6 for the first IM240 (which followed a 30-minute idle period) and for the immediate retest As observed in the figure, the concentration profile for the first test is higher than for the second test up to about second 200, where the two profiles converge (indicating that the vehicles, on average, are fully warmed up at that point) The difference in HC concentration profiles is even more pronounced for vehicles that failed the first and went on to pass the second test (based on the start-up IM240 standards). This is illustrated in Figure 7. Although the concentration profiles do not completely converge for these vehicles, it is clear that the vehicles are warming up as the first test progresses This is also seen in Figure 8, which shows the ratio of the first test HC concentration to the second test HC concentration for vehicles failing the first and passing the second test (fail/pass) and for vehicles failing both tests (fail/fail). As might be expected, the slope of the ratio with test duration is steeper for the fail/pass sample than it is for the fail/fail sample

* While the equation is considered acceptable for the purpose used in this analysis, the assumptions on which it is based introduce some error Sources of error include the assumption that emissions are measured on a "wet" basis (i e , without the removal of water from the sample), the inadequate accounting for the effects of pollutants in the background (dilution) air, and the fact that it becomes less accurate as the air-fuel ratio of the vehicle under test deviates from stoichiometric Required adjustments to the equation to address these issues, while feasible, are beyond the scope of this analysis and are not necessary at this time

Figure 6

Mean Second-by-Second IM240 HC Concentration for All Vehicles in the Replicate IM240 Sample

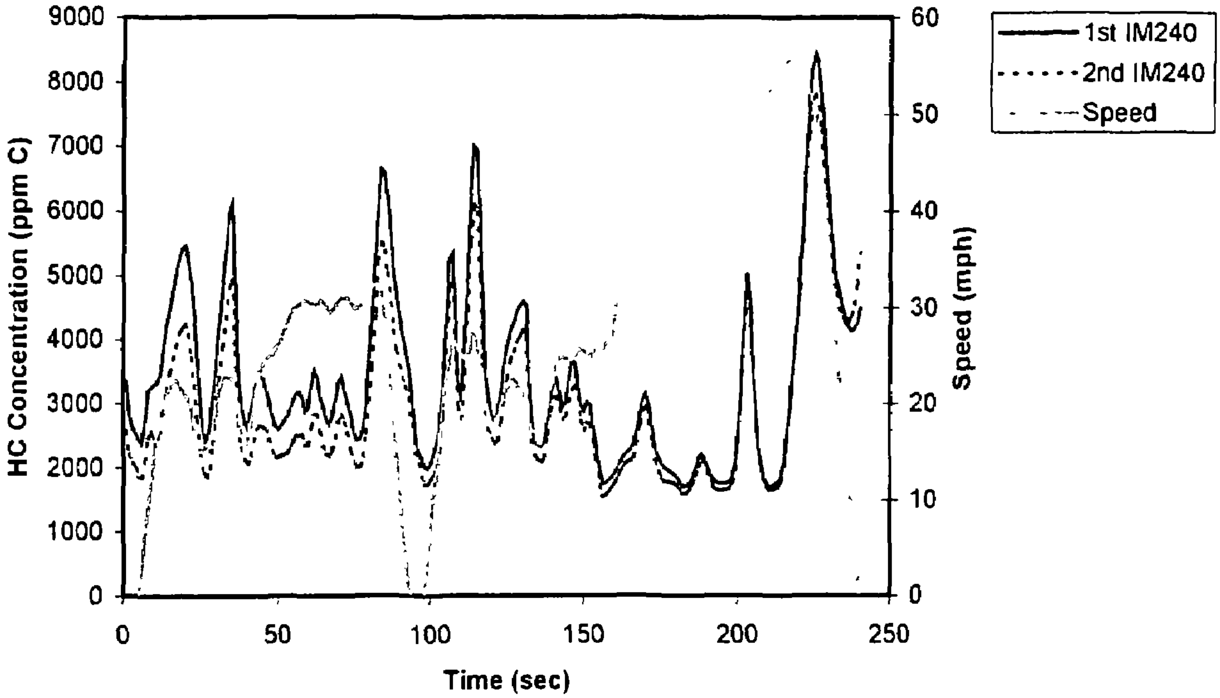


Figure 7

Mean Second-by-Second IM240 HC Concentration for Vehicles in the Replicate IM240 Sample Failing the First Test and Passing the Second

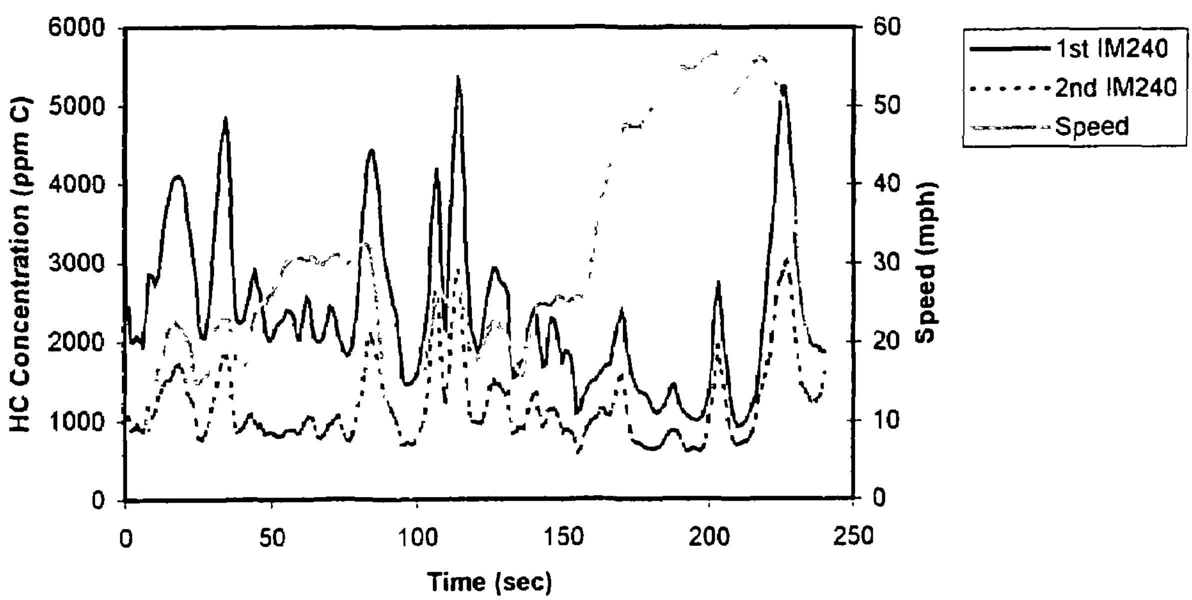
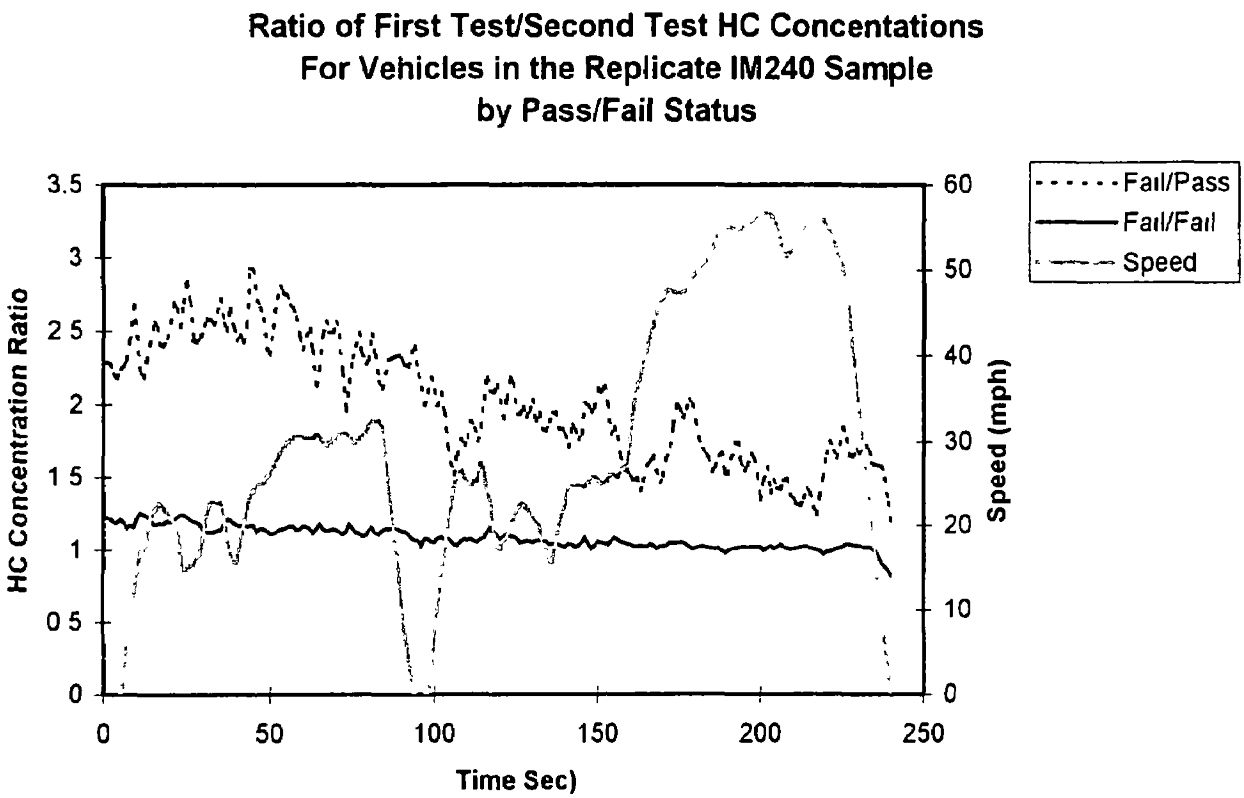


Figure 8

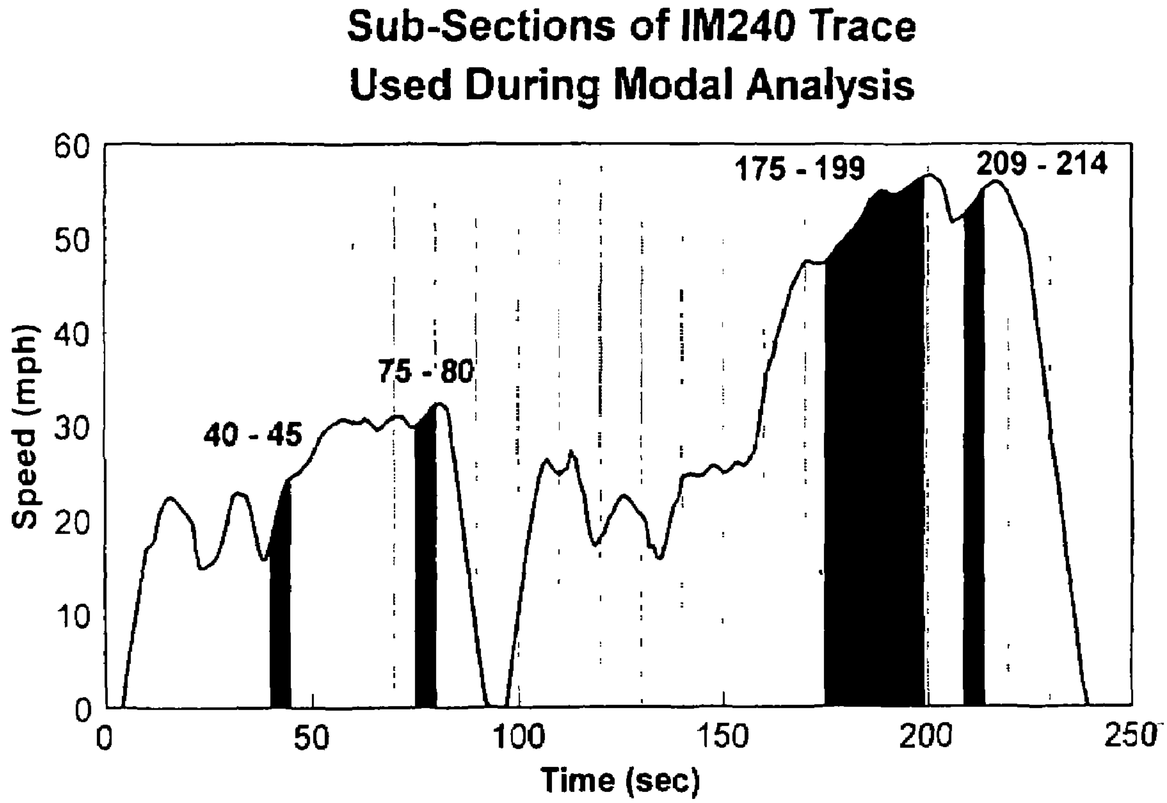


Identifying Inadequate Preconditioning - The results of the 1996 preconditioning study showed that emissions occurring during specific portions of the IM240 test were significant in indicating whether the vehicle was adequately preconditioned. The following four sections were of particular interest

- seconds 40 to 45 (for NOx concentration),
- seconds 75 to 80 (for HC and CO concentration),
- seconds 175 to 199 (for HC, CO, and NOx mass), and
- seconds 209 to 214 (for HC, CO, and NOx concentration)

The designations of these particular segments of the IM240 speed-time trace are consistent with EPA's convention of initiating data collection at second "0" and making the last reading at second "239" Each of the four sections of the IM240 trace is illustrated in Figure 9 Other parameters determined to be important in whether a vehicle passed a second test after failing the first were (1) average emissions over Phase 2 (i e., seconds 94 to 239), and (2) the difference between Phase 1 (i.e , seconds 0 to 93) and Phase 2 emissions A detailed description of the retest algorithm developed in the 1996 preconditioning study can be found in the final report on the study,[2] a brief summary is provided below

Figure 9



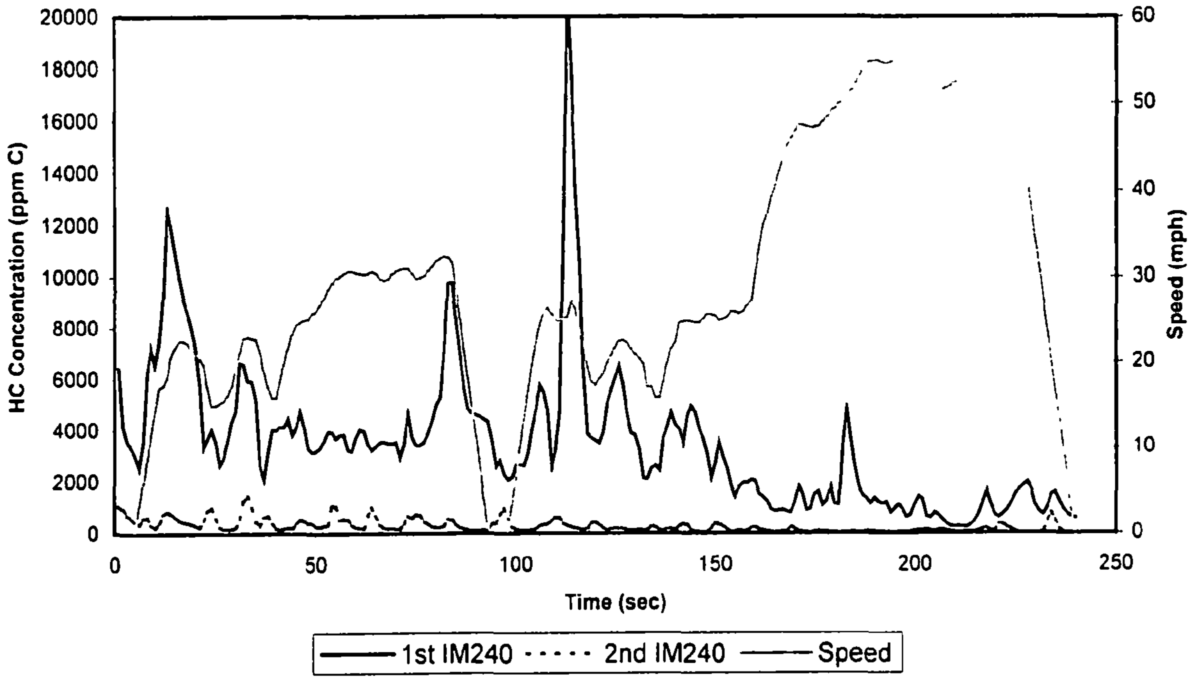
For HC and CO emissions, the 1996 analysis indicated that one of the primary determinants of whether a vehicle would pass a second IM240 after failing the first test was the ratio of the average tailpipe concentration near the end of the first phase of the test (seconds 75 to 80) to the tailpipe concentration near the end of the second phase (seconds 209 to 214) These two segments of the trace were selected because they are the last portions of each phase before the beginning of a deceleration. A high Phase 1/Phase 2 ratio indicates that the vehicle was not completely warmed-up in the first phase of the test.

Because it was found that many vehicles had very low NOx concentrations during seconds 75 to 80, regardless of whether the vehicle was fully warmed-up, NOx concentrations computed during the acceleration from second 40 to second 45 were used in calculating the concentration ratio between the start of the test and the end of the test. The same portion of Phase 2 (i e , seconds 209 to 214) used for the denominator of the HC and CO ratio was also used for the denominator of the NOx ratio

An example of a second-by-second HC concentration trace for a vehicle in the replicate IM240 database that failed the first IM240 but passed the second test is shown in Figure 10 That vehicle, a 1991 Chevrolet truck, had composite IM240 emissions of 2 84 g/mi on the first test and 0 20 g/mi on the retest (This level of reduction from the first IM240 to the second IM240 is on the high end of the spectrum for the vehicles tested in

Figure 10

Second-by-Second HC Concentration
1991 Chevrolet Truck - 4.3 Liter Engine
(1st IM240 = 2.84 g/mi; 2nd IM240 = 0.20 g/mi)



this program, but it illustrates the extent to which preconditioning effects can impact the test results.) Although both the first and second IM240 concentration traces are shown in the figure, the important one is the first test, since that would be used in an operating program to determine if the vehicle should receive a retest As observed in the first trace, the ratio of the HC concentration during seconds 75-80 to the concentration during seconds 209-214 is large (14 4) in this case. That information, coupled with the mean concentration during seconds 209 - 214 being less than 1,500 ppmC, would trigger a retest under the retest algorithm developed in the 1996 preconditioning study.

<u>Application of Preconditioning Retest Algorithm to the Replicate IM240 and Replicate Phase 2 Samples</u> - The preconditioning retest algorithm developed in the 1996 preconditioning study was applied to the back-to-back IM240 data collected during this study This included the 336 vehicles tested in the replicate IM240 phase of the program (which were random IM240 failures based on the start-up cutpoints), and the 101 vehicles in the replicate Phase 2 testing. (Recall that this sample of vehicles included passing and failing vehicles that were tested on back-to-back IM240s following a 30-minute idle period)

The performance of the retest algorithm applied to the two databases generated for this study is summarized in Table 9 As observed in that table, the retest algorithm was much more successful at correctly identifying the failing vehicles that would benefit from an immediate retest in the replicate Phase 2 sample than in the replicate IM240 sample In the replicate Phase 2 sample, 88% (7 out of 8) of the failing vehicles that passed the retest were correctly identified as needing a retest Only 60% (12 out of 20) of the vehicles passing the retest in the replicate IM240 test sample were correctly identified as needing a retest This result was not unexpected, however, since the 1996 preconditioning retest algorithm was based on vehicles that had passed the start-up cutpoints and failed the final cutpoints (i e , they were "marginal" failures under the final IM240 standards). Thus, one would expect that algorithm to perform better on a random sample of failures than on a sample that failed the start-up cutpoints on the initial test and passed the final cutpoints on the retest.

Table 9
Performance of 1996 Preconditioning Retest Algorithm in Identifying Vehicles Needing a Retest in the 1997 Databases (IM240 Failures Based on Final Standards)

Database	Sample Size	# Failing 1st IM240	1st Test Failures Passing 2nd Test	1st Test Failures Correctly ID'd for a Retest	1st Test Failures Incorrectly ID'd for a Retest
Replicate IM240	336	336	20	12	20
Replicate Phase 2[a]	101	24	8	7	3

[a] Note that the replicate Phase 2 database included back-to-back IM240 testing on the same vehicles following a 30-minute idle period.

Overall, the 1996 retest algorithm performed quite well, since it was designed to predict when a vehicle failing the final standards would need a retest Assuming that roughly half of the failures under the final standards would be "marginal" failures (i e , passing the start-up cutpoints but failing the final cutpoints) and half would fail the start-up standards, it is estimated that 86% of those vehicles needing a retest would be correctly identified [*] This is consistent with the results of the 1996 preconditioning study

Revisions to the Retest Algorithm Based on the Results of the 1997 Testing - Although the results presented above indicate that the 1996 retest algorithm successfully identifies a large fraction of vehicles needing a retest (i e., fail/pass vehicles) without identifying an excessive number of fail/fail vehicles for retesting, the data collected in the 1997 test programs made it possible to further refine the retest algorithm. This was particularly true for light-duty trucks, which do not make up as large a fraction of the test sample (or the fleet) as passenger cars The proposed revisions to the retest algorithm are outlined below

- *Passenger Cars*

  a. For vehicles failing HC and CO on the initial test, a retest is recommended if $massHC_{175-199} < 0\ 25$ g and $massCO_{175-199} < 5\ 0$ g.

  b For vehicles failing HC and NOx, a retest is not recommended if $ppmHC_{209-214} > 1{,}200$ or $ppmNOx_{209-214} > 1{,}200$ (This is simply a change to the NOx concentration from 1,000 ppm to 1,200 ppm.)

- *Light-Duty Trucks*

  a For 1988 and later LDT2s failing NOx, a retest is recommended if $massNOx_{175-199} < 2\ 5$ g.

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[*] Starting with 100 vehicles failing the final cutpoints, approximately 50 would fail the start-up cutpoints and 50 would pass the start-up cutpoints (i e , these are marginal failures) Based on the results of the replicate IM240 testing, 6% of the start-up cutpoint failures would pass the final standards on a retest (60% of these would be identified by the retest algorithm) Based on the results of the 1996 preconditioning study, 50% of the marginal failures would pass the final standards on a retest (88% of these would be identified by the retest algorithm) These two sets of vehicles can be combined as follows

Vehicles Passing an Immediate Retest

Start-up Standard Failures	50	×	0 06 =	3
Marginal Failures	50	×	0 50 =	25

Vehicles Correctly Identified as Needing a Retest

Start-up Standard Failures	3	×	0 60 =	2
Marginal Failures	25	×	0 88 =	22

Using the above assumptions, of 100 vehicles failing the final IM240 standards on their initial test, 28 would go on to pass an immediate retest, and 24 of those would be identified as needing a retest Thus, the 1996 retest algorithm correctly identifies 86% (24/28) of the vehicles needing a retest b For 1984 and later LDTs failing HC, a retest is not recommended if Phase 2 HC > 3 2 g/mi

Applying the revised algorithm to the replicate IM240 sample resulted in an increase from 12 to 16 in the number of vehicles correctly identified as needing a retest, and a decrease from 20 to 18 in the number of vehicles incorrectly identified as needing a retest (See Table 9) These revisions caused no change to the results for the replicate Phase 2 sample

A complete summary of the IM240 retest algorithm, including the revisions recommended above, is contained in Appendix A.

Conclusions and Recommendations from the Preconditioning Analysis

Based on the analyses presented above, the following conclusions are reached

- The data collected in the current study support the previous conclusion that most vehicles are not thoroughly warmed up by running Phase 1 of the IM240 test if they have been waiting in a queue for 15-30 minutes prior to the test This is true regardless of whether the engine is idled during queuing

- Using the current IM240 test procedures, it is estimated that 19% of the vehicles currently failing the start-up IM240 standards would pass those cutpoints with further preconditioning It is estimated that 6% of the vehicles failing the start-up cutpoints would pass the final cutpoints if adequately preconditioned

- Newer (1986 and later model year) vehicles appear to be more sensitive to preconditioning than the older vehicles

- A single Phase 2 of the IM240 test procedure is as effective as a full IM240 plus a Phase 1 at preconditioning a vehicle that has been idling in a queue for 30 minutes.

- While Phase 2 of the IM240 is a much more effective preconditioning cycle than Phase 1, it is unclear that I/M program managers would be receptive to eliminating the current IM240 in favor of a Phase 2 cycle due to the high-speed operation associated with Phase 2

- It may be worthwhile to consider limiting the HC cutpoints to 1 2 g/mi for older (i e , pre-1991) vehicles as a trade-off between cutpoint stringency and emission benefits This would also have a beneficial impact on limiting false failures due to inadequate preconditioning

- The results of the current study further support the modal analysis of emissions recorded during the IM240 test as a way to identify vehicles that would benefit from further preconditioning It is estimated that the retest algorithm developed in the 1996 study would correctly identify 86% of those vehicles needing a retest.

- Proposed refinements specific to passenger cars and light-duty trucks have been developed for the 1996 retest algorithm

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5. DEVELOPMENT OF IM240 FAST-PASS CUTPOINTS

This work assignment called for a reevaluation of IM240 fast-pass standards The task included the evaluation of the methodological approach used in setting the current standards, as well as an investigation of possible changes or enhancements to the previous approach This section of the report presents an evaluation of previous methodologies used to develop fast-pass standards and the results of the approach selected to develop fast-pass standards under this work assignment. (Although not part of this work assignment, the methodology used for the analysis could also be used to develop fast-fail standards) After the methodology was developed, it was applied to the available second-by-second IM240 data from the Arizona program to generate revised fast-pass standards for a variety of different cutpoints.

Background

Because of the long duration of the IM240 test (relative to other I/M tests), there has been interest on the part of states and I/M contractors in shortening the test time This interest has grown as states have begun to focus on the need to offset the growth in test volumes projected to result from (1) the increased failure rates that will occur as the states move toward implementation of more stringent cutpoints, and (2) increases in the number of vehicles subject to the IM240 testing in high growth areas such as Arizona Shortening test times will help lessen queue time and the need to increase existing network capacity, ultimately resulting in the need for fewer inspection lanes, and lower or at least stable costs to motorists

One means of shortening the average test time of the IM240 is to implement "fast-pass" and/or "fast-fail" standards in which vehicles with emissions that appear to be well below or well above the full duration cutpoints would have a pass-fail decision made based on a portion of the test. This possibility was recognized early in the development of EPA's enhanced I/M regulations, and a discussion of fast-pass/fast-fail strategies was included in the Regulatory Impact Analysis prepared for that rulemaking [4] Based on an evaluation of IM240 data available at that time, EPA estimated that roughly 33% of the vehicles tested could be fast-passed or fast-failed based on results of Phase 1 of the IM240 (i e., the first 93 seconds of the test) EPA went on to point out that once second-by-second data were collected, algorithms could be developed that would allow very clean cars to pass well before the 93-second point

Previous Methodology

Currently, every I/M program that has IM240 testing is using a fast-pass algorithm to reduce average test time In addition, the Phoenix program is also using a fast-fail algorithm The fast-pass cutpoints and methodology used in these programs are based on work that EPA did about four years ago,* which is described in a letter from Gene Tierney of EPA to the I/M community [5] In that method, the cumulative emissions (in grams) at each second of the test are compared to the cutpoints (also in grams) established for each second of the test The first point at which a vehicle can fast-pass is at second 30 Because of the "two ways to pass" criteria (i.e., different standards have been established for the composite IM240 and Phase 2 of the test, with the thought that Phase 1 of the test serves as a preconditioning cycle for vehicles that are not completely warmed up at the start of the IM240), fast-pass standards have also been developed for Phase 2 of the test Thus, it is possible for a vehicle that has cumulative IM240 emissions higher than the fast-pass cutpoints for the composite test to fast-pass based on its cumulative emissions in Phase 2 of the IM240 Although the original approach allowed a fast-pass determination in Phase 2 to be made at the start of that phase (i.e , from second 94 forward), that determination has been changed to second 109 forward in EPA's current high-tech guidance document [1] This is a positive revision, since seconds 94 to 97 are idle periods in the IM240 Thus, making a fast-pass decision during that period is akin to spending a significant amount of money on a very good preconditioning cycle, only to measure emissions at idle

The fast-pass (and fast-fail) cutpoints developed by EPA were based on an analysis of second-by-second data from 3,718 tests conducted in Arizona. According to the documentation available on the development of the fast-pass/fast-fail cutpoints, the <u>fast-pass</u> cutpoints for each second "represent the tenth lowest cumulative emission levels in that second obtained for vehicles failing the IM240 using the two-ways-to-pass criteria." Thus, vehicles that fall below these cutpoints have lower cumulative emissions than almost all of vehicles that fail the full IM240 and, therefore, pass the test. Similarly, the <u>fast-fail</u> standards were based on the highest cumulative emission levels from vehicles that passed the full test. Thus, a vehicle failing these cutpoints has emissions that are higher than the dirtiest vehicles that pass the full test

Alternative Methodologies

Although the aforementioned methodology used to develop fast-pass cutpoints provides a workable solution to establishing fast-pass cutpoints, it does not make full use of the information that has been collected on a second-by-second basis Rather, the fast-pass

* Note that the fast-fail algorithm being used in the Arizona program is not based on the EPA cutpoints and methodology The Arizona program uses an extremely conservative approach under which a vehicle fast-fails only if its cumulative emissions exceed the total mass required to fail the entire test For example, if the full-test cutpoint is 0 8 g/mi HC, then the total mass required to fail is 0 8 g/mi × 1 96 mi = 1 57 grams Thus, if a vehicle has emitted a total of 1 58 grams of HC at second 150, the vehicle fast-fails at that point.

decision is simply made by comparing cumulative emissions at each second to a particular emission standard at each second With the intent of improving the performance of the current fast-pass methodology and standards (i e , shorter test time and fewer false passes), alternative approaches to predicting passing or failing results based on a portion of the IM240 were investigated. The methodologies proposed by two different research teams to predict full-cycle IM240 scores from partial test results are summarized below. This is followed by Sierra's recommendations for re-evaluating IM240 fast-pass cutpoints

Resources for the Future (RFF) - RFF has recently conducted an analysis[6] of second-by-second data collected in Phoenix to

- develop a methodology to use actual IM240 test data in program evaluations when tests in the sample range in length from 31 to 240 seconds, and
- use that methodology to evaluate the accuracy of fast-pass and fast-fail algorithms.

The methodology developed by RFF, which is described below, estimates full IM240 emissions from partial test results using (1) the second at which the test ended, (2) the cumulative emissions at that point, and (3) the model year of the vehicle

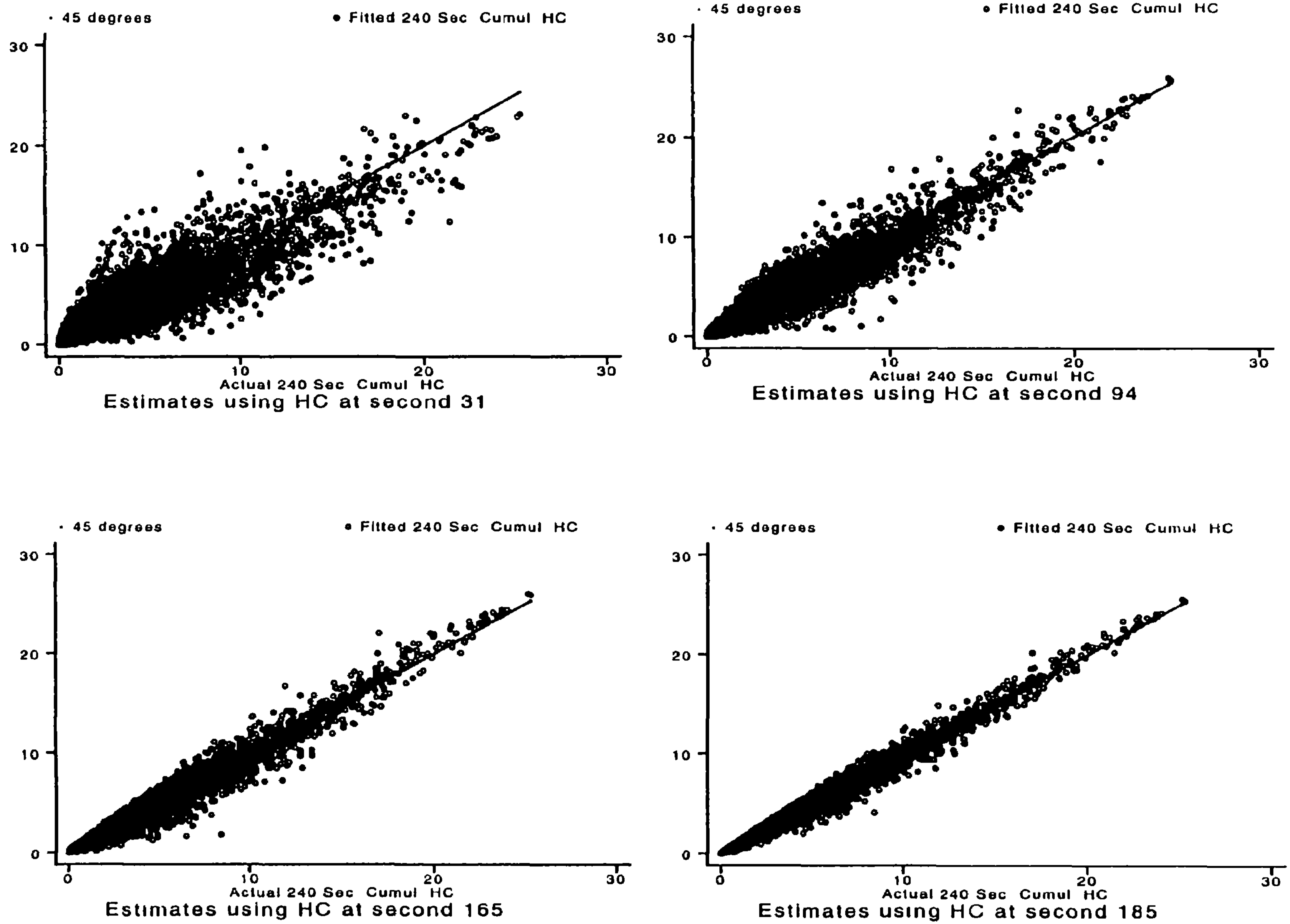
RFF developed a regression technique to predict full-test IM240 emissions from partial test results This technique used full-duration, second-by-second data from 12,647 tests conducted in the Phoenix program from January to June 1996 Using these data, a regression was performed based on the following formula.

$$\begin{aligned} P240 = \; & a + b{*}Px \\ & + c1{*}MY81 + c2{*}MY82 + \cdots + c15{*}MY95 \\ & + d1{*}Px{*}MY81 + d2{*}Px{*}MY82 + \cdots + d15{*}Px{*}MY95 \end{aligned}$$

where P240 is the predicted full-duration IM240 score for pollutant P, Px is the cumulative emissions at second x, and MY## is a dummy variable indicating whether the test was performed on a vehicle of model year ## (i e., this variable is assigned a value of one for the model year of interest, otherwise it is zero) Overall, 627 equations were developed by RFF based on the above methodology – one for each pollutant (HC, CO, NOx) at each of 209 seconds (i e , tests ending after 31 seconds through 239 seconds) Using this approach, full-cycle IM240 emissions can be predicted based on the length of the test, the cumulative emissions at the end of the test, and the model year of the vehicle

Scatter plots showing predicted versus actual IM240 HC emissions using the RFF technique are given in Figure 11 for tests ending at second 31, second 94, second 165, and second 185 As expected, and as observed in that figure, the predictions improve as the length of the test is increased.

Figure 11



· 45 degrees
● Fitted 240 Sec Cumul HC
Actual 240 Sec Cumul HC
Estimates using HC at second 31
Estimates using HC at second 94
Estimates using HC at second 165
Estimates using HC at second 185

New York Department of Environmental Conservation (NYDEC) - NYDEC has also recently completed an analysis of IM240 data with the intent of predicting full-cycle scores from partial test results [7] That work was motivated by a desire to

- reduce test time and queues (through the use of fast-pass/fast-fail algorithms), and
- avoid the high-speed driving that occurs during the last 70 seconds of the test.

The methodology developed by NYDEC makes use of a regression technique in which total cycle emissions are predicted from modal emissions data (rather than cumulative emissions at each second) from the IM240 In that approach, the IM240 is broken up into 12 different modes, as shown in Figure 12, and the mass of each mode is calculated. A regression is then performed according to the following equation:

$$\hat{E}_{IM240} = K + \left\{ \sum_{i=1}^{j} C_i \times E_i \right\}$$

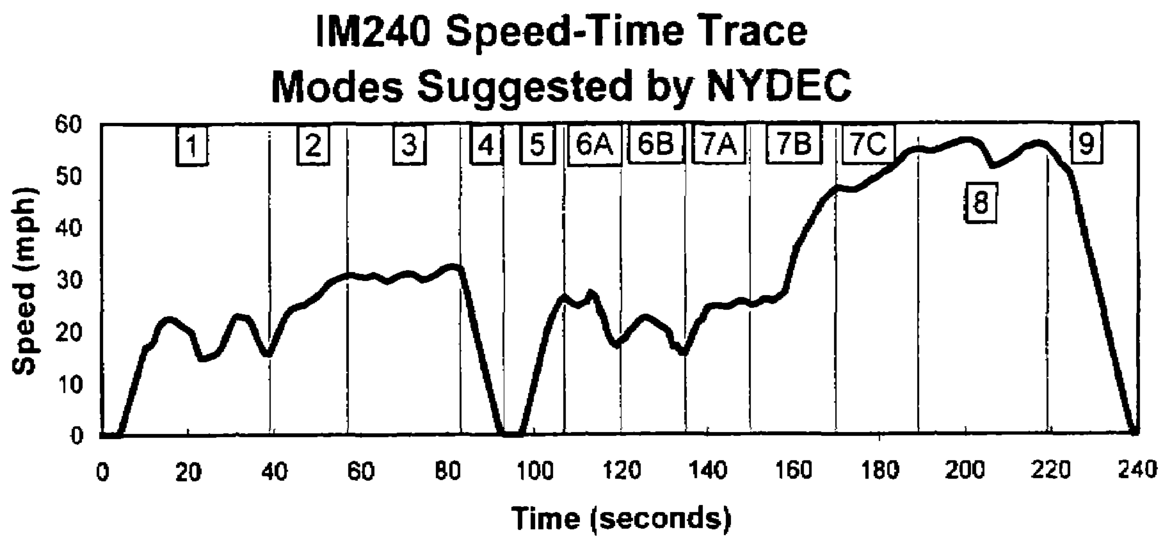
$$E_{IM240} = \hat{E}_{IM240} + \epsilon$$

where

$\hat{E}_{IM240}$	=	predicted full-cycle IM240 emissions
E_{IM240}	=	actual full-cycle IM240 emissions
K	=	regression constant
C_i	=	regression coefficient for mode I
E_i	=	emissions in mode I (in grams)
j	=	number of modes in the model
ϵ	=	error term

Using this approach, a different set of coefficients is developed based on the number of modes included in the model (i.e., up to mode j); as the number of modes is increased, the coefficient of determination (i.e , the r^2 value) improves Because one of the goals of its analysis was to eliminate the high-speed component of the test, NYDEC performed regressions (and presented results) based on nine modes, or up through second 170 of the trace That analysis was performed with data collected in the Phoenix I/M program and EPA's Hammond, Indiana, IM240 pilot lane

Figure 12

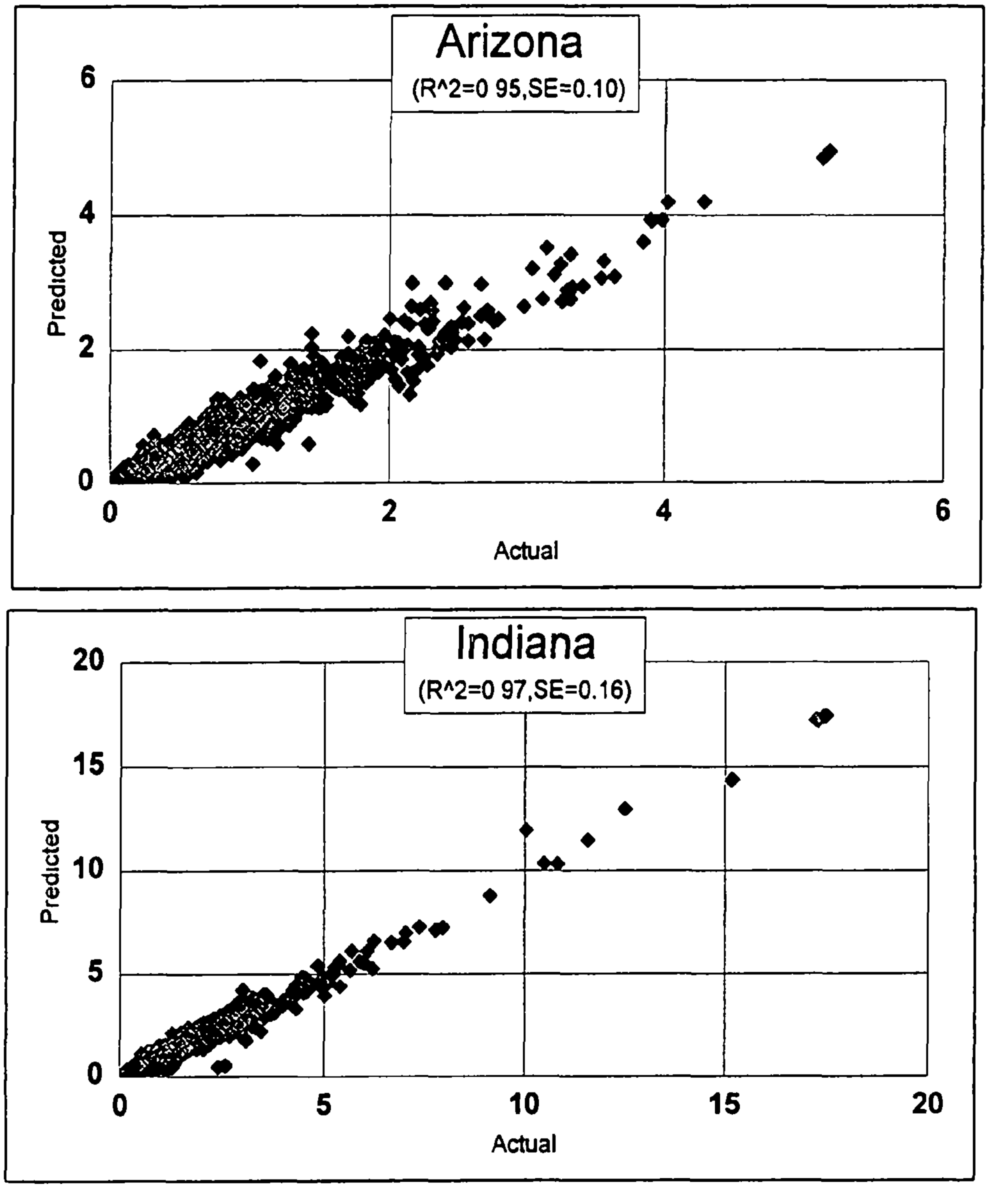


Scatter plots of predicted versus actual IM240 HC scores based on regressions performed through mode 6 (or second 120 of the trace) are shown in Figure 13. As observed in the figure, the model developed by NYDEC appears to be doing a very good job of predicting full-cycle emissions from just one-half of the test, with the results from the Indiana program being slightly better than results from the Phoenix program (in terms of the r^2 value)

Overall, NYDEC concluded that the above methodology can provide both fast-pass and fast-fail decision capability and has the advantage of providing an estimate of full-cycle IM240 emissions, which is not possible with the EPA's current fast-pass/fast-fail procedure. NYDEC also concluded that the minimum test time needed to make a fast-pass/fast-fail decision using this technique is on the order of 120 to 170 seconds. However, as discussed below, it appears that by using appropriate statistical safeguards, a modal regression technique should be able to make a fast-pass decision with reasonable certainty well before 120 seconds in many cases.

Figure 13

IM240 G/Mi HC Emissions -- Actual vs. Predicted
120-Second Modal Model



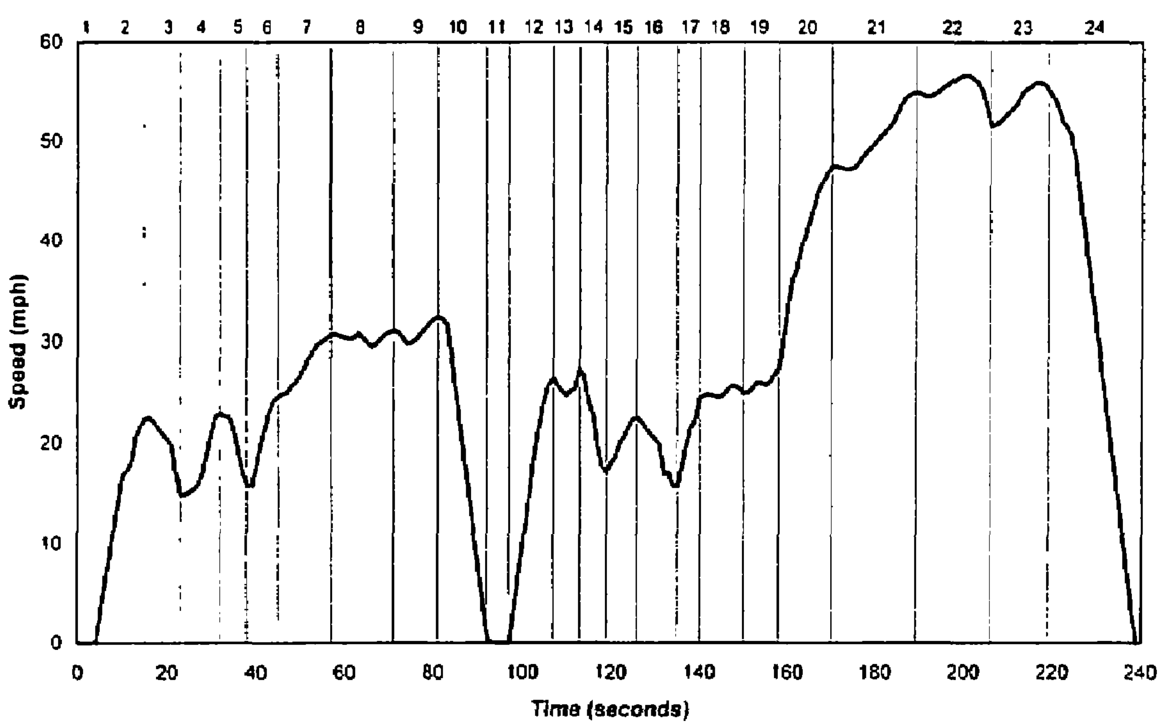
Selected Approach

In reviewing various approaches that might be used to develop a revised set of fast-pass standards (or a revised fast-pass methodology), the method that had the most appeal (both from an engineering and a statistical perspective) was the modal regression technique developed by NYDEC Although the current use of cutpoint tables could easily be continued, such an approach essentially ignores valuable information collected during different modes of vehicle operation that might allow a better prediction of how a particular vehicle will perform on the entire test In addition, the use of modal data is consistent with the methodology developed in the 1996 preconditioning study (described in the previous section) to determine if a vehicle failing an IM240 test had been adequately preconditioned. Thus, the methodology developed by NYDEC forms the basis of the approach used to generate revised IM240 fast-pass standards under this study

The primary change that was made to the modal regression model described above was to add modes and to shift some of the existing modes One reason for this change is that it allows vehicles to fast-pass between the modes established in the NYDEC work, which was expected to have a positive impact on reducing test time A total of 24 modes were therefore selected as the basis of the regression model developed for this study These modes are illustrated in Figure 14.

Figure 14

IM240 Speed-Time Trace
Modes Used for Development of Fast-Pass Cutpoints



Because the regression statistics improve with the duration of the test (and therefore with the number of modes included in the regression equation), a means to build a safety margin into the fast-pass decision is desirable, especially for fast-pass decisions made early in the test. This can be accomplished by first calculating the predicted full-cycle IM240 score from the regression coefficients, adding on a positive error term, and then comparing the result to the full-cycle IM240 cutpoint (As written in the equation above, the error term, ϵ, can be positive or negative.) As the test progresses and more modes are completed, the error term would decrease The same approach can also be taken in determining compliance with Phase 2 of the test under the two-ways-to-pass criteria.

The error term is measured by the confidence limits, CL, for the predicted value of $\hat{E}_{IM240}$. Those confidence limits (with probability $1 - \alpha$) are given by the following equation [8]

$$E_{IM240} = \hat{E}_{IM240} \pm t_{\alpha/2,n-j-1}\, s_{y|x} \sqrt{1 + \frac{1}{n} + \sum_{i=1}^{J}\sum_{k=1}^{J} c_{ik}\, x_i^*\, x_k^*}$$

The new terms introduced in this equation are defined below.

- $t_{\alpha/2,n-j-1}$ = the ordinate of the Student's t distribution for a two-tailed significance level, α, and n-j-1 degrees of freedom
- n = the number of data points in the IM240 data set used to generate the regression coefficients K and C_i
- $s_{y|x}$ = the standard regression error of the estimated IM240 emissions
- c_{ik} = an element of the inverse matrix of the matrix of the corrected sums of squares and cross products used in determining the regression coefficients
- x_i^* = $X_i^* - \bar{X}_i$
- X_i^* = the value of the i^th^ emission mode during the IM240 test of the vehicle for which a fast-pass decision is to be made
- $\bar{X}_i$ = the average value of the i^th^ emission mode in the regression data set

For large regression sample sizes, the elements of the inverse matrix, c_{ik}, are quite small and the double summation term can be neglected This was confirmed by a review of these terms in the SAS output for an initial sample of regressions. Since the number of observations is very large (on the order of several thousand), the 1/n term can also be neglected Thus, the confidence limit, CL, on the predicted IM240 emissions can be simply written as follows

$$CL = t_{\alpha/2,n-j-1}\, s_{y|x}$$

Since the value of the $t_{\alpha/2}$ term for a 95% confidence level is approximately two for large sample sizes, the error term can be estimated by simply doubling the standard error estimate calculated for each regression equation.

To test this approach, a subset of the Arizona full-cycle second-by-second data was initially used to develop regression coefficients (for HC) based on the modal methodology described above with the modes outlined in Figure 14 Only light-duty gasoline vehicles (i.e , passenger cars) were included in the analysis, and three model year groups were considered·

- 1981 to 1984,
- 1985 to 1989, and
- 1990 and later.

It is interesting to note that the r^2 values increase significantly as modes are added to the regression equation As the r^2 value increases, the value of $s_{x|y}$ decreases. This means that there is greater confidence in the regression prediction The method used for determining the fast-pass described below uses the value $s_{x|y}$ (multiplied by the t distribution ordinate) to determine the safety factor Because of this, the safety factor is automatically adjusted as the confidence in the predicted result increases

Once the regression coefficients were developed, <u>predicted</u> full-duration IM240 scores (i e , $\hat{E}_{IM240}$) were generated for a separate set of full-duration IM240 test results (i e., these were not used in developing the regression coefficients). At each mode (beginning with mode 4, which ends at second 32 of the IM240 test), a fast-pass decision was made based on the following

if $(\hat{E}_{IM240} + CL) \leq 0.8$ g/mi HC, then the vehicle passes, otherwise continue the test.*

This approach was used to investigate how well the modal regression equations predicted fast-pass results with a small sample of second-by-second full IM240 tests from the Phoenix program. The results are presented in Table 10 Three different approaches to developing the regression coefficients (and the corresponding standard errors) were investigated.

- using all data within the model year groups;
- using only test scores that complied with the 0 8 g/mi HC composite cutpoint; and
- using only test scores that were less than or equal to 1 2 g/mi.

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* The value of $\hat{E}_{IM240}$ and of CL is different for each mode of the test

Table 10
Performance of a Regression-Based Modal Emissions Algorithm to Determine Pass/Fail Status Under a Variety of Constraints (Based on a 0.8 g/mi HC IM240 Cutpoint)

Model Year	Method	Sample Size	Correct Passes	Mean Pass Time	False Passes
1981 to 1984	Modal - All Data	206	39	192.5	0
	Modal ≤ 1.2 g/mi HC	206	39	105 5	3
	Modal ≤ 0.8 g/mi HC	206	39	73.8	11
	Current Cutpoint Table	206	39	80 6	9
1985 to 1989	Modal - All Data	214	100	156.4	1
	Modal ≤ 1 2 g/mi HC	214	100	80 8	2
	Modal ≤ 0 8 g/mi HC	214	100	45 6	11
	Current Cutpoint Table	214	100	82.3	4
1990 and later	Modal - All Data	127	107	52.5	2
	Modal ≤ 1.2 g/mi HC	127	107	41.3	4
	Modal ≤ 0 8 g/mi HC	127	107	39.1	7
	Current Cutpoint Table	127	107	63 3	2

Also shown in Table 10 are the results from using the current second-by-second cutpoint tables.

As observed in Table 10, the performance of the modal methodology is dependent on whether all vehicles are included in the regression estimates or whether only the cleaner cars are included If all vehicles are included, then the error term is greater, and it generally takes much longer to pass the test. (Recall that to fast-pass, the predicted IM240 plus the error term is compared to the full-cycle cutpoint Thus, a larger error term results in longer average test duration.) However, it appears that through the proper construction of a modal model, the number of false passes can be reduced without a significant increase in test time This is particularly true of the 1981 to 1984 model year group.

Development of Fast-Pass Standards

Based on the above evaluation, it was decided to use the modal regression technique to develop a revised set of fast-pass standards for the IM240 test Full-duration, second-by-second IM240 data collected in the Arizona I/M program were used for this analysis. Nearly 110,000 individual tests were in the database used in the analysis, which is comprised of all full-duration IM240 tests conducted in Arizona from April 1995 through April 1997 Consistent with the methodology presented above, cutpoints (or, more correctly, regression coefficients) were generated separately for light-duty gasoline vehicles (i e., passenger cars) and light-duty trucks for the following model year groups

- 1981 to 1984,
- 1985 to 1989, and
- 1990 and later

Regression coefficients were developed for HC, CO, and NOx and for both the composite IM240 and for Phase 2 of the IM240 The Phase 2 regressions used mode 11 (see Figure 14) as the first mode and continued through mode 23 The composite IM240 regressions used modes 1 through 23 (Although 24 modes are shown in Figure 14, if a fast-pass decision is not made by mode 23, then the vehicle would run the full IM240. At that point, a pass/fail decision should be made on the actual IM240 score, not the predicted score) Finally, it is recommended that the first mode at which a pass/fail decision should be made is mode 4 (which ends at second 32 of the IM240) for a composite IM240 prediction, or mode 13 (which ends at second 113 of the IM240) for a Phase 2 prediction.

The regression coefficients for a 0 8 g/mi HC composite IM240 cutpoint are given in Appendix B, along with the coefficients for a 0 5 g/mi HC Phase 2 IM240 cutpoint. The full series of regression coefficients developed in this effort were provided to EPA electronically, and a listing of the corresponding cutpoints is contained in Appendix B

Although the next section of the report presents a detailed analysis of the impacts of the revised cutpoints (and preconditioning procedures) on test time, it is useful to review summary results at this point Using the 2% Random Sample from the Arizona program (which consists of 26,000 records), pass/fail rates were calculated with the modal regression procedures outlined above as well as the current fast-pass cutpoint tables This analysis was performed using the final IM240 HC, CO, and NOx standards, and the results are presented in Table 11

As observed in Table 11, the revised fast-pass methodology results in a lower fraction of false passes than the current method, particularly for older cars However, this improvement in failing vehicle identification is offset by a longer average test time for passing vehicles in the older model year groups For newer vehicles (i e , 1990 and later), the revised methodology results in significant improvements in average test time, without a significant increase in the fraction of false passes

Table 11
Comparison of Current and Revised Fast-Pass Methodologies Under the Final IM240 Standards (26,000 Vehicle Sample)

Vehicle Class	Model Year Group	"True" Failure Rate[a]	Current Fast-Pass		Revised Fast-Pass	
			Failure Rate	Pass Time (seconds)	Failure Rate	Pass Time (seconds)
LDV	81 - 84	79%	76%	125	78%	157
	85 - 89	45%	41%	130	43%	121
	1990+	8%	7%	88	7%	57
LDT	81 - 84	62%	51%	71	60%	113
	85 - 89	42%	35%	70	40%	93
	1990+	9%	7%	60	7%	57

[a] The "true" failure rate is based on full-duration IM240 test scores

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6. IMPACT OF PRECONDITIONING AND CUTPOINTS ON TEST DURATION

Task 2 of Work Assignment #2-04 called for an evaluation of the impact on test cycle duration of implementing EPA's final IM240 cutpoints coupled with the need for preconditioning to avoid false failures This section presents the results of an analysis of failure rates and test cycle duration under the current start-up cutpoints, the final cutpoints, and a set of "interim" cutpoints that fall between the start-up and final cutpoints In addition, failure rates and test cycle duration were also evaluated for the revised modal cutpoints described in Section 5 of this report. Finally, the impact on test duration of implementing the preconditioning procedures described in Section 4 of this report is presented in this section

IM240 Failure Rates Using the Current Fast-Pass Procedures

The first step in determining the effect of tighter cutpoints on test cycle duration (and the resulting impact on lane throughput) was to evaluate IM240 failure rates under the current program and under alternative cutpoints Failure rates directly impact the total load on an IM240 network by virtue of the retests required – a higher failure rate translates into additional retests In addition, there may be differences in average test time for vehicles subject to a retest compared to the average test time of initial tests.

Table 12 summarizes the light-duty gasoline vehicle (LDGV) IM240 initial test failure rates under the current Arizona program (which is using the start-up cutpoints outlined in the high-tech guidance document) Those failure rates were calculated using all IM240 tests conducted from January 1996 through September 1996 Also contained in Table 12 is a summary of the IM240 failure rates based on a subset of the Arizona database that received a full IM240 test (rather than a fast-pass or fast-fail). This subset is flagged in the Arizona database with a '2', indicating it is the 2% random sample of vehicles that are given a full IM240 test (The 2% Random Sample used in this analysis consisted of vehicles tested from June 1995 to April 1997) Three sets of cutpoints were applied to this sample

- start-up cutpoints,
- "interim" cutpoints, and
- final cutpoints.

Table 12
LDGV IM240 Initial Test Failure Rates in the Arizona Program Using the Current Fast-Pass Procedures (No Preconditioning)

Model Year Group	Pollutant	Current Program (Start-Up)[a]	Cutpoint Stringency (2% Sample Results)[b]		
			Start-Up	Interim	Final
1981 to 1983	Any	45%	42%	62%	78%
	HC	31%	29%	48%	65%
	CO	17%	16%	26%	37%
	NOx	19%	20%	31%	45%
	Sample Size	28,000	1,400		
1984 to 1987	Any	25%	24%	39%	55%
	HC	14%	14%	28%	42%
	CO	11%	11%	19%	27%
	NOx	11%	12%	19%	30%
	Sample Size	90,000	4,600		
1988 to 1990	Any	7%	6%	14%	25%
	HC	3%	3%	9%	17%
	CO	2%	2%	5%	9%
	NOx	4%	3%	7%	12%
	Sample Size	78,000	4,000		
1991 and Later	Any	2%	2%	5%	5%
	HC	1%	1%	3%	3%
	CO	1%	1%	2%	2%
	NOx	1%	1%	2%	2%
	Sample Size	139,000	7,000		
All Vehicles	Any	13%	12%	21%	29%
	HC	8%	8%	15%	22%
	CO	5%	5%	9%	13%
	NOx	6%	6%	10%	16%
	Sample Size	335,000	17,000		

[a] Based on an analysis of all test records from January 1996 to September 1996

[b] Based on an analysis of the 2% random sample of full IM240 tests from June 1995 through April 1997

The start-up and final cutpoints used in this analysis are those recommended by EPA in the high-tech guidance document, while the interim cutpoints were chosen to fall between the start-up and final cutpoints To determine the pass/fail status of each vehicle, the second-by-second cumulative mass data from the 2% Random Sample were compared to the existing fast-pass standards (corresponding to the appropriate composite and phase 2 IM240 cutpoints) at each second (beginning at second 30 in the trace) If a vehicle ran the full test without being fast-passed, the pass/fail determination was made based on the composite and phase 2 IM240 gram per mile values. The fast-pass cutpoint tables for the current (start-up) cutpoints were obtained from Gordon-Darby, while the fast-pass tables in the high-tech guidance document were used for the final cutpoints In some cases, the interim cutpoints required interpolation between the start-up and final fast-pass cutpoint tables, while in other cases cutpoint tables from the start-up or final cutpoints (from other vehicle classes or model year groups) could be used directly Because of the low failure rates of 1991 and later model year vehicles under the final cutpoints, the final cutpoints were used in the interim cutpoint scenario for those model years.

The results in Table 12 indicate that the 2% Random Sample failure rates for the start-up cutpoints are nearly identical to the failure rates observed in the entire fleet Thus, the 2% Random Sample appears to be a very good representation of the fleet (Note that the 2% Random Sample used in this analysis, which contains only initial tests, consisted of 26,000 vehicles The database used to determine failure rates for the current program consisted of 522,000 initial tests) Also of note in Table 12 are two obvious findings (1) failure rates increase for older model year vehicles, and (2) failure rates increase under the more stringent cutpoints reflected in the interim and final cutpoints Overall, initial-test IM240 failure rates for LDGVs are estimated to increase from 12% to 29% with the final cutpoints if nothing is done to deal with possible false failures as a result of inadequate preconditioning Under the interim standards evaluated in this effort, the overall LDGV failure rates are estimated to increase from the current 12% to 21%

Similar results are also observed with light-duty gasoline trucks 1 (LDGT1, i.e , under 6,000 lbs GVWR) and with light-duty gasoline trucks 2 (LDGT2, i e , from 6,000 lbs to 8,500 lbs GVWR). A summary of the IM240 failure rates for LDGVs, LDGT1s, and LDGT2s is given in Table 13 The sample sizes used to compute the failure rates for each vehicle group are also shown As observed, the failure rates for the light-duty trucks are slightly lower than for LDGVs This is partially a result of different cutpoints (and new vehicle certification standards) that apply to passenger cars versus light trucks

Table 13
IM240 Initial Test Failure Rates by Vehicle Class in the Arizona Program Using the Current Fast-Pass Procedures (No Preconditioning)

Vehicle Class	Pollutant	Current Program (Start-Up)[a]	Cutpoint Stringency (2% Sample Results)[b]		
			Start-Up	Interim	Final
LDGV	Any	13%	12%	21%	29%
	HC	8%	8%	15%	22%
	CO	5%	5%	9%	13%
	NOx	6%	6%	10%	16%
	Sample Size	335,000	17,000		
LDGT1	Any	8%	7%	14%	20%
	HC	4%	4%	7%	14%
	CO	2%	2%	3%	6%
	NOx	3%	4%	8%	10%
	Sample Size	147,000	7,000		
LDGT2	Any	9%	9%	19%	24%
	HC	6%	6%	10%	19%
	CO	4%	3%	5%	8%
	NOx	3%	3%	11%	11%
	Sample Size	40,000	2,000		
All Vehicles	Any	11%	11%	19%	26%
	HC	7%	6%	12%	20%
	CO	4%	4%	8%	11%
	NOx	5%	5%	10%	14%
	Sample Size	522,000	26,000		

[a] Based on an analysis of all test records from January 1996 to September 1996

[b] Based on an analysis of the 2% random sample of full IM240 tests from June 1995 through April 1997

IM240 Failure Rates Using Full IM240 Test Scores

To serve as a check on how well the existing fast-pass cutpoints correctly identify vehicles passing the full IM240 test, failure rates from the 2% Random Sample were also calculated based on using the full IM240 test scores, rather than the fast-pass procedures outlined above The results from this analysis are presented in Table 14, which shows that there is a moderate number of errors of omission (i.e , vehicles failing the full IM240 that pass the fast-pass cutpoints) when using the current fast-pass cutpoints Under both the start-up and final IM240 cutpoints, using the full IM240 test scores to determine pass/fail status increases the overall failure rates by about 3 percentage points. Also of note in Table 14 is that the fraction of errors of omission is higher for NOx than for HC and CO This is likely the result of the fast-pass algorithm passing vehicles before the highest speed portion of the IM240 is entered (i e , beginning at second 156 of the trace, the vehicle is accelerated from 26 mph to nearly 57 mph at second 200 of the trace), where one might expect a large contribution of NOx emissions to the overall IM240 NOx score

Table 14
IM240 Initial Test Failure Rates in the Arizona Program
Current Fast-Pass Methodology Versus Full IM240 Test Scores
from the 2% Random Sample Vehicles[a]
(26,000 Vehicle Sample with No Preconditioning)

Pollutant	Start-Up Cutpoints		Final Cutpoints	
	Fast-Pass	Full IM240	Fast-Pass	Full IM240
Any	11%	14%	26%	29%
HC	6%	7%	20%	21%
CO	4%	5%	11%	12%
NOx	5%	7%	14%	16%

[a] These results are based on an analysis of the 2% random sample of full IM240 tests from June 1995 through April 1997

Impact of Revised Fast-Pass Procedures on IM240 Failure Rates and Total Test Time

The revised fast-pass procedures (i e , the modal analysis methodology described in Section 5) were applied to the 26,000 initial test scores in the 2% Random Sample database to determine how well that procedure correctly identified passing vehicles The results of that analysis are summarized in Tables 15, 16, and 17 for the start-up, interim, and final IM240 standards, respectively Results are presented separately for light-duty trucks (i e , LDGT1 and LDGT2 combined) and light-duty vehicles (i e., passenger cars), and for three model year groups 1981 to 1984, 1985 to 1989, and 1990 and later Also shown in Tables 15, 16, and 17 are the same results based on the current fast-pass methodology and cutpoints.

Using Table 15 as a guide, the third column (marked " 'True' P/F") is the pass/fail result based on the full-duration test The fourth column (marked "Fast-Pass P/F") is the pass/fail result based on the fast-pass algorithm Vehicles receiving a "P" in column 3 and a "P" in column 4 were correctly identified as passing vehicles by the fast-pass algorithm. Vehicles receiving an "F" in column 3 and a "P" in column 4 are failing vehicles that were incorrectly passed by the fast-pass algorithm (i e., errors of omission or false passes). Vehicles with an "F" in both columns ran the full IM240 under the fast-pass algorithm and were correctly logged as failures Also shown in the tables is the average test time for the vehicles fast-passing the test (in seconds), as well as the total test time (in hours) for all vehicles in the sample (i e , this is simply the number of vehicles in each category multiplied by the average test time). At the bottom of each table is the total test time under the fast-pass scenario being investigated as well as the number of incorrect passes and the number of true failures.

The results presented in Tables 15 to 17 indicate that the revised fast-pass algorithm does a better job of identifying passing vehicles without increasing overall test time Although the fast-pass test duration increases for the older model year groups, this is generally offset by a shorter fast-pass test duration for the newer model year groups, which have a larger number of passing vehicles. One way to look at the false passes is as a fraction of the total "true" failing vehicles (i.e , based on full-duration IM240 scores) Thus, under the start-up cutpoints (the results of which are summarized in Table 15), the current fast-pass algorithm results in 745 false passes out of 3,522 "true" failures, i.e , 21% of the failing vehicles are incorrectly fast-passed On the other hand, the revised fast-pass algorithm results in only 10% of the failing vehicles being incorrectly fast-passed, even though the overall test time did not increase appreciably (i e , 563 versus 566 hours of total dynamometer time)

A summary of the false passes and the total test time for the three sets of cutpoints analyzed in this study is shown in Table 18. It is interesting to note that the revised fast-pass algorithm results in an approximate 50% reduction in the number of false passes under each of the cutpoint scenarios shown in Table 18 In addition, with the exception of the start-up standards, the revised algorithm results in an overall decrease in total test time (or dynamometer time) relative to the current fast-pass methodology This occurs despite the fact that there are more failing vehicles (which run the full 240 seconds) under the revised fast-pass algorithm (Note that only fast-pass algorithms were investigated in this study; fast-fail approaches were not evaluated)

Table 15
Comparison of Current and Revised Fast-Pass Methodologies
Under the Start-Up IM240 Cutpoints
(26,000 Vehicle Sample)

Fast-Passes Based on Current Second-by-Second Cutpoints

Vehicle Class	MY Group	"True" P/F[a]	Fast-Pass P/F	Sample Size	Test Time (sec)	Total Time (hours)
LDT	81-84	F	F	162	240	10 8
		F	P	74	100	2 1
		P	P	701	54	10 4
	85-89	F	F	393	240	26 2
		F	P	129	82	2 9
		P	P	2,538	62	44 0
	1990+	F	F	144	240	9 6
		F	P	52	112	1 6
		P	P	4,876	49	66 7
LDV	81-84	F	F	922	240	61 5
		F	P	209	96	5 6
		P	P	1,163	68	21 9
	85-89	F	F	939	240	62 6
		F	P	235	114	7 4
		P	P	5,183	57	82 0
	1990+	F	F	217	240	14 5
		F	P	46	114	1 5
		P	P	8,043	59	131 7
					Total Time (hrs)	563 0
					Incorrect Passes	745
					True Failures	3,522

Fast-Passes Based on Revised Modal Analysis Methodology

Vehicle Class	MY Group	"True" P/F[a]	Fast-Pass P/F	Sample Size	Test Time (sec)	Total Time (hours)
LDT	81-84	F	F	220	240	14 7
		F	P	16	71	0 3
		P	P	701	73	14 1
	85-89	F	F	486	240	32 4
		F	P	36	70	0 7
		P	P	2,538	66	46 7
	1990+	F	F	153	240	10 2
		F	P	43	71	0 8
		P	P	4,876	44	59 0
LDV	81-84	F	F	1,084	240	72 3
		F	P	47	104	1 4
		P	P	1,163	105	33 9
	85-89	F	F	1,045	240	69 7
		F	P	129	82	2 9
		P	P	5,183	67	96 2
	1990+	F	F	188	240	12 5
		F	P	75	78	1 6
		P	P	8,043	43	96 6
					Total Time (hrs)	566 1
					Incorrect Passes	346
					True Failures	3,522

[a] "True" pass/fail status is based on the full-duration IM240 score

Table 16
Comparison of Current and Revised Fast-Pass Methodologies
Under the "Interim" IM240 Cutpoints
(26,000 Vehicle Sample)

Fast-Passes Based on Current Second-by-Second Cutpoints

Vehicle Class	MY Group	"True" P/F[a]	Fast-Pass P/F	Sample Size	Test Time (sec)	Total Time (hours)
LDT	81-84	F	F	339	240	22 6
		F	P	132	98	3 6
		P	P	466	60	7 7
	85-89	F	F	707	240	47 1
		F	P	206	92	5 3
		P	P	2,147	54	32 2
	1990+	F	F	300	240	20 0
		F	P	97	103	2 8
		P	P	4,675	58	75 3
LDV	81-84	F	F	1,359	240	90 6
		F	P	135	139	5 2
		P	P	800	94	20 9
	85-89	F	F	1,717	240	114 5
		F	P	241	142	9 5
		P	P	4,399	92	112 5
	1990+	F	F	495	240	33 0
		F	P	68	153	2 9
		P	P	7,743	83	178 3
					Total Time (hrs)	784 0
					Incorrect Passes	879
					True Failures	5,796

Fast-Passes Based on Revised Modal Analysis Methodology

Vehicle Class	MY Group	"True" P/F[a]	Fast-Pass P/F	Sample Size	Test Time (sec)	Total Time (hours)
LDT	81-84	F	F	445	240	29 7
		F	P	26	111	0 8
		P	P	466	100	12 9
	85-89	F	F	869	240	57 9
		F	P	44	87	1 1
		P	P	2,147	84	49 9
	1990+	F	F	326	240	21 7
		F	P	71	88	1.7
		P	P	4,675	56	72 2
LDV	81-84	F	F	1,457	240	97.1
		F	P	37	128	1 3
		P	P	800	130	28 8
	85-89	F	F	1,802	240	120 1
		F	P	156	99	4 3
		P	P	4,399	84	103 0
	1990+	F	F	466	240	31 1
		F	P	97	84	2 3
		P	P	7,743	54	116 0
					Total Time (hrs)	751 9
					Incorrect Passes	431
					True Failures	5,796

[a] "True" pass/fail status is based on the full-duration IM240 score

Table 17
Comparison of Current and Revised Fast-Pass Methodologies
Under the Final IM240 Cutpoints
(26,000 Vehicle Sample)

Fast-Passes Based on Current Second-by-Second Cutpoints

Vehicle Class	MY Group	"True" P/F[a]	Fast-Pass P/F	Sample Size	Test Time (sec)	Total Time (hours)
LDT	81-84	F	F	474	240	31.6
		F	P	109	98	3.0
		P	P	354	63	6.2
	85-89	F	F	1,062	240	70.8
		F	P	217	103	6.2
		P	P	1,781	66	32.8
	1990+	F	F	348	240	23.2
		F	P	83	113	2.6
		P	P	4,641	59	76.1
LDV	81-84	F	F	1,732	240	115.5
		F	P	88	144	3.5
		P	P	474	122	16.0
	85-89	F	F	2,597	240	173.1
		F	P	253	162	11.4
		P	P	3,507	128	124.6
	1990+	F	F	606	240	40.4
		F	P	81	162	3.6
		P	P	7,619	87	185.1
					Total Time (hrs)	925.7
					Incorrect Passes	831
					True Failures	7,650

Fast-Passes Based on Revised Modal Analysis Methodology

Vehicle Class	MY Group	"True" P/F[a]	Fast-Pass P/F	Sample Size	Test Time (sec)	Total Time (hours)
LDT	81-84	F	F	560	240	37.3
		F	P	23	114	0.7
		P	P	354	113	11.1
	85-89	F	F	1,210	240	80.7
		F	P	69	101	1.9
		P	P	1,781	93	46.2
	1990+	F	F	371	240	24.7
		F	P	60	94	1.6
		P	P	4,641	57	73.5
LDV	81-84	F	F	1,791	240	119.4
		F	P	29	157	1.3
		P	P	474	157	20.6
	85-89	F	F	2,702	240	180.1
		F	P	148	124	5.1
		P	P	3,507	121	117.4
	1990+	F	F	563	240	37.5
		F	P	124	100	3.4
		P	P	7,619	56	119.5
					Total Time (hrs)	882.2
					Incorrect Passes	453
					True Failures	7,650

[a] "True" pass/fail status is based on the full-duration IM240 score

Table 18 Summary of False Passes and Total Test Time for the Current and Revised Fast-Pass Algorithms (Based on 26,000 Vehicles from the Arizona 2% Random Sample)				
	Current Fast-Pass Algorithm		Revised Fast-Pass Algorithm	
Cutpoints	False Passes[a]	Test Time (hrs)	False Passes[a]	Test Time (hrs)
Start-Up	21%	563	10%	566
Interim	15%	784	7%	752
Final	11%	926	6%	882

[a] Reported as a percentage of the "true" IM240 failures based on the full-duration test scores

Test Cycle Duration for the Current Program

The analysis of test time under the current and revised fast-pass algorithms presented above provided only an estimate of initial test gross dynamometer time for each of the cutpoint scenarios investigated However, under an operating program, vehicles being retested (after failing their initial test) would also be subject to fast-pass standards, and it is not clear that those vehicles would have the same fast-pass characteristics as vehicles undergoing their initial test. Thus, this section presents an analysis of test cycle duration for the current program, evaluating test times for both initial tests and retests In addition, the current program in Arizona makes use of a fast-fail algorithm as well as a fast-pass algorithm, and the average test times for failing vehicles under the current program were also analyzed in this effort

To determine the average test time for the current program, the January 1996 to September 1996 database analyzed above was used Test time is included in the test record, so it was a fairly straightforward process to determine average test cycle duration This was estimated for passing and failing vehicles on their initial test and on retests, and the results are presented in Table 19 by vehicle class For initial tests, the average test time for passing vehicles in the current Arizona program is 62 seconds, and the average test time for failing vehicles is 183 seconds On retests, the average test time for passing vehicles is 82 seconds, and for failing vehicles it is 191 seconds

An analysis of test time was also performed with the 2% Random Sample database (which consists of initial tests only) The results are shown in Table 19 for the start-up cutpoints, the interim cutpoints, and the final cutpoints using the current fast-pass procedures. Only passing vehicle test time estimates are given in Table 19 for the 2% Random Sample, since an analysis of test times for vehicles failing the start-up and final cutpoints under the Arizona fast-fail algorithm (based on the 2% Random Sample) indicated nearly identical

Table 19 IM240 Test Time Duration Under the Current (i.e., Second-by-Second) Fast-Pass Procedures (Seconds)						
Vehicle Type	Test Type	Current Program[a]		2% Random and 3% Repair Sample Passing Vehicles Only[b]		
		Failing	Passing	Start-Up	Interim	Final
LDGV	Initial	182	66	60	89	103
	Retest	191	88	81	106	125
LDGT1	Initial	187	54	47	57	63
	Retest	193	71	181	74	78
LDGT2	Initial	186	58	83	66	67
	Retest	191	74	176	71	76
All Vehicles	Initial	183	62	59	78	88
	Retest	191	82	109	94	105

[a] Based on a 522,000-vehicle sample

[b] Based on a 26,000-vehicle sample for initial tests and a 12,000-vehicle sample for retests

values (i e , 180 seconds) as failures in the current program.* For passing vehicles, the average test time increases as the cutpoints become more stringent

Table 19 also summarizes retest duration under the three sets of cutpoints evaluated in this analysis Those results are based on an evaluation of the second-by-second data in the 3% Repair Sample from Arizona. (This sample consists of vehicles that fail their initial test and receive a retest[s] after repair Vehicles in the sample are tested over the full IM240) A comparison of test duration for all vehicles in Table 19 reveals that the average initial test time of the current program is reasonably consistent with the results from the 2% Random Sample However, the results for retests are quite different, particularly for light trucks It is unclear why this occurs, although it may be due to the smaller sample sizes of the light trucks or the fact that the 3% Repair Sample is not a completely random mix of vehicles (Included in the 3% Repair Sample are failing vehicles that were not flagged as a '3' at the start of the test, but became a '3' because they ran the full IM240 and failed)

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* Intuitively, one might expect the fast-fail test time under more stringent cutpoints to be less than under the current cutpoints. However, the algorithm used in Arizona requires that a decision be made (either fast-pass or fast-fail) for each pollutant before the vehicle receives a fast-pass or fast-fail for the overall test. Thus, although a vehicle might fast-fail early in the test for one pollutant, the test will continue until a decision is made for each pollutant A review of a limited number of test records indicated that the fast-pass decision for one pollutant was often the limiting factor in ending a test where a vehicle fast-failed for another pollutant

Because of this difference, the retest times from the current fleet were used in the analyses that follow

Impact of Tighter Cutpoints and Preconditioning on Test Times and Lane Throughput With the Current Fast-Pass Procedures

The failure rates contained in Table 13 were combined with the test duration estimates in Table 19 to arrive at the overall impact that tighter cutpoints will have on IM240 test duration and lane throughput using the current fast-pass procedures In addition, the combined impact of more stringent cutpoints and vehicle preconditioning procedures was also included in this analysis A description of these estimates follows.

Impact of Tighter Cutpoints - Before evaluating the impact of more stringent cutpoints on IM240 test time, it was necessary to estimate the average test time of the current program. This was accomplished by using 1,000 initial tests as the basis, and generating the total test time for the following components:

- Initial test passes (890 tests × 60 seconds per test)
- Initial test failures (110 tests × 180 seconds per test)
- Retest passes (99 tests × 80 seconds per test)
- Retest fails (77 tests × 190 seconds per test)

The failure rate of 11% for the current program came from Table 13, and the test times are from Table 19 (after rounding to multiples of 10) The fraction of vehicles subject to retests was estimated from the January 1996 to September 1996 data, which contained 59,000 initial test failures, 52,000 retest passes, and 42,000 retest failures. Thus, it was assumed that approximately 90% of the initial test failures ultimately pass a retest (i.e., 52,000 ÷ 59,000), and the total volume of retest failures is approximately 70% (42,000 ÷ 59,000) of the initial failures In actuality, a fair number of vehicles will pass the first retest, while others will fail several retests. It should be noted that these are only approximations that reflect an average of the fleet tested from January to September 1996 A more rigorous analysis would track individual vehicles (e g , by VIN) from initial test until they pass, receive a cost waiver, or remove themselves from the program

Average dynamometer test time is estimated to be 81 seconds in the current program A total of 1,176 tests are conducted for every 1,000 initial tests (This ignores any special testing that might be conducted and does not attempt to remove the 2% Random Sample nor the 3% Repair Sample from the analysis.) Multiplying total tests by average test time results in a total dynamometer testing time of 26 6 hours per 1,000 initial tests (This does not include the time during which no vehicle is in the lane or when other functions are occurring, e g , collection of vehicle information from the motorist.) A summary of the above calculations is presented in the "Current Program" column shown in Table 20

Table 20
Summary of IM240 Test Time Per 1000 Initial Tests
Using the Current Fast-Pass Procedures
(Fail Rates Based on 26,000 Vehicle Sample)

Parameter	**No Preconditioning**						**With Preconditioning**			
	Current Program		Interim Cutpoints		Final Cutpoints		Interim Cutpoints		Final Cutpoints	
	No of Tests	Time (sec)	No of Tests	Time (sec)	No of Tests	Time (sec)	No of Tests	Time (sec)	No of Tests	Time (sec)
Initial Tests	1000		1000		1000		1000		1000	
Initial Pass/No Precond	890	60	810	80	740	90	810	80	740	90
Precondition Pass	---		---		---		48	350	65	350
Initial Fail/No Precond	110	180	190	180	260	180	104	240	143	240
Precondition Fail	---		---		---		38	420	52	420
Retest Pass	99	80	171	80	234	80	121	80	161	80
Precondition Pass	---		---		---		7	350	14	350
Retest Fail	77	190	133	190	182	190	73	240	100	240
Precondition Fail	---		---		---		27	430	36	430
Total Tests/Time	1176	95750	1304	137950	1416	166700	1227	163584	1312	203052
Average Test Time		81		106		118		133		155
Net Testing Time Per 1000 Initial Tests (Hours)		26 6		38 3		46 3		45 4		56 4

Similar estimates were prepared for the interim cutpoints and the final cutpoints, and the results are also included in Table 20 Results are shown for both sets of cutpoints with and without preconditioning 1,000 initial tests are assumed for each analysis scenario Under each scenario, two columns are shown The first is the number of each particular type of test (e.g , initial pass, initial fail, retest pass, etc) that would be conducted The second column contains the average dynamometer test time (in seconds) estimated for each type of test

For the scenarios involving preconditioning, there are additional test types that are called either "Precondition Pass" or "Precondition Fail " The numbers shown in these rows represent the number and overall test times of vehicles that are projected to fail an initial IM240 and then be flagged for an immediate retest using modal data from the initial test The times shown for these tests include both the initial test and immediate retest For example, under the interim cutpoints it is projected that 48 out of 1,000 vehicles would fail the initial test but then be flagged for retesting and pass an immediate retest An additional 38 vehicles would fail and be flagged for retesting, but not pass the retest. 106 other vehicles would fail and not be flagged for retesting. The remaining 810 vehicles (out of the initial 1,000) would pass the initial test Further details on this subject are provided below

Average dynamometer test time (in seconds) for each scenario is shown on the next-to-the-final row of the table The final row shows the total dynamometer test time (in hours) associated with the 1,000 initial tests for each scenario, including all retests

Based on the analysis of the 2% Random Sample database presented in Table 19, it was assumed that vehicles passing the initial test would run 80 seconds under the interim cutpoints and 90 seconds under the final cutpoints The initial test failure rate was assumed to be 19% under the interim cutpoints and 26% under the final cutpoints (from Table 13) The same fraction of passing and failing retests (i e , 90% of initial test failures and 70% of initial test failures, respectively) was assumed for the interim and final cutpoints Unfortunately, no data exist with which to develop independent retest rates for the interim and final cutpoints (which would be a function of how well the repair industry could identify and repair vehicles failing the more stringent cutpoints) Finally, it was assumed that the test time for vehicles failing the more stringent cutpoints would be approximately the same as for vehicles failing the current (i e., start-up) cutpoints, which, as described above, was verified through an analysis of the 2% Random Sample

Significant increases in average dynamometer test time, number of total tests per 1,000 initial tests, and total dynamometer testing time per 1,000 initial tests are predicted when going to the more stringent cutpoints analyzed in this effort Implementation of the final IM240 cutpoints, *based on the current fast-pass cutpoint tables and without considering preconditioning procedures*, is estimated to result in a 20% increase in total tests, a 46% increase in average dynamometer test time, and a 74% increase in total dynamometer testing time

Impact of Tighter Cutpoints and Preconditioning - Based on the results of the 1996 preconditioning study previously conducted by Sierra and Gordon-Darby, it became clear that implementation of EPA's final IM240 cutpoints would result in a significant number of false failures due to inadequate preconditioning That study also recommended several preconditioning procedures that would minimize the fraction of false failures Based on one of those options (i e , using modal data from a full IM240 to determine whether a vehicle should be retested), the impact of more stringent cutpoints *and* preconditioning procedures on IM240 test time was estimated.

As noted above, 1,000 initial tests were used as the basis for this calculation, the results of which are summarized in Table 20 Using the final IM240 cutpoints as an example, the following assumptions were made

- The initial test failure rate of 26% (from Table 13) was reduced to 19.5% based on the finding that approximately 25% of the vehicles failing the final IM240 cutpoints would be false failures The test time for those vehicles that would pass after preconditioning (i.e , 6 5% of the initial tests) was assumed to be the initial 240 seconds plus 110 seconds. The 110-second test time of the second test was based on an analysis of back-to-back IM240 tests performed on passing vehicles that failed the first IM240. (This data set was analyzed in our previous analysis of preconditioning)

- The test time for initial test failures was assumed to be 240 seconds for vehicles that did not receive a second IM240 after failing the first. Based on the algorithm developed to determine if a failing vehicle would benefit from an immediate retest, it was found that approximately 20% of the initial test failures flagged for a retest would not pass a second test Thus, it was assumed those vehicles would run the full 240 seconds for the initial test and then would be subject to a fast-fail algorithm It was assumed that the test time of the second failing test would be equal to the average failing test in the current program

- The number of retest passes and retest fails was assumed to be the same as described above (i e , 90% of the initial test failures and 70% of the initial test failures, respectively). The split between those retests requiring preconditioning and those not requiring preconditioning was assumed to be the same fraction as observed in the initial tests (This is very simplistic and may understate the fraction of retested vehicles needing preconditioning) Test times were determined in the same manner as described above for the initial tests.

A similar approach was taken in estimating the test time increase for the interim cutpoints coupled with preconditioning procedures In that case, it was also assumed that 25% of the initial test failures would pass after a retest (see Section 4 of this report)

The implementation of more stringent cutpoints *and* preconditioning procedures results in a significant increase in average test time and the total testing time per 1,000 initial tests

However, the preconditioning procedures reduce the total number of tests relative to the more stringent cutpoints alone That is because there are fewer failures (and therefore fewer retests) when the preconditioning procedures are implemented Overall, implementation of EPA's final IM240 cutpoints with appropriate preconditioning procedures to reduce false failures is estimated to increase the number of tests required by 12%, the average dynamometer test duration by 91%, and the total dynamometer testing time by 112%

Overall, the net effect on test lane throughput will depend on how much time is required for other activities at the lane position where the dynamometer test occurs and how much time is required at the other lane positions In a three-position lane with a total of 3 minutes in each position, increasing the dynamometer testing time from 81 seconds to 155 seconds would increase the time in the position with the dyno test from 180 seconds to 254 seconds, reducing the maximum throughput from 20 vehicles/hour to 14.2/hour A 41% increase in lane capacity would be required to maintain the same system-wide maximum throughput It is possible that a smaller increase in capacity would be sufficient if certain functions could be shifted from the dyno test position to another lane position

For a two-position lane with 5 minutes in the dyno test position and 3 minutes in the other position, the same increase in test time would reduce the maximum throughput rate from 12/hour to 9.6/hour. A 25% increase in lane capacity would be needed to maintain system-wide throughput, unless certain functions could be shifted to the other lane position or a third position is created

Another factor that could affect the impact of the estimated increase in total testing time on IM240 network capacity requirements under more stringent cutpoints and preconditioning procedures is the existence of any "slack time" that can accommodate the additional tests and increased test time estimated above According to Gordon-Darby, however, the current Arizona IM240 test network is at or near capacity during peak periods when queues develop Therefore, moving to more stringent cutpoints and preconditioning procedures is expected to have an impact on IM240 network requirements consistent with the calculations described above

Finally, it is important to note that the failure rates and test times estimated above were based on the current fast-pass cutpoint tables, results from a similar analysis prepared with the revised fast-pass methodology are presented below

Impact of Tighter Cutpoints and Preconditioning on Test Times and Lane Throughput With the Revised Fast-Pass Procedures

To evaluate the impact of tighter cutpoints and preconditioning procedures on test times under the revised fast-pass procedures, an analysis similar to that described above was performed. This first required a more detailed analysis of mean test times with the revised fast-pass procedures than that presented earlier in this section The results of that analysis are shown in Table 21, which closely parallels Table 19 in format Comparing the results in Table 21 to those in Table 19, one observes that the average initial test time for passing vehicles under the revised fast-pass procedures is 3 seconds lower than the current procedures for the start-up cutpoints, 8 seconds lower for the interim cutpoints, and 11 seconds lower for the final cutpoints

Table 21
IM240 Test Time Duration Under the Revised (i.e., Modal) Fast-Pass Procedures (Seconds)[a]

Vehicle Type	Test Type	2% Random and 3% Repair Sample Passing Vehicles Only		
		Start-Up	Interim	Final
LDGV	Initial	57	70	81
	Retest	96	104	113
LDGT1 and LDGT2	Initial	53	67	70
	Retest	66	98	101
All Vehicles	Initial	56	70	77
	Retest	85	102	108

[a] Initial test results based on a 26,000-vehicle sample, retest results based on a 12,000-vehicle sample

As described above, the revised fast-pass procedures result in an approximate 50% reduction in false passes (i.e , errors of omission) Thus, the IM240 failure rate would increase under the revised procedures relative to the current procedures at the same cutpoint level The failure rates with the revised fast-pass procedures were therefore assumed to be midway between the current fast-pass failure rate and the failure rate calculated from the full-duration IM240 scores (see Table 14 of this section) These failure rates, along with the test duration estimates shown in Table 21, were used to generate estimates of total testing time per 1,000 initial tests for the revised fast-pass procedures with and without a preconditioning algorithm Those results are summarized in Table 22, which is formatted identically to Table 20.

In comparing Tables 20 and 22, one observes that the total testing time per 1,000 initial tests is very similar between the current fast-pass procedures and the revised fast-pass procedures. Although the revised fast-pass procedures result in shorter test duration for passing vehicles, the failure rate is higher than under the current fast-pass algorithm This results in a longer test duration for the additional initial test failures (i e , a full 240 seconds) and in more failing vehicles that must be retested

Table 22
Summary of IM240 Test Time Per 1000 Initial Tests
Using the Revised (i.e., Modal) Fast-Pass Procedures
(Fail Rates Based on 26,000 Vehicle Sample)

Parameter	**No Preconditioning**						**With Preconditioning**			
	Current Program		Interim Cutpoints		Final Cutpoints		Interim Cutpoints		Final Cutpoints	
	No of Tests	Time (sec)	No of Tests	Time (sec)	No of Tests	Time (sec)	No of Tests	Time (sec)	No of Tests	Time (sec)
Initial Tests	1000		1000		1000		1000		1000	
Initial Pass/No Precond	875	60	795	70	725	80	795	70	725	80
Precondition Pass	---		---		---		51	350	69	350
Initial Fail/No Precond	125	180	205	180	275	180	113	240	151	240
Precondition Fail	---		---		---		41	420	55	420
Retest Pass	113	80	185	100	248	110	130	100	169	110
Precondition Pass	---		---		---		8	350	16	350
Retest Fail	88	190	144	190	193	190	79	240	106	240
Precondition Fail	---		---		---		29	430	39	430
Total Tests/Time	1201	100760	1329	138410	1441	171450	1246	165114	1330	207674
Average Test Time		84		104		119		132		156
Net Testing Time Per 1000 Initial Tests (Hours)		28 0		38 4		47 6		45 9		57 7

Conclusions from the Analysis of Test Duration

Based on the results presented above, the following conclusions are reached

- Moving to more stringent cutpoints will result in a significantly higher number of failing vehicles, which will increase the average time per IM240 test as well as the total number of tests (due to retests of failing vehicles).

- Implementing preconditioning procedures to reduce the number of false failures will decrease the total number of tests. However, because the preconditioning procedures eliminate the possibility of fast-failing vehicles on the initial test (since the retest decision is based on a modal analysis of the entire IM240 test), the total time per test increases significantly This results in an overall increase in total test time per 1,000 initial tests when preconditioning procedures are implemented.

- Use of the revised (modal) fast-pass procedures developed in this study results in a shorter test duration and fewer false passes relative to the current procedures The shorter test duration is offset by the higher number of failing vehicles at a given set of cutpoints, resulting in very similar estimates of total test time per 1,000 initial tests for both the revised and current fast-pass procedures

###

7. ASSESSMENT OF IM240 SPEED VARIATION CRITERIA

In addition to preconditioning analysis, an evaluation of the effects of speed variations currently allowed in IM240 testing was conducted. Under Tasks 3 and 4 of the Work Assignment, modal Arizona IM240 data were analyzed to identify alternative statistical measures that better isolated emissions-affecting speed variations in the IM240 test traces This section of the report discusses the results of that analysis and presents recommended alternative statistical criteria to the current standard error (SE) tolerance

Examination of Current Criteria

Background - The prescribed driving cycle for the transient IM240 test consists of varying second-by-second speeds ranging from zero (i e., idle) to 56 7 mph, with maximum speed changes of ±3 3 mph/sec. During actual IM240 testing, the driver watches a graphical display of the prescribed or "reference" speed/time IM240 trace overlayed with the actual second-by-second trace as it is being driven as an aid to following the reference trace and anticipating upcoming speed changes (The visual display also indicates prescribed shift points for manual transmission vehicles along the trace)

Since each vehicle has different performance characteristics, it is impossible, even for highly skilled drivers, to precisely follow the second-by-second reference trace speeds during actual "one-time-only" testing As a result, EPA has specified two types of speed tolerance limits that define the "leeway" allowed to the driver in trying to follow the reference trace for the test to be considered valid: (1) speed excursion limits, and (2) speed variation limits Each of these criteria are described below [9]

Speed Excursion Limits [85.2221 (e) (4)] - Speed excursion limits shall apply as follows:

(I). The upper limit is 2 mph higher than the highest point on the trace within 1 second of the given time.

(ii). The lower limit is 2 mph lower than the lowest point on the trace within 1 second of the given time.

(iii). Speed variations greater than the tolerances (e.g., during gear changes) are acceptable provided they occur for no more than 2 seconds on any occasion.

(iv). Speeds lower than those prescribed during accelerations are acceptable provided they occur for no more than 2 seconds on any occasion.

Speed Variation Limits [85.2221 (e) (5)]

(i). A linear regression of feedback value on reference value shall be performed on each transient driving cycle for each speed using the method of least squares, with the best fit equation having the form: $y = mx + b$, where:

(A). y = the feedback (actual) value of speed;

(B). m = the slope of the regression line;

(C). x = the reference value; and

(D). b = the y-intercept of the regression line.

(ii). The standard error of estimate (SE) of y on x shall be calculated for each regression line. A transient driving cycle lasting the full 240 seconds that exceeds the following criteria shall be void and the test shall be repeated:*

(A). SE = 2.0 mph maximum.

(B). $m = 0.96 - 1.01$.

(C). $r^2 = 0.97$ minimum.

(D). $b = \pm 2.0$ mph.

EPA suspended the use of the speed variation limits on November 23, 1993, pending further evaluation.

Analysis of Current Criteria - Under this Work Assignment, the effectiveness of the speed variation criteria was examined (No analysis of the speed excursion limits was performed.)

* EPA's IM240 test procedures guidance includes "placeholders" for yet-to-be-defined criteria that apply to fast-pass or fast-fail tests that end prior to 240 seconds The development of second-by-second speed variation criteria for tests that end before 240 seconds was one of the goals of this work assignment

Sierra's analysis investigated the adequacy of the linear regression-based statistical tolerances contained in the speed variation limits to identify emissions-producing speed variations. It was found that although the current regression statistics provide an adequate means for ensuring that actual IM240 speeds generally follow the reference trace, they don't adequately identify speed variations that can dramatically affect emissions Sierra constructed a series of three hypothetical, easily driven IM240 speed traces, all of which complied with the current regression-based tolerances (and the speed excursion limits), as follows.

1 Smooth - a trace that generally lagged the peaks and valleys of the reference IM240 trace in a manner that "smoothed" their amplitudes to allowed limits;

2. Very Aggressive - a trace that contained a number of high-frequency oscillations (over 20) about the reference trace between the speed excursion limits, characteristic of extremely "jerky" driving behavior, and

3 Less Aggressive - a variation of the Very Aggressive trace in which the number of high-frequency oscillations were roughly halved and their durations were doubled to reflect mildly aggressive behavior

Figures 15 through 17 graphically illustrate each of these traces. (The thinly dashed lines in each of these figures show the speed excursion limits "envelope," indicating that each of these traces also meets the speed excursion criteria) "Least-squares" linear regression statistics (i e., SE, m, r^2, and b) based on second-by-second speeds in each trace against the reference IM240 trace were calculated and compared to the allowed speed variation tolerances Table 23 shows these comparisons

Table 23
Regression Statistics of Speed Variation-Compliant IM240 Traces

Trace	SE (Std Error)	m (Slope)	r^2 (Correlation)	b (Intercept)
Smooth IM240	1 99	0 97	0 98	-0 56
Very Aggressive IM240	1 86	1 00	0 99	0 11
Less Aggressive IM240	1.96	0 99	0 98	0 89
Current Allowed Limits	**< 2.0**	**0.96 to 1.01**	**> 0.97**	**< ± 2.0**

Figure 15
"Smooth" Speed Variation-Compliant IM240 Trace

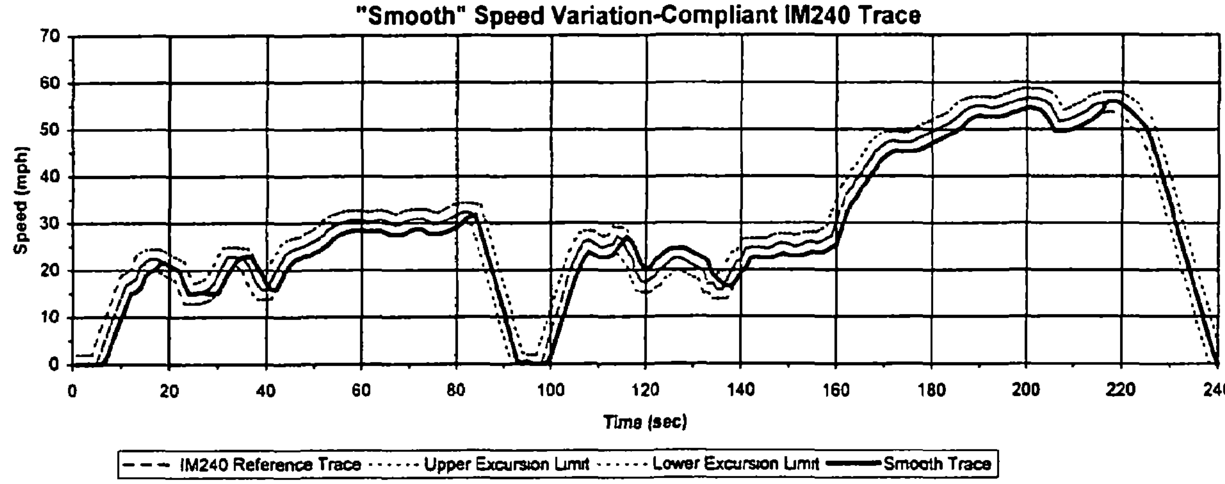


Figure 16
"Very Aggressive" Speed Variation-Compliant IM240 Trace

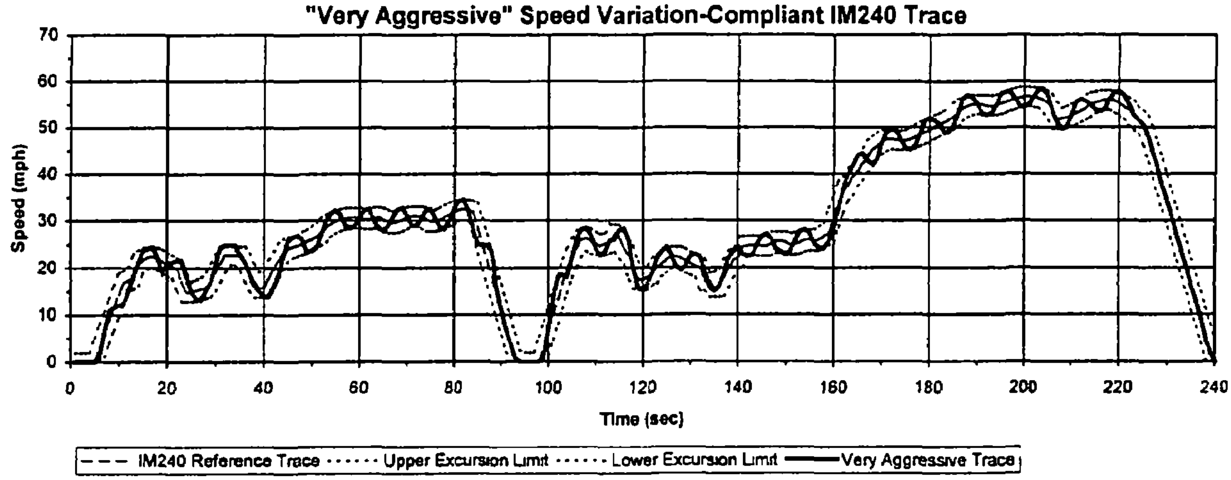
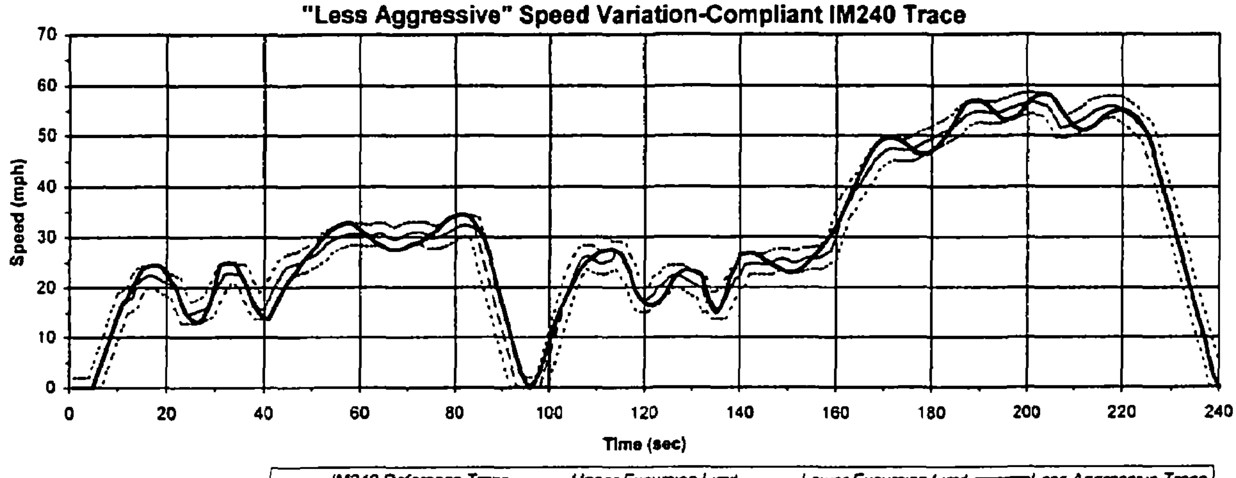


Figure 17
"Less Aggressive" Speed Variation-Compliant IM240 Trace

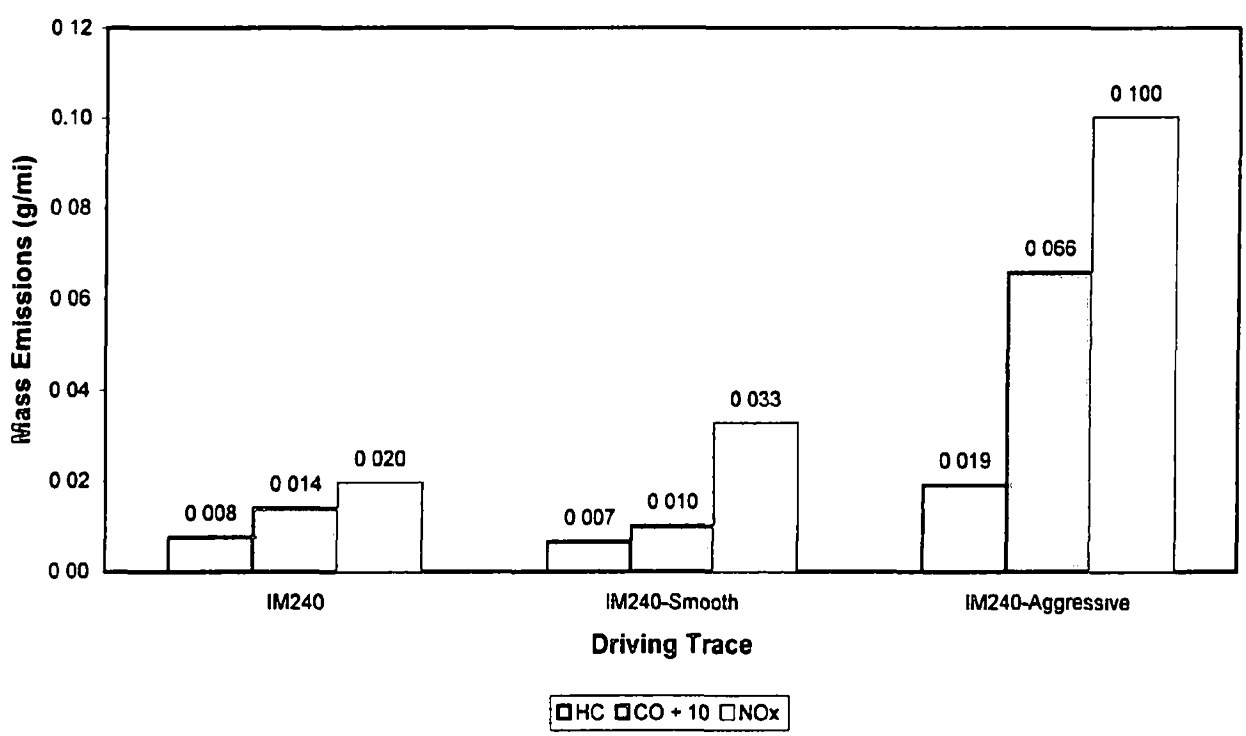


As shown in Table 23, all of the linear regression-based statistics for each of these hypothetical traces are within the allowed limits of the current speed variation criteria, and thus would be considered valid traces if driven in an IM240 test lane.

To demonstrate the inadequacy of speed variation criteria based on these linear regression statistics, IM240 emissions were measured for the Smooth and Very Aggressive traces as well as the reference IM240 trace when driven over on a chassis dynamometer Each of these second-by-second traces were input into a "driver's aid" display similar to that used in IM240 test lanes and then driven by a single, well-trained driver for two fully warmed, late-model vehicles in good condition - a 1997 Ford Taurus and a 1996 Honda Accord The driver was instructed to follow each trace as well as possible

The measured emission differences between the Reference, Smooth and Very Aggressive traces were significant, as illustrated in Figure 18 When driven aggressively but still within current tolerance limits, average IM240 emissions for the two vehicles were 2-5 times higher than when the same vehicles were driven over the reference trace. In addition, moderate CO and NOx differences were observed for the Smooth trace in comparison to the Reference trace emissions.

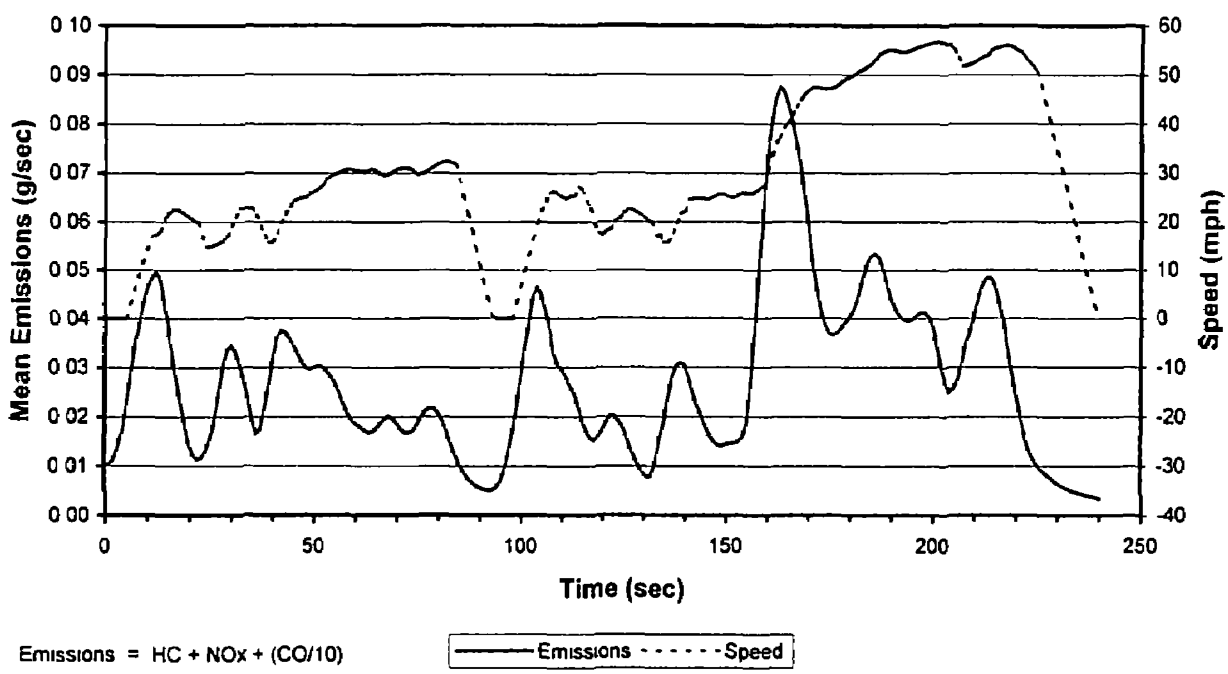
Figure 18
Comparison of IM240 Emission Test Results for Current Speed Variation-Compliant Traces



The point of this limited emission testing was not to represent the magnitude of emissions variations occurring in actual IM240 testing under the current speed variation limits, but to merely demonstrate, by example, the inadequacy of these regression-based statistics to identify high emissions-producing speed variations. This it does clearly

To better understand why these regression statistics cannot isolate high-emission speed variations, Figure 19 presents a comparison of second-by-second IM240 emissions against speed compiled from a large sample of Arizona IM240 tests* (To equate the scales of HC, CO and NOx, the emissions shown at each second represent the sum of mean HC and NOx emissions (in grams) plus CO divided by 10 as compiled from the Arizona test data.) Emissions are plotted against the left axis, speed against the right

Figure 19
Mean Second-by-Second Arizona IM240
Emissions vs. Speed
(Sample Size = 16,581)



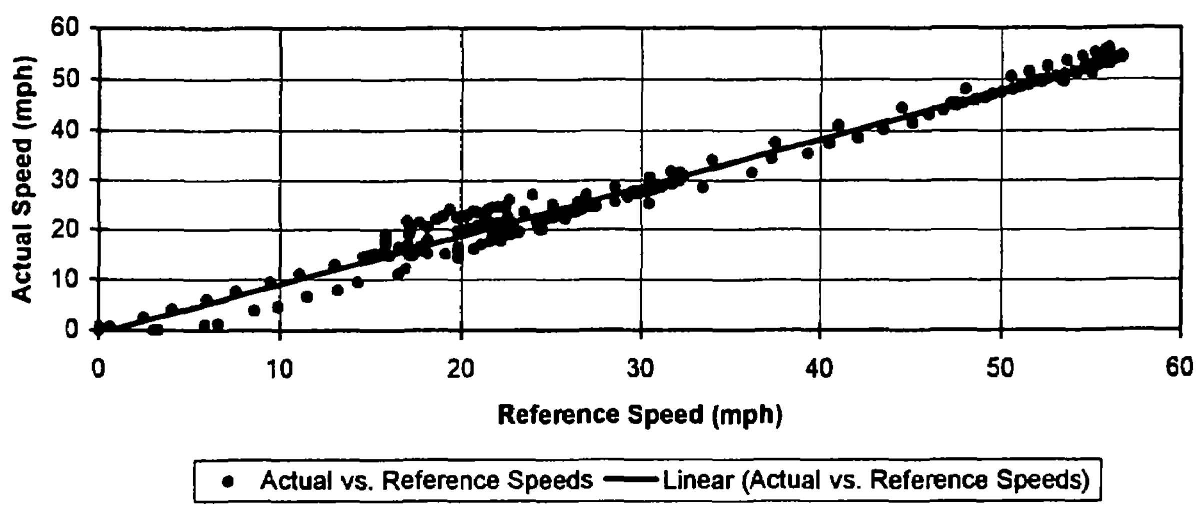
* The sample of modal Arizona IM240 data used throughout this speed variation analysis consisted of 16,581 tests conducted between January 1995 and October 1996 in which full 240 second IM240's were run (irrespective of fast-pass status) constituting the "2% random full-test" element of the program.

Figure 19 shows that the high-emission sections of the transient IM240 test (e g , seconds 10-15, 100-110 and 160-170) generally occur during periods of high acceleration (or moderate acceleration at high speeds) This is not surprising The behavior of late-model emission control systems under high speed and load conditions has become much better understood in recent years[10]. Under high engine loads, vehicles can go into "open loop" operation in which fuel enrichment can result in much higher emissions than under normal engine loads, even with a fully warmed engine and catalyst.

The current speed variation statistical tolerances are based on the relationship of actual to reference speeds and weight speed deviations equally over the range of the IM240 trace They cannot be expected to isolate the critical "high-emissions" portions of the trace which are more directly affected by engine load.

Figure 20 helps to illustrate this point. It shows a scatter plot of actual versus reference IM240 speeds for the hypothetical Smooth trace described earlier, along with the calculated "least-squares" regression line

Figure 20
Scatter Plot of Actual vs. Reference Speeds for "Smooth" IM240 Trace



The standard error (SE) statistic represents the sum of the squared vertical deviations of each of the data points to the regression line (and divided by the number of data points)[11] Mathematically, the standard error is given by the following equation

$$SE = \sqrt{\frac{\sum (y_i - \hat{Y})^2}{N - 2}}$$

where y_i are the actual data values (i e., actual IM240 speeds), $\hat{Y}$ is the regression line, and N is the number of data points (in this case, 240). As seen in Figure 20, a given deviation at low speeds is weighted the same as an equal deviation at high speeds in calculating the standard error. In other words, an actual speed of 12 mph for which the reference speed is 10 mph yields a 4 mph (2^2) squared deviation, which is equally weighted with a similar deviation for an actual speed of 52 mph when the reference speed is 50 mph The standard error statistic does not give "appropriate" higher weighting to speed deviations occurring at the critical high-emission points along the IM240 trace, and thus (along with the other regression statistics used in the current speed variation criteria), is ill-suited to identifying those speed deviations that substantially affect IM240 emissions.

The Work Assignment called for an evaluation of the efficacy of reducing the allowable standard error. However, as this analysis indicates, reducing the allowed tolerance will not further identify high-emission speed variations Therefore, no further evaluation of modifying the regression-based tolerances was conducted Instead, other statistical measures were investigated, as an alternative to the current regression parameters as explained in the following section.

Evaluation of Alternative Statistical Measures

Based upon similar work conducted by the New York Automotive Emissions Laboratory (AEL,)[12] two easily determined, alternative statistical metrics were evaluated for their ability to identify and quantify IM240 speed variations that significantly affect emissions:

(1). DPWRSUM - the sum of absolute changes in specific power, and

(2). Positive Kinetic Energy (PKE) - the sum of positive differences in kinetic energy per unit distance

Each of these metrics are explained in more detail below

DPWRSUM - Specific power is defined as power per unit mass, which can be restated as follows.

$$\text{specific power} = \frac{\text{power}}{\text{mass}} = \frac{\text{work}}{\text{mass} \times \Delta\text{time}} = \frac{\Delta\text{kinetic energy}}{\text{mass} \times \Delta\text{time}} = \frac{\frac{1}{2} \times \text{mass} \times \Delta V^2}{\text{mass} \times \Delta\text{time}}$$

Over a transient driving cycle of second-by-second speeds, EPA defines the specific power P at any time t (and dropping the factor of ½) as

$$P_t = V_t^2 - V_{t-1}^2$$

The absolute difference in specific power at time t can then be written as

$$\Delta P_t = |P_t - P_{t-1}| = |V_t^2 - 2V_{t-1}^2 + V_{t-2}^2|$$

The DPWRSUM statistic then is defined over a cycle of N seconds as

$$DPWRSUM = \sum_{t=0}^{N} \Delta P_t = \sum_{t=0}^{N} |V_t^2 - 2V_{t-1}^2 + V_{t-2}^2|$$

<u>PKE</u> - Positive Kinetic Energy has been defined mathematically[13] as

$$PKE = \frac{\sum_{t=0}^{N} PP_t}{\int_0^x dx}$$

over a traveled driving cycle of distance x where PP is the <u>positive</u> specific power and is given by

$$PP_t = V_t^2 - V_{t-1}^2$$

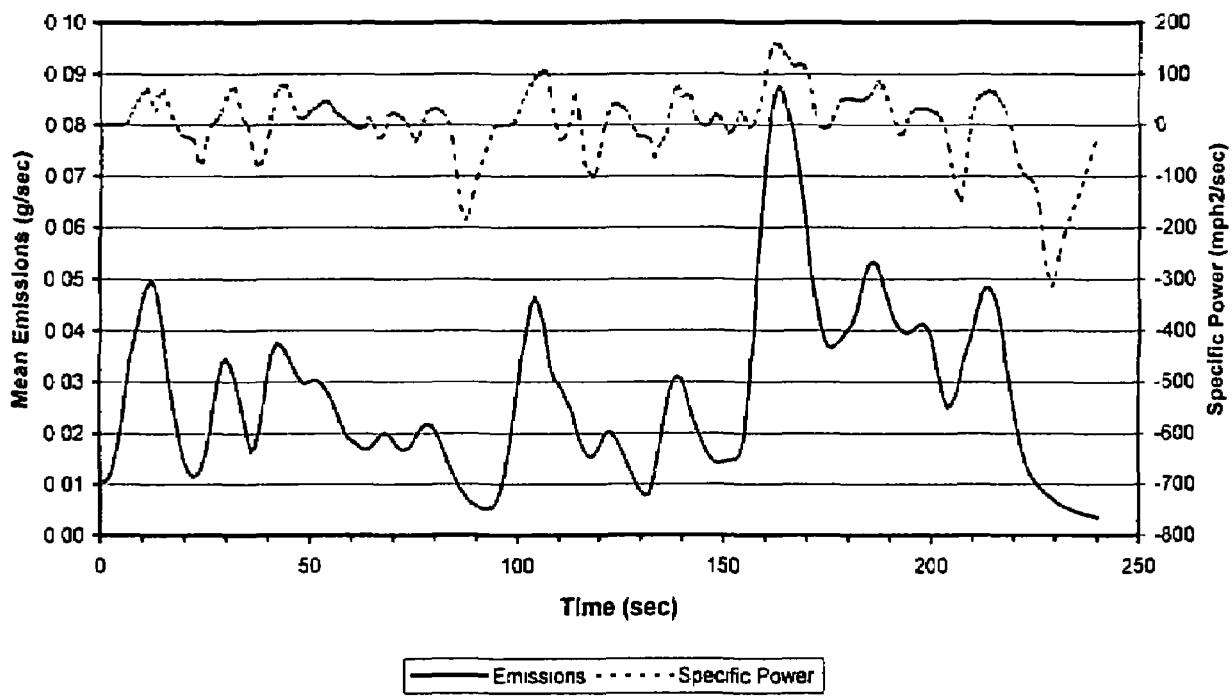
when $V_t > V_{t-1}$, and <u>is zero</u> when $V_t \le V_{t-1}$.

Each of these metrics can be easily computed from the second-by-second speed measurements collected in IM240 testing. In comparing their relative ability to identify speed variations that produce high emissions, it is helpful to consider <u>which</u> speed variations contribute to the value of each metric (similar to the earlier examination of the SE statistic) over an IM240 test.

Note that although both DPWRSUM and PKE are affected by differences in specific power or squared speeds over "adjacent" seconds of an IM240 trace, the value of DPWRSUM is increased <u>during decelerations</u> as well as accelerations. PKE on the other hand, is only increased during acceleration periods. This was an important distinction in evaluating which metric was best-suited to "tracking" significant emission-producing speed variations from the reference trace.

Figure 21 contains a comparison of second-by-second IM240 emissions against specific power compiled from the sample of Arizona IM240 tests cited earlier (Figure 21 is identical to Figure 19 presented earlier, except specific power is displayed instead of speed)

Figure 21
Mean Second-by-Second Arizona IM240
Emissions vs. Specific Power
(Sample Size = 16,581)



Note that during intervals of negative specific power (i.e., decelerations), such as between seconds 20-25, 85-95, and 195-205, mean emissions for those periods are much lower than emissions during positive specific power intervals (e.g., between seconds 10-15, 100-110, and 160-170). In other words, unlike DPWRSUM, the value of the PKE metric is not "diluted" with speed variations during decelerations that have little effect on emissions, and is only affected during accelerations Depending on the pollutant, 70%-80% of the overall average IM240 cycle emissions from the Arizona data sample were measured during periods of acceleration

Further evidence of the superiority of the PKE statistic over DPWRSUM is provided in Table 24, which compares the values of both statistics for each of the hypothetical speed variation-compliant IM240 traces described in the previous sub-section to the corresponding values for the reference IM240 trace

Table 24 Comparison of Alternative Statistics for Speed Variation-Compliant IM240 Traces		
Trace	PKE (miles/hr^2)	DPWRSUM (mph^2/sec)
Reference IM240	**3,269**	**6,370**
Smooth IM240	3,272	5,915
Very Aggressive IM240	5,865	18,245
Less Aggressive IM240	3,987	5,815

As shown, both metrics clearly distinguish the Very Aggressive trace from the IM240 reference values The PKE statistic also "properly" represents the behavior of the Less Aggressive trace, quantifying it between the Very Aggressive and Reference traces. However, the DPWRSUM value for the Less Aggressive trace is even lower than that of the Smooth trace Although the PKE statistic does not clearly distinguish the Smooth trace from the reference, as shown earlier in Figure 18, emissions over Smooth trace are not likely to differ notably from emissions over the Reference trace It was therefore concluded that PKE is a better measure than DPWRSUM for identifying those IM240 speed variations from the reference trace that significantly affect measured emissions

The next sub-section describes the methodology used to develop IM240 PKE variation limits to replace the current speed variation limits and presents the results.

Development of PKE-Based Variation Limits

The basic approach used to develop PKE-based speed variation criteria for the IM240 consisted of the following elements.

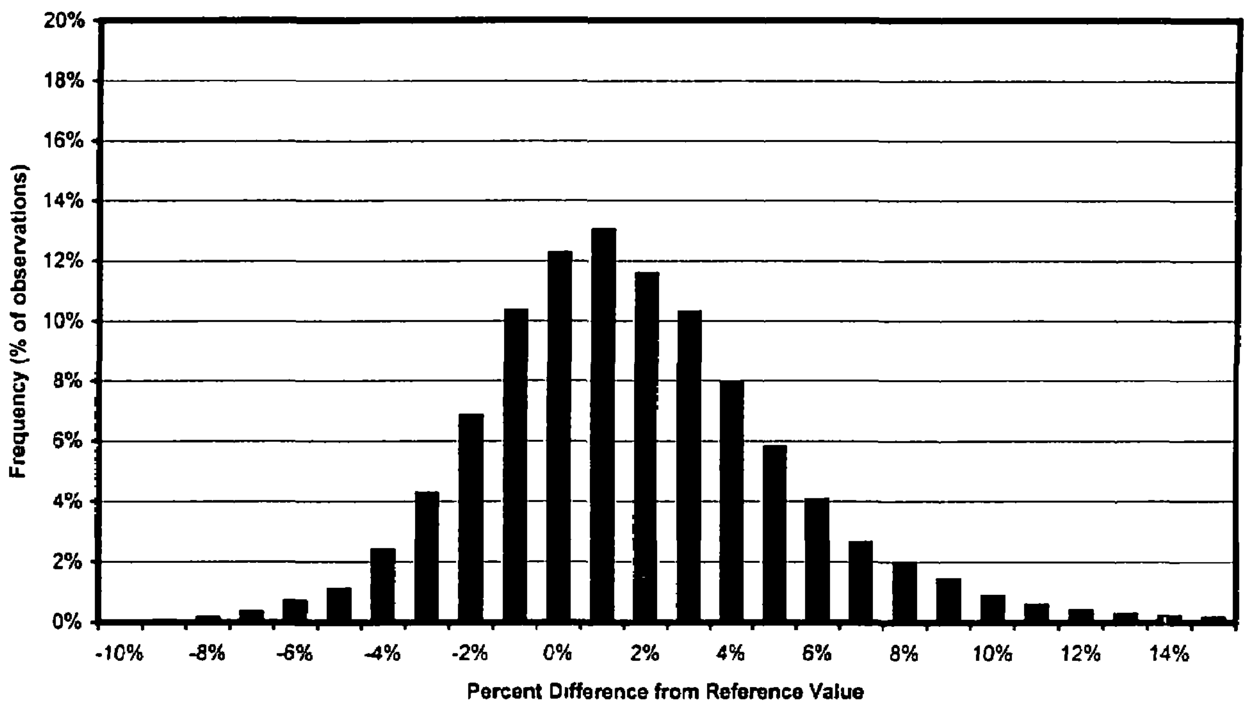
1 establishing upper and lower "composite" PKE limits for full 240-second tests from the Arizona data sample; and

2. scaling these composite limits based on the cumulative PKE at each second of the IM240 reference trace to produce second-by-second PKE limits.

Development of Composite Limits - As seen from the hypothetical "Aggressive" IM240 traces discussed earlier, values of PKE for a full 240-second IM240 test which significantly exceed the reference value of 3,269 miles/hr^2 may be indicative of higher measured emissions than if the reference trace were more closely followed In turn, PKE values for full IM240 traces that are well below the reference PKE may identify "under-measured" emissions.

Figure 22 shows the distribution of composite (i e , 240-second) PKE calculated from the second-by-second actual speeds in the Arizona data sample, expressed as the percent difference between actual and reference IM240 PKE As the figure shows, actual PKE appears normally distributed, although the median PKE is approximately 1% higher than the reference value

Figure 22
Distribution of Arizona IM240 PKE Differences
(% Difference Between Reference and Actual PKE, Sample Size = 16,581)



Note Sierra data are normalized

To determine how far to go along the "tails" of the PKE differences distribution to set composite limits, PKE differences among the test lane drivers in the Arizona data were examined. The basic concept applied in setting the PKE limits was to identify a significant fraction of drivers who, historically, could always (or nearly always) run IM240 tests within the selected PKE limits Given a mixture of ability among individual drivers to follow the reference trace, Sierra sought to identify the fraction of "competent" drivers who could follow the trace more consistently than others when conducting IM240 tests for a range of vehicles This subset of competent drivers and tests was used to establish composite PKE limits

The Arizona IM240 data sample (16,581 tests) was first sorted into groups by individual driver [*] A total of 502 drivers were found in the sample Driver groups containing fewer than 25 tests were then discarded, this left a total of 247 driver groups, which encompassed 86% of the tests in the total sample (i e before discarding small-sample driver groups). Composite PKE was then calculated for each test in the remaining driver groups. The mean and standard deviation of PKE from the tests within each driver group were also computed. The driver groups were then ranked by increasing PKE standard deviation and the top 50% of the drivers (based on lowest PKE standard deviation were used to compute possible composite PKE cutpoints. Table 25 lists a series of possible PKE cutpoints computed from the percentile PKE variance among the top 50% drivers For example, the PKE cutpoints shown for the 2% row under the "Top 50% Percentile" column indicates that 96% (100% - 2 x 2%) of the tests from the top 50% drivers had composite PKE within 3,148 and 3,522 miles/hr^2.

Table 25
Preliminary PKE Cutpoints (miles/hr^2) Based on Top-50% Drivers
(Sample Size = 6,749 Tests)

Top-50% Driver Percentile	Low-End PKE (miles/hr^2)	High-End PKE (miles/hr^2)	Interval Width (miles/hr^2)
±0 5%	3,104	3,592	488
±1.0%	3,125	3,551	426
±2 0%	3,148	3,522	374
±3.0%	3,161	3,500	338
±4 0%	3,170	3,483	312
±5 0%	3,178	3,469	291
±6.0%	3,186	3,459	273
±7.0%	3,193	3,449	256
±8.0%	3,198	3,441	232
±9 0%	3,203	3,435	220

Note that these preliminary cutpoints are not centered about the IM240 reference PKE value of 3,269 miles/hr^2 (as evidenced by the PKE distribution shown earlier in Figure 22) To generate a series of "final" cutpoints for evaluation, Sierra applied the interval widths

[*] Identified by the 4-digit "InspectorID" field in the database

shown in Table 25 to the reference PKE value to produce "centered" cutpoints about the reference value.

Incremental abort test rates for each set of centered cutpoints were then calculated based on both the entire 16,581 test Arizona data sample and the top-50% dnver subset The results are presented in Table 26, which lists both "simple" and "effective" abort rates Simple abort rates represent the fraction of tests in the sample for which the composite PKE cutpoints would have been exceeded Effective abort rates were calculated from simple rates by subtracting the fractions of <u>emission-pass</u> tests that exceeded the upper PKE cutpoint. The idea is that tests on vehicles that had passing emission scores but were driven with high PKE should not be aborted. In addition to the calculated <u>test</u> abort rates, Table 26 also shows the percentage of <u>drivers</u> who are always within the limits of each set of PKE cutpoints

Table 26
Centered PKE Cutpoints and Resulting Test Abort Rates

	Centered PKE Limits (mi/hr²)			Abort Rates (%) from All Tests		Abort Rates (%) from Top-50% Dnver Tests		Percentage of All Dnvers Within Limits	
Top-50% Dnver Percentile	Lower PKE Limit	Upper PKE Limit	Interval Half-Width	Simple Abort Rate	Effective Abort Rate	Simple Abort Rate	Effective Abort Rate	> Lower Limit	< Upper Limit
±0 5%	3,025	3,513	243 9	6 5%	1 2%	2 4%	0 3%	95 8%	48 0%
±1 0%	3,056	3,482	213 0	9 3%	1 8%	4 2%	0 6%	91 8%	40 4%
±2.0%	3,082	3,456	186.8	12.9%	2.9%	6.6%	1.2%	86.1%	32.9%
±3 0%	3,099	3,438	169 2	16 1%	3 7%	9 0%	1 6%	79 9%	28 7%
±4 0%	3,113	3,425	156 2	18 8%	4 5%	11 3%	2 1%	75 3%	26 1%
±5 0%	3,123	3,414	145 5	21 5%	5 2%	13 6%	2.7%	71 5%	23 9%
±6 0%	3,132	3,405	136 3	24 1%	6 0%	15 7%	3 1%	67 3%	21 5%
±7 0%	3,141	3,397	128 1	26 7%	6 9%	18.2%	3 8%	63 3%	20 3%
±8 0%	3,147	3,390	121 4	29 0%	7 6%	20 3%	4 3%	60 4%	19 1%
±9 0%	3,153	3,385	115 9	30 8%	8 3%	22 2%	4 9%	58 0%	18 5%
Sample Size	-	-	-	16,581 Tests		6,749 Tests		502 Dnvers	

Based on the results given in Table 26, Sierra proposes the use of composite lower and upper PKE limits of 3,082 and 3,456 miles/hr², respectively (shown in the shaded row in Table 26) As indicated in the table, these composite PKE limits would increase the abort test rate by just under 3% based on historical test data If dnvers are selected based on their ability to perform as well as the best 50% of the current drivers, then the abort rate would drop to just over 1%. In practice, it is expected that the abort rate will increase by less than this amount as drivers "adjust" to the new limits.

Development of Second-by-Second PKE Limits - Using the recommended composite PKE limits of 3,082 and 3,456 miles/hr, second-by second limits were generated by scaling the percentage difference of these limits from the composite reference value (5 7%) to the cumulative PKE calculated at each second from the reference trace This approach was further modified as described below

1. Similar to fast-pass emission standards, second-by-second PKE limits were not imposed until t=30 seconds, and

2 To further accommodate the wider variations in cumulative second-by-second PKE at the beginning of the transient IM240 test, a "PKE Multiplier" factor was applied that widened the allowed PKE limits. From its maximum value beginning at t=30 seconds, the PKE multiplier factor was linearly decreased to a value of unity (i.e., 1.0) at t=239 In other words, at the end of the test, the PKE limits were set equal to the composite PKE limits.

Figure 23 shows the effect on the effective abort rate resulting from use of various PKE multipliers between two and five times the composite PKE limits. Based on this analysis, Sierra generated second-by-second PKE variation limits using a PKE multiplier of 4 0. Figure 24 illustrates the successive narrowing of the second-by-second limits using this approach. Appendix C provides a listing of the recommended second-by-second PKE variation limits

Figure 23
Effect of Initial PKE Multiplier Stringency on Effective IM240 Abort Rate (Sample Size = 16,581)

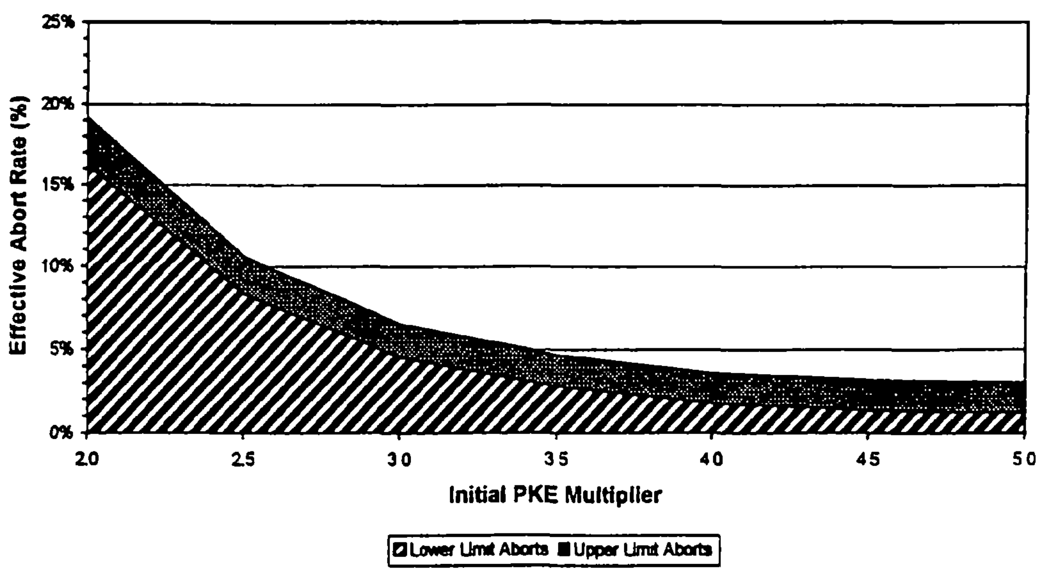
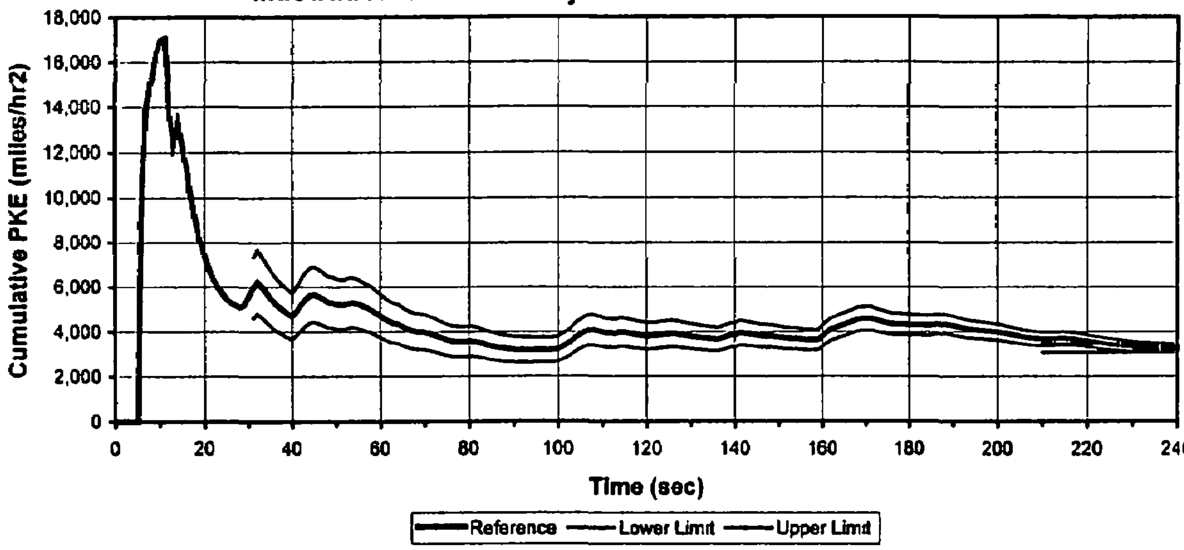


Figure 24
Illustration of Second-by-Second PKE Variation Limits



Other Issues - The effects of the proposed PKE variation limits by vehicle type and transmission type (e.g , manual versus automatic) were also investigated. Table 27 presents the effective abort rates for the Arizona data sample as a function of vehicle type when subjected to the recommended second-by-second PKE limits listed in Appendix C

Table 27
Effective IM240 Abort Rates by Vehicle Type with Proposed Second-by-Second PKE Variation Limits

Vehicle Type	Sample Size	Effective Test Abort Rate (%)		
		Lower Limit	Upper Limit	Total
Automobiles	10,770	2 0%	1 9%	3 9%
Light-Duty Truck 1	4,457	1 7%	1 5%	3 3%
Light-Duty Truck 2	1,354	0 8%	1 9%	2.7%
All Vehicles	16,581	1.8%	1 9%	3 6%

As Table 27 shows, the recommended PKE variation limits will not cause appreciably different test abort rates for individual light-duty vehicle types The Arizona IM240 program is limited to light-duty vehicles; therefore, no evaluation of the PKE limits on heavy-duty vehicles was performed

No evaluation of the PKE variation limits by transmission type was performed in this analysis. In the previous New York AEL study (cited earlier), a mathematical evaluation of manual "shift" events versus those observed from an automatic transmission was conducted. It was found that manual shift events would not cause an appreciable change in driving behavior statistics such as PKE (Although AEL used the DPWRSUM metric for this analysis, its second-by-second changes are a function of velocity-squared differences, like PKE. Therefore, Sierra believes the conclusions are the same for the PKE statistic.)

Finally, data from the Arizona I/M program were analyzed to determine whether the ability to meet the proposed speed variation criteria might be affected by vehicle age or demographic differences between the population in the vicinity of various test facilities Based on a random sample of 2% quality audit data (involving full I/M240 testing of each vehicle, regardless of whether it qualified for a fast pass or fast fail), violations of the proposed criteria (high and low side combined) by model year are shown below

1981 - 10 8%
1982 - 12 9%
1983 - 13 8%
1984 - 15 5%
1985 - 15 6%
1986 - 16.8%
1987 - 16.3%
1988 - 19.4%
1989 - 14 7%
1990 - 14.6%
1991 - 12 9%
1992 - 13.4%
1993 - 11.9%
1994 - 11.4%
1995 - 9.3%
1996 - 9 8%

The analysis indicates that older vehicles are roughly 50% more likely to fail the proposed speed variation criteria, as might be expected due to the increased frequency of defects in older vehicles. Some of these defects are expected to create drivability problems

Potential demographic differences if the failure to meet the proposed speed variation criteria were evaluated by comparing the results from test facility number 4 to test facility number 10 Gordon-Darby suggested that these two stations would reflect the ends of the spectrum in terms of the demographics of the surrounding areas Facility number 4 was expected to attract an older population of vehicles that might have greater maintenance problems

Analysis of the data showed that 14 5% of the 2% audit tests at facility number 4 failed to meet the proposed criteria compared to 10 3% of the vehicles tested at facility number 10 Much of this difference was related to the age distribution difference rather than differences between vehicles of the same age For example, 15 2% of 1985 -7 model year vehicles failed to meet the proposed criteria at facility number 4 compared to 14 6% of the same age group tested at facility number 10

The analysis described above indicates that differences in the ability of different categories of vehicles to meet the proposed speed variation criteria is not a major concern

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8. EVALUATION OF NOx CORRECTION FACTORS

Early studies on the mechanism of pollutant formation in engine combustion showed that the formation of oxides of nitrogen had a strong temperature dependence [14] Any changes in the initial fuel charge that reduce the peak combustion temperature will reduce the engine-out NOx concentration This concept has been used as the basis for control of NOx by the addition of exhaust gases as a diluent in exhaust gas recirculation (EGR) or by the use of water injection In addition to forming the basis for controlling engine-out emissions, the strong temperature dependence of NOx formation leads to changes in NOx due to changes in ambient conditions A higher ambient air temperature will lead to a higher combustion temperature which in turn will produce more NOx. Increased amounts of water vapor in the inlet air stream will act as a diluent, which will reduce the peak combustion temperature and reduce NOx Because of their strong temperature dependence, small changes in ambient conditions (i e , temperature and humidity) can have a significant impact on vehicle NOx emissions

Existing Correction Factor Equation

Because of the observed effects of initial conditions on NOx formation, several experimenters evaluated the effects of temperature and humidity on engine NOx emissions during the late 1960s and early 1970s These studies led to the current NOx correction factor, which first appeared in the January 15, 1972 Federal Register and has not been changed since that date. The same correction factor has been incorporated into EPA's high-tech IM240 test guidance The correction factor, K_H, is multiplied by the measured NOx emissions to yield the reported results For gasoline-powered vehicles, the NOx correction factor is given by the following equation·

$$K_H = \frac{1}{1 - 0\,0047\ (H - 75)} \qquad [8\text{-}1]$$

where H is the absolute humidity in units of grains of water per pound of dry air The absolute humidity is computed from the relative humidity, R_a, the ambient (barometric) pressure, P_B, and the saturation vapor pressure of water, P_v, by the following equation·

$$H = \frac{43\,478\ R_a\ P_v}{P_B - \frac{R_a}{100} P_v} \qquad [8\text{-}2]$$

In this equation, the relative humidity is in percent and any set of consistent units may be used for the pressures.* The correction procedure contained in EPA's high-tech guidance for computing NOx emission results during IM240 testing caps the temperature used to determine the vapor pressure of water at 86°F However, the value of humidity computed with this temperature cap is less than the actual absolute humidity The effect of the temperature cap on the correction factor is shown in Table 28 The correction factors contained in the column for a temperature of 86°F are the maximum correction factors allowed under the cap.

Table 28
Effect of Temperature Cap on Humidity Correction Factor

Relative Humidity	Humidity Correction Factor without Temperature Cap for Various Temperatures			
	86°F	90°F	100°F	110°F
0%	0 74	0 74	0 74	0 74
10%	0 79	0.80	0.82	0.85
20%	0 85	0 86	0 92	1.01
30%	0 92	0 95	1.05	1 24
40%	1 00	1.05	1 23	1 62
50%	1.09	1.17	1 49	2 35*
60%	1 21	1 33	1 90	4 37*
70%	1 36	1 54	2 61*	33 74*
80%	1 55	1.84	4 21*	-5 77*
90%	1.81	2.28*	11.15*	-2 63*
100%	2 18*	3 01*	-16 58*	-1 69*

*These correction factors are extrapolated beyond the region in which experimental data were available and regression analysis for those data was conducted

* The constant 43 478 is the ratio of the molecular weight of water to the molecular weight of air multiplied by 70 The factor of 70 is the unit conversion factor of 7000 grains per pound divided by 100 The division by 100 allows the use of relative humidity as a percent instead of a fraction This constant should actually be 43 537 if accurate molecular weights are used This error of 0 14% does not make any significant difference in the final correction factor

For certification tests, where the maximum cell temperature is 86°F, this temperature cap is not an issue. However, ambient temperatures during I/M testing may be higher than 86°F, particular in the Arizona IM240 program If an actual temperature in excess of 86°F were used in the equation, the calculated correction factor would be larger. The increase in the correction factor with the use of an uncapped formula depends on the relative humidity and temperature as shown in Table 28

At the highest relative humidity and temperature values shown in the table, the absolute humidity exceeds 288 grains of water per pound of dry air At this humidity and above, the correction factor equation yields a negative value The equation is obviously not valid in this region. A review of the original data, discussed below, shows that the measurements used to derive the correction factor did not include values above 180 grains of water per pound of dry air. Substituting this value into equation [8-1] yields a maximum correction factor for the range of experimental data of approximately 2.0.

$$K_H = \frac{1}{1 - 0.0047\ (180 - 75)} = 1\ 97 \approx 2\ 0 \qquad [8\text{-}3]$$

Humidity correction factors above this value have been marked by an asterisk in Table 29 to show that they have been extrapolated beyond the range of experimental data.

If the temperature used to compute the vapor pressure of water was not capped, it would be more difficult to pass an I/M test at higher temperatures At present the NOx correction factor for a relative humidity of 50% and a temperature of 110°F is 1 09, this value is found in the first numeric column of Table 28 for the capping temperature of 86°F. Without this cap, the humidity correction factor would be 2 35 at this temperature and relative humidity This is 116% greater than the present value and could cause a failure for a vehicle that would pass using the current correction factor

However, the capping procedure accounts in part for the lack of a temperature term in the correction factor At constant absolute humidity, higher temperatures would be expected to lower the correction factor. Thus, the temperature cap on the vapor pressure provides a qualitatively correct effect that is not present in the present humidity correction formula (equation [8-1]). a lowering of the humidity correction factor at higher temperatures.

Review of the Original Data

Sierra discussed the development of the humidity correction factor with EPA staff.[15*] The derivation of the final version of the correction factor was presented in an SAE paper[16]

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* The information and references provided by Mr Don Paulsell of EPA's Testing Service Division, NVFEL, was a great benefit to Sierra in the performance of this task His assistance is gratefully acknowledged

based on the Scott Laboratories study discussed immediately below The details of this development are discussed in the context of the Scott study

Scott Laboratories (1970) - Under funding from the National Air Pollution Control Administration, Scott Laboratories[17] examined the effects of temperature and humidity on "five typical American made vehicles and three foreign-made vehicles " All vehicles were from the 1969 model year with odometer readings of 12,385 miles or less Although individual vehicle results were analyzed for all eight vehicles, the study found that the results from the foreign-manufactured vehicles were "considerably different" from the domestic vehicles. Accordingly, the composite results were limited to the analysis of the five domestic vehicles.

Experimental temperatures used ranged from 59°F to 95°F, humidities ranged from 20 to 180 grains of water per pound of dry air Tests were made on the seven-mode cycle which was used for certification of vehicles at the time of the study Results were presented on both a concentration basis and a gram-per-mile basis

The data analysis used linear regression to derive an additive correction factor, CF_A. With the additive correction factor, emissions at standard conditions ($E_o = E[T_o,H_o]$) are related to emissions at the measured temperature and humidity (E[T,H]) by the following equation.

$$E(T_o,H_o) = E(T,H) + CF_A = E(T,H) + a(H - H_o) + b(T - T_o) \qquad [8\text{-}4]$$

The coefficients a and b were found by linear regression The study was done in two phases. The same vehicles and the same set of temperature and humidity data points were used in each phase. The report presents the data and analysis from both phases separately because the data from the second phase were found to be more reliable.

Derivation of the Humidity Correction Factor in Equation [8-1] - The actual regression equation from the Scott study used to derive the regulatory correction factor is shown below

$$E(T,H) = 7.165 + 0.0290(T - 78) - 0.0337(H - 75) \qquad [8\text{-}5]$$

A comparison of equations [8-4] and [8-5] shows that the following dimensional variables have been defined:

E(T,H) = actual NOx emissions in grams/mile,
$E(T_o,H_o)$ = 7 165 grams/mile NOx at the reference condition,
H_o = 75 grains of water per pound of dry air (reference humidity),
T_o = 78°F (reference temperature);

a	=	0 0337 grams/mile NOx/grain of water per pound of dry air, and
b	=	-0 0290 grams/mile NOx/°F

According to the SAE paper,[15] a humidity correction factor for certification test purposes was derived from equation [8-5] in the following manner. The reference temperature, T_o, was chosen as 78°F because it is near the midpoint of the allowed 68-86°F temperature range for certification testing. Within this range, the contribution of the temperature term ranged from -5.4% to +4 4% of the standard value. This effect was considered small and the temperature term was dropped from the equation Next, a multiplicative correction factor, K_H, was defined as the ratio of $E(T_o,H_o)$ / $E(T,H)$. Using equation [8-5] for $E(T,H)$ and the value of $E(T_o,H_o)$ = 7.165 grams NOx/mile yields the humidity correction factor used for certification testing.

$$K_H = \frac{E(T_o,H_o)}{E(T,H)} = \frac{7\ 165}{7\ 165\ -\ 0\ 0337\,(H\ -\ 75)} = \frac{1}{1\ -\ 0\ 0047\ (H\ -\ 75)} \qquad [8\text{-}6]$$

Reanalysis of Scott Data - Sierra checked this result by reanalyzing the Scott Phase II NOx data to determine a multiplicative correction factor * The approach used in this analysis is called the "dummy variable" or "absorption" technique This approach uses the following regression equation.

$$\ln E = \sum_{j=1}^{N} \alpha_j \delta_j + a(H - H_o) + b(T - T_o) \qquad [8\text{-}7]$$

The dummy variable, δ_j, is defined to be 1 for measurements on the j[th] vehicle and is zero otherwise These dummy variables are added to the actual experimental data that give a value for the emissions at a particular temperature and humidity. The combination of the experimental measurements and the dummy variables are the input data for the regression analysis. That regression analysis of equation [8-7] determines the coefficients a, b and α_1 toα_N, where N is the number of vehicles in the study The analysis below shows that the regression coefficients α_j are related to the reference emission values for each vehicle.

For any one vehicle (e g., vehicle k), the value of δ_j in equation [8-5] will be zero unless j = k. If j = k, all values of δ_j will be zero except for δ_k which will equal one So, for one vehicle, equation [8-7] may be written as follows:

$$\left[\ln E = \alpha_k + a(H - H_o) + b(T - T_o)\right]_{for\ vehicle\ k} \qquad [8\text{-}8]$$

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* The data used in this analysis, and some statistical results, are presented in Appendix D

When $T = T_0$ and $H = H_0$, the emissions are the reference emissions $E_0 = E(T_0,H_0)$. But, when $T = T_0$ and $H = H_0$ the right hand side of equation [8-8] is α_k. Thus, setting $T = T_0$ and $H = H_0$ in equation [8-8] shows that the regression coefficient α_k is simply the natural logarithm of the emissions at the reference conditions for that vehicle

$$\left[\ \ln E_o = \alpha_k\ \right]_{for\ vehicle\ k} \qquad [8\text{-}9]$$

Substituting this value for α in equation [8-8] gives the following result.

$$\left[\ \ln E = \ln E_o + a(H - H_o) + b(T - T_o)\ \right]_{for\ vehicle\ k} \qquad [8\text{-}10]$$

The "for vehicle k" subscript notation can be dropped, since this equation is valid for any vehicle. Combining the log terms and exponentiating both sides of the resulting equation gives a multiplicative humidity correction factor This factor is denoted as K_H^* to distinguish it from the existing correction factor contained in equation [8-1]

$$\ln\left(\frac{E}{E_o}\right) = a(H - H_o) + b(T - T_o) \qquad [8\text{-}11]$$

$$K_H^* = \frac{E_o}{E} = \frac{1}{e^{a(H - H_o) + b(T - T_o)}} \qquad [8\text{-}12]$$

The correction factor equation can be simplified by using the series expansion for e^x

$$e^x = 1 + x + \frac{x^2}{2} + \cdots \qquad [8\text{-}13]$$

Only the linear terms are retained for a small correction, giving the approximate equation shown below

$$K_H^* = \frac{E_o}{E} \approx \frac{1}{1 + a(H - H_o) + b(T - T_o)} \qquad [8\text{-}14]$$

This has the same form as the existing equation for the humidity correction factor if the temperature effect is ignored

The Phase II NOx data, on a gram-per-mile basis, for the five domestic vehicles were used in a regression analysis with equation [8-7] as the model The reference humidity and temperature were taken as 75 grains of water per pound of dry air and 75°F, respectively * The results were run in three ways (1) with no temperature or humidity correction terms, (2) with the humidity correction only, and (3) with both the temperature and humidity correction. When only humidity is considered, the value of a is -0 0043 pounds of dry air per grain of water; when both humidity and temperature are considered, the respective values of a and b are -0 00498 pounds of dry air per grain of water and 0.00445/°F The two values for the humidity coefficient bracket the value of -0 0047 pounds of dry air per grain of water used in the equation [8-1] for K_H. If the temperature term from the Scott/EPA analysis had been retained, the equation for K_H would have a temperature coefficient of 0 0290/7 165 = 0 00405/°F, which is similar to the one found by Sierra's analysis.

The statistical significance of adding the temperature and humidity corrections was evaluated. With no consideration of temperature or humidity, the net effect of the regression is to set the emissions for each data point equal to the average for the vehicle that generated that data point. This regression has an R^2 value of 0 25 Adding only the consideration of humidity gave an R^2 value of 0.76 Adding the temperature increased the R^2 value from 0 76 to 0.82. An F test on the incremental improvement obtained by each additional step showed that the addition of both variables adds significant explanatory power to the model. [The probability (p value) that the humidity has no effect is 1×10^{-24}, the p value that the addition of temperature to the humidity data has no effect is 5×10^{-7}] Thus, the Scott Laboratories data show that both the temperature and humidity corrections are statistically significant. The original rationale for not including the temperature effect within the temperature range of the Federal Test Procedure (FTP) is reasonable For applicability to IM240 testing, however, the temperature effect could be important. Because the temperature effect is smaller than the humidity effect, it is more difficult to detect the temperature coefficient accurately The regression equation for temperature and humidity has the following 95% confidence intervals for the coefficients

- Humidity coefficient: 0.000641 or 13% of the coefficient (-0 00498), and
- Temperature coefficient. 0.00231 or 52% of the coefficient (0 00445)

When humidity alone (in addition to the dummy variables) was used in the regression equation, the 95% confidence interval for the humidity coefficient was 0.000612, or 14% of the coefficient's value of -0 00430.

Values of the humidity correction factor predicted by equation [8-12] are shown in Table 29 The Table 29 results are presented for the same range of temperatures shown in

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* This reference temperature was chosen to have the same numerical value as the reference humidity

Table 28 except that smaller temperature increments are used In addition, the bold lines in Table 29 divide that table into the following four regions

1 The upper left-hand region has no extrapolations beyond the region of the experimental data;

2. The upper right-hand region extrapolates temperature, but not humidity, beyond the range of experimental data,

3. The lower left-hand region extrapolates humidity, but not temperature, beyond the range of experimental data; and

4. The lower right-hand region extrapolates both temperature and humidity beyond the region of experimental data.

Table 29
Temperature-Humidity Correction Factors from Equation [8-12]

Relative Humidity	Humidity-Temperature Correction Factors for Temperatures Shown					
	T = 86°F	T = 90°F	T = 95°F	T = 100°F	T = 105°F	T = 110°F
10%	0 72	0 71	0 71	0 71	0 71	0 71
20%	0 79	0 79	0 80	0 82	0 84	0 86
30%	0.86	0 88	0 91	0 95	0 99	1 05
40%	0 95	0 98	1 03	1 10	1 18	1 29
50%	1 04	1 09	1 17	1 27	1 40	1 58
60%	1 15	1 22	1 33	1 48	1 67	1 94
70%	1 26	1.36	1 51	1 72	2 00	2 40
80%	1.39	1 52	1 73	2 01	2 40	2.97
90%	1 53	1 70	1 97	2 35	2 90	3 70
100%	1.69	1 90	2 25	2 76	3 50	4 63

Definition of Regions in Table 29	
No extrapolations	T extrapolated
H extrapolated	T and H extrapolated

As shown in Table 29, the effect of temperature at constant *relative humidity* is smaller in this case than in the results shown in Table 28. In Table 28, the correction factor at 50% relative humidity increased from 1.09 to 2.35 as the temperature increased from 86°F to 110°F That effect was simply due to the increase in absolute humidity In Table 29, the correction factor at 50% relative humidity increased from 1 04 to 1 58 as for the same change in temperature. The correction factor at 50% relative humidity and 110°F is suspect since it lies in that region of Table 29 in which both temperature and humidity have been extrapolated beyond the range of experimental data. The actual correction factor used in practice for 50% relative humidity and any temperature at or above 85°F would be 1 04. This is set by the formula that uses 86°F as the maximum temperature for computing the saturation vapor pressure of water

The Scott report is very cautious about any conclusion that can be drawn from the test fleet of five vehicles The final plots of the regression analyses for the combined fleet are included in an attachment whose cover page has the following heading

Composite Vehicle Correction Factors

(Based on a small sample - for

illustrative purposes only)

The report concludes that

> *... judgement must be exercised in applying these correction factors because they are based on a small sample of vehicles. The regression analyses show quite clearly that additional work with a larger sample of vehicles is desirable.*

Ethyl Research Laboratories (1970) - The Automobile Manufacturer's Association (AMA) sponsored a study by Ethyl Research[18] that tested ten vehicles Eight vehicles (seven from the 1969 model year and one from the 1968 model year) were supplied by AMA. The maximum odometer reading on these vehicles was 7,772 miles Two additional vehicles from another project were tested simultaneously, but were not included in the composite results. Tests were made on a seven-mode cycle and reported on a concentration basis. The temperature for all runs was controlled to 76±5°F and the humidity ranged from 20 to 120 grains of water per pound of dry air.

The Ethyl results were presented as a quadratic regression equation for the correction factor The final equation presented by Ethyl can be modified into the form that uses (H - 75) instead of H as the variable The Ethyl equation, modified into this form, is shown below.

$$K_H^{**} = 1 + 0\,0037\,(H - 75) + 1.29x10^{-5}\,(H - 75)^2 \qquad [8\text{-}15]$$

This can be compared to the usual equation for the humidity correction factor by using the series expansion for 1/(1-x)

$$\frac{1}{1 - x} = 1 + x - \frac{x^2}{2} + \cdots \qquad [8\text{-}16]$$

Using this only the first two terms in this series expansion and ignoring the quadratic term in equation [8-15], the Ethyl equation for K_H^{**} can be written approximately as follows

$$K_H^{**} = \frac{1}{1 - 0\ 0037\ (H - 75)} \qquad [8\text{-}17]$$

This shows less of an effect of humidity as compared to the certification/IM240 formula in which the factor multiplying the (H - 75) term is 0 0047 pounds of dry air per grain of water (instead of 0.0037 pounds of dry air per grain of water shown in the Ethyl results) However, both equations [8-1] and [8-17] are defined to have the same correction factor – one – at a humidity of 75 grains of water per pound of dry air Consequently, the difference in the humidity correction factors between these two equations is small, and the Scott/EPA SAE paper called the NOx results from the Scott and Ethyl data "remarkably similar."[15] Sierra did not analyze the original data in the Ethyl paper However, average data were presented in the Ethyl paper for K_H at various humidity values These data were used in a linear regression to obtain a humidity factor of 0 0036 pounds of dry air per grain of water

The authors of the paper concluded that "[f]actors have been derived for correcting observed concentrations of nitrogen oxides from the actual intake air moisture content at the time of test to 75 grains of water/lb dry air at 76 F "

Ford - Ford published a study by Robison[19] describing the effects of intake air humidity on a single six-cylinder engine operated on an engine dynamometer The engine model year was not identified in the paper, but it must have been earlier than the 1970 publication data of the paper. This study examined steady-state NO concentrations at a variety of carefully controlled engine conditions. The goal of this study was not to determine a fleet-average correction factor, but rather to show how different engine operating variables interacted with intake air humidity to affect NO concentrations. Robison used an additive correction factor, CF_A, to analyze the NO concentration data.

$$[NO]_o = [NO] + CF_A\ (H - H_o) \qquad [8\text{-}18]$$

In this equation, [NO] represents the NO concentration in ppm and $[NO]_o$ is that concentration at the reference humidity, H_o Robison found that the correction factor increased with NO levels in most cases The exception was for rich mixtures where the correction factor did not depend on NO concentrations He also found an effect of air/fuel ratio on the humidity correction factor He developed two empirical functions of the air/fuel ratio, X(A/F) and Y(A/F), to express this relationship Robinson's final equation for the additive humidity correction factor is given by equation [8-19]

$$CF_A = \frac{X(A/F) + Y(A/F)\,[NO]}{1 - Y(A/F)\,H} \qquad [8\text{-}19]$$

Robison's work is based on a single engine and does not develop a correction factor that can be applied to mass emissions in general. Instead, this work shows a wide variation in the humidity correction factor depending on the engine operating conditions. The range of observed values does contain the values of humidity correction found from other studies

This work shows that humidity effects do depend on engine operating conditions To the extent that engine operations have shifted from the air/fuel ratios and NOx levels that existed in late-1960s model year engines, Robison's work would predict that the humidity effects would change as well

Heavy-Duty Correction Factor - Ethyl Research Laboratories also determined the humidity correction factor for gasoline-powered trucks [20] The experimental plan was similar to the one performed by Ethyl for light-duty passenger cars. Specifically, the tests were done at a single controlled temperature while the humidity was varied. Seven engines were tested over the nine-mode cycle used for heavy-duty vehicles at the time of the study Ethyl presented data on a multiplicative correction factor averaged over all the vehicles in the test fleet. Sierra used a regression analysis to convert the humidity coefficient into the form of the present correction factor equation The value was found to be 0.0042 pounds of dry air per grain of water This is even closer to the value of 0 0047 in equation [8-1] than the value found from the Ethyl data for light-duty vehicles This study shows that the humidity effect on gasoline-fueled vehicles is relatively independent of the engine classification.

Discussion of Results

The experimental studies underpinning the current humidity correction factor are generally in good agreement However, all of those studies were conducted nearly 30 years ago Although the fundamentals of engine thermochemistry have not changed in that period, emission control and fuel management systems have changed significantly. As discussed above, the study by Robison[18] found that the humidity correction varied with air/fuel ratio and NOx level As a result, the decrease in NOx emissions associated with the use of decreased compression ratios and exhaust gas recirculation (EGR) should reduce the impact of humidity. However, operation at leaner air/fuel ratios should increase the effect of humidity The ultimate effect of humidity on engine-out NOx levels and the changes in those levels over a catalytic converter cannot be determined without a test program on modern automobile engines

If extended use of a correction factor is required (i e , in operating IM240 programs) pending completion of such a test program, the original data used to derive the humidity correction factor could be used to develop a modified correction factor for use in the interim. The temperature-humidity correction factor that was found from the Sierra reanalysis of those data is shown in Equation [8-12]. Using constants a = -0 004977 pounds of dry air per grain of water and b = 0.004447/°F, that equation can be rewritten as follows

$$K_H^* = \; = e^{0\,004977 (H \,-\, 75) \,-\, 0\,004447 (T \,-\, 75)} \qquad [8\text{-}20]$$

This equation uses temperature in °F and humidity in grains of water per pound of dry air to produce the dimensionless correction factor The correction factor found from equation [8-20], over the range of data used in the original study,[16] is shown in Table 30 In contrast with previous tables, this table uses absolute humidity instead of relative humidity. When the humidity values are presented in this fashion, the relatively small effect of temperature as compared to absolute humidity is clearly seen

In actual I/M tests, there will be a large range of temperatures and humidities that will be beyond the range in which the original measurements were obtained Some consideration must be given to the proper extrapolation of equation [8-20] beyond this experimental-data region. One possible form for limiting the application of this equation is shown in Table 31. This table shows the correction factors as a function of temperature and relative humidity. Also shown for comparison are the maximum humidity correction factors, for a given relative humidity, computed using the formula contained in the high-tech guidance

As shown in the table, the maximum value with the current correction factor is 2 19 (at a relative humidity of 100% and a temperature of 86°F or greater); this could be used to limit the correction factor computed from equation [8-20]. This would be consistent with the current approach and require only a small region of temperatures and humidities (which are shaded in the table) to be set to this maximum value

Although the correction factors in Table 31 provide a better representation of the original high temperature data, they still have the limitation that the data were obtained on older cars and may not be applicable to present-day automobiles. The net effect of these factors for individuals taking an I/M test would only occur at higher temperatures above the current cap of 86°F The modified factors would be lower (which improves the likelihood of passing the NOx cutpoints) at relative humidities of 20% or less, and higher (more likely to fail) at relative humidities of 40% or more Between these two relative humidities, the change in the factor depends on the temperature

Table 30
Temperature-Humidity Correction Factors from Equation [8-20]

Absolute Humidity (gr/lb)	Temperature-Humidity Correction Factor for Temperatures Shown					
	T = 60°F	T = 70°F	T = 80°F	T = 85°F	T = 90°F	T = 95°F
20	0.81	0.78	0.74	0.73	0.71	0.70
40	0.90	0.86	0.82	0.80	0.79	0.77
60	0.99	0.95	0.91	0.89	0.87	0.85
80		1.05	1.00	0.98	0.96	0.94
100		1.16	1.11	1.08	1.06	1.04
120			1.22	1.20	1.17	1.14
140	Temperature/humidity combinations in this region are not possible.		1.35	1.32	1.29	1.26
160				1.46	1.43	1.40
180				1.61	1.58	1.54

Absolute Humidity (gr/lb)	**For comparison with previous tables, the relative humidities for the temperatures and absolute humidity entries are shown below**					
	T = 60°F	T = 70°F	T = 80°F	T = 85°F	T = 90°F	T = 95°F
20	26%	19%	13%	11%	10%	8%
40	52%	37%	26%	22%	19%	16%
60	78%	55%	39%	33%	29%	24%
80		73%	52%	44%	38%	32%
100		91%	65%	55%	47%	40%
120			78%	66%	56%	48%
140	This region has relative humidities greater than 100%		90%	77%	66%	56%
160				87%	75%	64%
180				98%	83%	71%

Table 31
Temperature-Humidity Correction Factors beyond Experimental Range

Relative Humidity	Temperature-Humidity Correction Factor at Temperatures Shown									Current Factor for T>86°F
	T=40°F	T=50°F	T=60°F	T=70°F	T=80°F	T=90°F	100°F	110°F	120°F	
0%	0.80	0.77	0.74	0.70	0.67	0.64	0.62	0.59	0.56	0.74
10%	0.82	0.79	0.76	0.74	0.73	0.71	0.71	0.71	0.73	0.79
20%	0.83	0.81	0.79	0.78	0.78	0.79	0.82	0.86	0.94	0.85
30%	0.85	0.83	0.82	0.83	0.84	0.88	0.95	1.05	1.23	0.92
40%	0.86	0.86	0.86	0.87	0.91	0.98	1.10	1.29	1.61	1.00
50%	0.88	0.88	0.89	0.92	0.99	1.09	1.27	1.58	2.12	1.09
60%	0.90	0.90	0.93	0.98	1.06	1.22	1.48	1.94	2.82	1.21
70%	0.91	0.93	0.96	1.03	1.15	1.36	1.72	2.40	3.78	1.36
80%	0.93	0.95	1.00	1.09	1.25	1.52	2.01	2.97	5.10	1.56
90%	0.95	0.98	1.04	1.15	1.35	1.70	2.35	3.70	6.93	1.82
100%	0.96	1.00	1.08	1.22	1.46	1.90	2.76	4.63	9.50	2.19

Note: Shaded cells with correction factors would have the correction factor set to the current maximum value of 2.19

The factors in Table 31 provide a more accurate representation of the original data However, they still have some degree of extrapolation beyond the region of the experimental data. In addition, because these factors were developed on late 1960s vehicles, their applicability to current automobiles is uncertain. Until additional test results or analyses are available, the correction factor we have derived from the original data set would appear to improve the accuracy of the NOx correction

Use of IM240 Data

One approach to developing an improved NOx correction factor may be to use IM240 data from Arizona The main problem with such data is that they do not contain repeated measurements on the same vehicle in the same state of repair with different values of ambient temperature and humidity However, because of the large size of the database, it should be possible to find a large number of tests on a vehicle with the same make and model year If newer vehicles were selected for the study, the vehicle-to-vehicle variation in emissions should be small This could provide a large enough sample in which the temperature and humidity effect could be distinguished from the variation among the different vehicles. The Arizona IM240 data base typically contains approximately 320,000 records per year Limiting the data sample to the 2% random sample of full 240-second tests means that roughly 16,000 records/year are available for analysis * Selecting the most popular models (e.g., Ford Taurus) in recent model years may provide a sample of approximately 100 vehicles with the same make and model year for 10-20 combinations of make and model year Data from these vehicles could be analyzed using the method outlined in equations [8-7] to [8-14].

It is not clear if such an approach would work The variation from vehicle to vehicle could overwhelm the effect of ambient conditions. However, the validity of the results could be determined by examining their statistical significance. In particular, the significance test could determine if the regression coefficients for humidity and temperature effects are statistically different from zero. In addition, the standard error of the regression coefficients could be used as an indication of the validity of this approach. Such an approach has the value that it does not require a large and expensive test program Furthermore, if such a method were found to work, it could be periodically updated on newer vehicles at very little cost

Conclusions

The humidity correction factor presently used for certification and IM240 testing was derived from tests on late 1960 model year vehicles. Its applicability to modern vehicles is

* Until earlier this year, all ambient test temperatures in excess of 86°F in the Arizona IM240 test program were recorded as 86°F Because this significantly limits the available data, this analysis approach was not used in the current Work Assignment The analysis could, however, be undertaken in future years

uncertain. The initial tests were aimed at corrections for certification tests run between 68°F and 86°F. The maximum temperature and humidity in the studies was 95°F and 180 grains of water per pound of dry air The extrapolation of the original data set beyond this region is questionable

A revised analysis, giving a multiplicative temperature and humidity correction factor that could be applied to I/M tests at higher temperatures, was developed Although this procedure provides a better representation of the original data to higher temperatures, the applicability of that data set to current automobiles is uncertain There have been significant changes in technology and a new emissions test cycle since the time that the original data set for the correction factor was developed It is likely that new emission control and fuel management technologies have changed the effect of humidity on average automobile operation over the emission test cycle For this reason, the most technically sound approach to developing a revised NOx correction factor would be to conduct an experimental test program involving current technology automobiles

An alternate approach to developing a temperature-humidity NOx correction factor that involves the analysis of Arizona IM240 data could be undertaken as either a substitute or a precursor to a detailed test program This approach would require only a small analytical effort Although the success of this approach is uncertain, its cost would be extremely low compared to a large experimental program It is therefore recommended that such an IM240 analysis be completed before undertaking any experimental program to determine temperature-humidity correction factors on current automobiles

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Appendix A

IM240 Retest Criteria

IM240 Retest Criteria for Passenger Cars

Using the replicate IM240 data collected by Gordon-Darby, it was possible, through trial and error, to identify criteria to determine whether a vehicle failing an initial IM240 is inadequately preconditioned and should be tested again This analysis was performed for each pollutant individually, and then for all pollutants combined. The evaluation followed a step-wise progression in which the aim was to maximize the identification of vehicles that could benefit from a second test, while minimizing retesting of vehicles likely to fail a second test. Recommendations for passenger cars are summarized below A similar set of conditions was also developed for light-duty trucks, which are subject to different IM240 standards than passenger cars.

HC Failures - If $ppmHC_{209\text{-}214}$ is less than 1,500, a retest is recommended if any of the following occur:

1. Phase 2 HC < 0 8 g/mi; or
2. $massHC_{175\text{-}199}$ < 0.2 g; or
3. $(ppmHC_{75\text{-}80}/ppmHC_{209\text{-}214})$ > 4.0.

For vehicles failing only HC, the following additional constraints are required for a vehicle to be retested:

1. $massHC_{175\text{-}199}$ < 0.3 g <u>and</u> $(ppmHC_{75\text{-}80}/ppmHC_{209\text{-}214})$ > 1.5; or
2. $massHC_{175\text{-}199}$ < 0.3 g <u>and</u> Phase 2 HC < 1.0 g/mi.

CO Failures - For CO failures, the above criteria for HC are recommended. In addition, the following constraints are recommended:

1. do not retest if Phase 2 CO > 20 g/mi <u>and</u> (Phase 1 CO/Phase 2 CO) <2; and
2. if the vehicle fails both HC and CO, retest if $massHC_{175\text{-}199}$ < 0.3 g <u>and</u> $massCO_{175\text{-}199}$ < 5.0 g.

If the vehicle is a CO-only failure, then a vehicle would benefit from a retest if:

1. $massCO_{175\text{-}199}$ < 6 0 g; or
2. $(ppmCO_{75\text{-}80}/ppmCO_{209\text{-}214})$ > 4 0, or
3. $massCO_{175\text{-}199}$ < 10 g and (Phase 1 CO > 0 75 × Phase 2 CO).

NOx Failures - For vehicles failing HC or CO and NOx, a retest is recommended if the following condition occurs.

1. $massNOx_{175\text{-}199} \leq 1\ 0$ g

For NOx-only failures, retest is recommended if the following criteria are met:

1. $massNOx_{175-199} < 0.9$; or
2. $massNOx_{175-199} < 1.1$ and $(ppmNOx_{40-45}/ppmNOx_{209-215}) > 1.5$; or
3. IM240 NOx < 2.2 and $(ppmNOx_{40-45}/ppmNOx_{209-215}) > 1.0$.

Multiple Pollutants - For multiple pollutant failures, a retest is eliminated under the following conditions:

1. the vehicle fails for all pollutants; or
2. the vehicle fails HC and CO and (Phase 2 CO > 20 g/mi and $massCO_{175-199}$ > 6.0 g); or
3. the vehicle fails HC and NOx and ($ppmHC_{209-214}$ >1,200) or ($ppmNOx_{209-214}$ > 1,200)

IM240 Retest Criteria for Light-Duty Trucks

Because they are subject to different numerical IM240 emission standards, a different set of retest criteria were developed for light-duty trucks. These criteria are similar to those established for passenger cars, with adjustments to account for standards differences.

HC Failures - For 1981 to 1983 model year vehicles, if $ppmHC_{209-214} < 2,000$ and any of the following conditions exist, then a retest is recommended:

1. Phase 2 HC < 3 0 g/mi; or
2. $massHC_{175-199} < 0.8$ g; or
3. $(ppmHC_{75-80}/ppmHC_{209-214})>4.0$.

In addition, if the full IM240 is less than 3 5 g/mi HC (regardless of the value of $ppmHC_{209-214}$), then a retest is recommended.

For 1984 and later model year vehicles, if $ppmHC_{209-214}<1,500$ and any of the following conditions exist, a retest is recommended:

1. Phase 2 HC < 2.0 g/mi; or
2. $massHC_{175-199} < 0.4$ g; or
3. $(ppmHC_{75-80}/ppmHC_{209-214})>4.0$.

In addition, if $0.4<massHC_{175-199}<0.8$ and $(ppmHC_{75-80}/ppmHC_{209-214})>2\ 0$ (regardless of the value of $ppmHC_{209-214}$) then a retest is recommended

A retest is not recommended if Phase 2 HC > 3.2 g/mi

CO Failures - For CO failures, the above criteria outlined for HC were also used. In addition, the following conditions were also imposed to cut down on the number of vehicles incorrectly identified as needing a retest:

1. If 1981 to 1983 model year and $massCO_{175-199}>36$ g then do not retest.
2. If 1984 or later model year and $massCO_{175-199}>18$ g then do not retest.
3. If Phase 2 CO >40 and Phase 2 CO > Phase 1 CO then do not retest.

NOx Failures - If the vehicle failed NOx and either HC or CO, the above criteria were used to determine the need for a retest For LDT1s, if the vehicle failed only NOx, then a retest is recommended if $massNOx_{175-199} < 1.4$ g. For 1988 and later LDT2s, a retest is recommended only if $massNOx_{175-199} < 2.5$ g.

Appendix B

Composite IM240 HC Regression Coefficients Developed from Modal IM240 Data Analysis
1981 to 1984 Model Year Light-Duty Gasoline Vehicles - 0.8 g/mi Cutpoint

Mode Number	RMS Error	Reg Constant	Regression Coefficients																						
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
1	0 301	0 566	5 043																						
2	0 253	0 378	0 187	2 802																					
3	0 247	0 371	-0 383	2 022	2 586																				
4	0 232	0 337	-0 363	0 828	0 771	3 854																			
5	0 228	0 325	-0 454	1 046	-0 497	2 884	3 156																		
6	0 214	0 286	0 371	0 566	0 327	-0 040	1 592	4 650																	
7	0 202	0 274	0 697	0 468	0 136	-0 077	1 315	2 032	2 632																
8	0 194	0 260	0 489	0 715	-0 044	-0 411	1 211	2 268	0 853	2 410															
9	0 189	0 247	0 452	0 747	0 049	-0 370	1 228	2 028	0 757	0 664	2 993														
10	0 185	0 242	0 163	0 947	-0 410	-0 223	0 801	1 855	0 909	0 463	2 017	2 189													
11	0 182	0 236	-0 613	1 036	-0 076	-0 458	0 652	1 882	0 997	0 312	1 900	1 397	4 130												
12	0 160	0 179	0 127	0 496	0 458	-0 049	0 861	0 657	0 532	0 742	0 756	1 363	1 119	2 786											
13	0 151	0 160	0 257	0 519	0 463	-0 050	0 494	0 783	0 574	0 498	0 793	1 013	1 266	2 081	2 388										
14	0 149	0 156	0 285	0 535	0 377	0 080	0 324	0 741	0 578	0 480	0 878	0 729	1 310	2 069	1 748	1 228									
15	0 146	0 152	0 397	0 612	0 326	-0 091	0 754	0 525	0 543	0 420	0 631	0 591	0 768	1 894	1 505	0 562	2 644								
16	0 144	0 150	0 428	0 652	0 276	-0 140	0 404	0 656	0 668	0 406	0 658	0 454	-0 393	1 833	1 390	0 498	1 810	1 915							
17	0 140	0 142	0 463	0 579	0 511	-0 148	0 619	0 189	0 756	0 455	0 462	0 632	-0 086	1 551	1 247	0 516	0 846	1 432	2 815						
18	0 138	0 140	0 505	0 566	0 462	-0 015	0 443	0 386	0 676	0 317	0 386	0 622	-0 033	1 600	1 086	0 435	0 399	1 133	1 908	1 738					
19	0 134	0 128	0 506	0 528	0 820	-0 205	0 294	0 539	0 735	0 259	0 147	1 098	-0 693	1 478	0 929	0 550	0 693	0 252	1 463	1 566	1 476				
20	0 102	0 058	0 441	0 520	0 567	0 283	0 334	0 275	0 678	0 396	0 600	1 082	0 232	0 525	0 815	0 244	0 831	1 083	0 721	1 244	0 809	0 931			
21	0 068	0 032	0 507	0 551	0 501	0 508	0 307	0 466	0 393	0 487	0 542	1 195	0 446	0 329	0 563	0 546	0 500	0 690	0 700	0 763	0 805	0 426	1 089		
22	0 041	0 013	0 518	0 516	0 564	0 503	0 329	0 622	0 398	0 508	0 395	1 055	0 557	0 394	0 483	0 526	0 715	0 469	0 615	0 618	0 444	0 540	0 430	1 148	
23	0 030	0 007	0 517	0 526	0 512	0 515	0 448	0 487	0 455	0 519	0 429	0 938	0 682	0 389	0 577	0 509	0 500	0 654	0 403	0 575	0 458	0 517	0 386	0 681	0 819

Note Results for only 23 modes are shown here because if the 24th mode is completed, the actual IM240 score would be used rather than the predicted score

Phase 2 IM240 HC Regression Coefficients Developed from Modal IM240 Data Analysis
1981 to 1984 Model Year Light-Duty Gasoline Vehicles - 0.5 g/mi Cutpoint

Mode Number	RMS Error	Reg Constant	Regression Coefficients												
			C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
11	0 179	0 346	8 141												
12	0 145	0 219	2 349	3 104											
13	0 136	0 198	1 727	2 209	2 823										
14	0 134	0 192	1 330	2 210	2 034	1 470									
15	0 131	0 188	0 571	1 862	1 732	0 807	2 665								
16	0 129	0 184	-0 983	1 887	1 610	0 588	1 883	2 208							
17	0 125	0 171	-0 505	1 456	1 415	0 728	0 712	1 820	3 193						
18	0 122	0 168	-0 516	1 481	1 215	0 533	0 276	1 426	2 227	1 985					
19	0 118	0 154	-0 904	1 381	1 041	0 803	0 703	0 602	1 573	1 758	1 711				
20	0 086	0 076	0 344	0 701	0 965	0 539	1 035	1 357	0 881	1 678	0 988	1 091			
21	0 061	0 041	0 994	0 508	0 691	0 796	0 735	1 173	0 792	1 146	0 925	0 640	1 372		
22	0 039	0 016	1 142	0 562	0 700	0 745	1 010	0 779	0 752	0 874	0 560	0 732	0 647	1 544	
23	0 029	0 007	1 198	0 561	0 777	0 755	0 770	1 005	0 484	0 833	0 607	0 715	0 560	0 975	1 098

Note Regression coefficients are presented only for modes 11 through 23 Mode 11 is the first mode of Phase 2 and if the 24th mode is completed, the actual IM240 score would be used rather than the predicted score

Composite IM240 HC Regression Coefficients Developed from Modal IM240 Data Analysis
1985 to 1989 Model Year Light-Duty Gasoline Vehicles - 0.8 g/mi Cutpoint

Mode Number	RMS Error	Reg Constant	Regression Coefficients																						
			C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
1	0.301	0.430	5.602																						
2	0.248	0.259	0.159	3.044																					
3	0.242	0.255	-0.183	2.108	2.824																				
4	0.224	0.223	0.012	1.015	0.555	3.864																			
5	0.219	0.212	-0.084	1.168	-0.763	2.919	3.395																		
6	0.207	0.189	0.424	0.758	-0.026	0.591	1.742	4.092																	
7	0.194	0.181	0.649	0.668	-0.372	0.443	1.314	1.053	3.066																
8	0.184	0.169	0.369	0.880	-0.438	0.037	1.302	1.440	0.797	2.830															
9	0.174	0.157	0.342	0.927	-0.266	-0.055	1.335	1.391	0.656	0.035	4.534														
10	0.171	0.154	0.180	1.101	-0.631	0.068	0.949	1.233	0.822	-0.082	3.332	2.217													
11	0.167	0.150	-0.536	1.168	-0.318	-0.082	0.705	1.264	0.846	-0.127	3.103	1.373	4.334												
12	0.144	0.106	0.170	0.593	0.221	0.266	0.883	0.515	0.448	0.428	1.462	1.314	1.001	2.829											
13	0.137	0.095	0.153	0.601	0.146	0.360	0.542	0.548	0.519	0.277	1.402	1.109	1.248	2.159	2.122										
14	0.135	0.091	0.169	0.583	0.126	0.499	0.226	0.547	0.530	0.265	1.482	0.760	1.225	2.183	1.358	1.490									
15	0.131	0.089	0.272	0.609	0.139	0.358	0.572	0.388	0.544	0.195	1.174	0.605	0.985	1.914	1.217	0.696	2.684								
16	0.129	0.087	0.278	0.683	0.092	0.322	0.166	0.487	0.671	0.212	1.115	0.457	-0.039	1.831	1.143	0.626	1.714	2.124							
17	0.125	0.081	0.348	0.641	0.274	0.241	0.418	0.209	0.775	0.207	0.887	0.657	0.145	1.602	0.944	0.500	0.969	1.584	2.648						
18	0.122	0.080	0.348	0.651	0.147	0.387	0.291	0.439	0.622	0.115	0.812	0.631	0.217	1.651	0.809	0.246	0.548	1.358	1.605	1.837					
19	0.116	0.070	0.355	0.591	0.583	0.180	0.199	0.559	0.697	0.082	0.426	1.018	-0.368	1.511	0.738	0.346	0.826	0.523	1.293	1.374	1.818				
20	0.085	0.029	0.432	0.465	0.545	0.443	0.311	0.226	0.677	0.359	0.604	1.148	0.387	0.555	0.731	0.187	1.034	0.908	0.755	1.211	0.916	0.953			
21	0.055	0.018	0.542	0.524	0.385	0.537	0.398	0.546	0.373	0.556	0.462	1.214	0.466	0.368	0.484	0.520	0.679	0.708	0.564	0.703	0.808	0.426	1.126		
22	0.035	0.009	0.575	0.503	0.544	0.511	0.339	0.596	0.434	0.512	0.371	1.085	0.490	0.400	0.498	0.500	0.819	0.484	0.555	0.610	0.493	0.533	0.467	1.096	
23	0.024	0.004	0.574	0.499	0.516	0.525	0.455	0.493	0.482	0.528	0.353	0.981	0.668	0.420	0.558	0.534	0.542	0.577	0.422	0.576	0.522	0.504	0.427	0.599	0.842

Note Results for only 23 modes are shown here because if the 24th mode is completed, the actual IM240 score would be used rather than the predicted score

Phase 2 IM240 HC Regression Coefficients Developed from Modal IM240 Data Analysis
1985 to 1989 Model Year Light-Duty Gasoline Vehicles - 0.5 g/mi Cutpoint

Mode Number	RMS Error	Reg Constant	Regression Coefficients												
			C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
11	0.177	0.259	9.328												
12	0.140	0.150	2.179	3.452											
13	0.132	0.131	1.779	2.527	2.741										
14	0.129	0.125	1.374	2.545	1.628	1.888									
15	0.125	0.121	0.861	2.070	1.387	1.001	2.991								
16	0.123	0.119	-0.368	2.053	1.269	0.818	2.160	2.195							
17	0.118	0.109	0.059	1.736	1.014	0.823	1.032	1.762	3.119						
18	0.115	0.107	-0.009	1.760	0.833	0.559	0.556	1.401	2.128	2.030					
19	0.109	0.094	-0.526	1.622	0.698	0.823	0.762	0.636	1.569	1.573	2.175				
20	0.077	0.041	0.637	0.716	0.900	0.635	1.081	1.205	1.005	1.455	1.267	1.123			
21	0.057	0.025	0.845	0.562	0.700	0.868	0.834	1.063	0.867	0.971	1.063	0.658	1.363		
22	0.037	0.013	0.917	0.590	0.738	0.748	1.105	0.785	0.740	0.839	0.583	0.740	0.631	1.554	
23	0.027	0.006	1.052	0.609	0.774	0.810	0.757	0.906	0.536	0.802	0.675	0.711	0.575	0.903	1.137

Note Regression coefficients are presented only for modes 11 through 23 Mode 11 is the first mode of Phase 2 and if the 24th mode is completed, the actual IM240 score would be used rather than the predicted score

Composite IM240 HC Regression Coefficients Developed from Modal IM240 Data Analysis
1990 and Later Model Year Light-Duty Gasoline Vehicles - 0.8 g/mi Cutpoint

Mode	RMS	Reg	Regression Coefficients																					
Number	Error	Constant	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
1	0.368	0.162	10.855																						
2	0.271	0.028	0.252	4.621																					
3	0.253	0.036	0.096	2.693	4.788																				
4	0.230	0.031	0.720	0.868	1.740	4.997																			
5	0.221	0.026	0.391	1.110	0.060	3.325	5.174																		
6	0.207	0.021	0.862	0.623	1.005	0.397	2.743	5.132																	
7	0.192	0.025	1.279	0.372	0.699	0.393	2.028	1.127	3.732																
8	0.175	0.030	1.076	0.515	0.477	0.150	1.178	1.750	0.608	3.725															
9	0.162	0.032	1.111	0.490	0.510	0.142	1.351	1.370	0.587	0.494	5.180														
10	0.155	0.034	0.742	0.835	-0.133	0.470	0.754	0.829	0.980	0.287	3.033	3.511													
11	0.149	0.037	-0.292	0.916	0.270	0.141	0.342	0.923	1.049	0.326	2.661	2.172	5.629												
12	0.123	0.028	0.433	0.321	0.650	0.528	0.818	-0.003	0.245	1.037	0.672	2.127	1.234	3.583											
13	0.115	0.025	0.578	0.296	0.562	0.394	0.374	0.234	0.492	0.715	0.629	1.553	1.271	2.743	2.839										
14	0.113	0.025	0.618	0.262	0.555	0.503	-0.034	0.227	0.569	0.714	0.776	1.121	1.069	2.758	1.607	2.069									
15	0.107	0.027	0.747	0.284	0.574	0.244	0.529	0.033	0.676	0.571	0.487	1.011	0.912	2.369	1.258	0.591	3.362								
16	0.102	0.027	0.719	0.462	0.356	0.136	0.065	0.303	0.778	0.668	0.345	0.659	-0.008	2.189	1.033	0.401	2.153	2.766							
17	0.098	0.026	0.794	0.426	0.518	0.062	0.242	0.168	0.786	0.737	0.079	0.882	0.127	1.928	0.726	0.488	1.245	1.994	2.960						
18	0.095	0.026	0.769	0.455	0.367	0.197	0.174	0.420	0.710	0.561	0.016	0.870	0.128	2.015	0.442	0.256	0.759	1.521	1.733	2.083					
19	0.090	0.023	0.816	0.385	0.654	0.080	0.083	0.642	0.717	0.557	-0.358	1.269	-0.488	1.916	0.340	0.282	0.819	0.888	1.357	1.477	1.846				
20	0.068	0.009	0.575	0.360	0.539	0.382	0.257	0.458	0.639	0.556	0.034	1.205	0.514	0.804	0.472	0.255	0.693	1.266	0.881	1.203	0.837	1.073			
21	0.041	0.007	0.544	0.483	0.489	0.528	0.539	0.520	0.388	0.588	0.284	1.157	0.523	0.367	0.461	0.575	0.548	0.853	0.677	0.674	0.583	0.370	1.309		
22	0.027	0.003	0.559	0.500	0.535	0.538	0.444	0.602	0.406	0.514	0.284	0.992	0.497	0.407	0.518	0.526	0.656	0.637	0.661	0.573	0.470	0.497	0.525	1.112	
23	0.019	0.002	0.553	0.496	0.515	0.537	0.525	0.518	0.438	0.535	0.349	0.870	0.650	0.429	0.549	0.567	0.521	0.624	0.554	0.536	0.443	0.510	0.387	0.654	0.853

Note Results for only 23 modes are shown here because if the 24th mode is completed, the actual IM240 score would be used rather than the predicted score

Phase 2 IM240 HC Regression Coefficients Developed from Modal IM240 Data Analysis
1990 and Later Model Year Light-Duty Gasoline Vehicles - 0.5 g/mi Cutpoint

Mode	RMS	Reg	Regression Coefficients												
Number	Error	Constant	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
11	0.153	0.098	13.195												
12	0.114	0.048	3.112	4.074											
13	0.102	0.041	1.873	2.680	3.765										
14	0.099	0.039	1.406	2.668	2.167	2.454									
15	0.095	0.040	1.107	2.141	1.738	1.122	3.342								
16	0.091	0.040	-0.030	2.065	1.365	0.858	2.119	3.157							
17	0.088	0.038	0.165	1.791	1.043	0.931	1.028	2.401	3.357						
18	0.085	0.038	0.093	1.843	0.719	0.663	0.610	1.854	2.189	2.206					
19	0.081	0.035	-0.272	1.779	0.514	0.829	0.678	1.356	1.669	1.515	1.952				
20	0.057	0.016	0.581	0.846	0.727	0.616	0.627	1.840	1.313	1.345	0.856	1.195			
21	0.040	0.010	0.817	0.585	0.723	0.936	0.588	1.434	1.014	0.886	0.731	0.623	1.512		
22	0.028	0.005	0.823	0.606	0.751	0.837	0.740	1.015	0.843	0.855	0.581	0.717	0.749	1.426	
23	0.020	0.003	0.909	0.612	0.790	0.837	0.609	0.957	0.714	0.775	0.632	0.719	0.591	0.868	1.158

Note Regression coefficients are presented only for modes 11 through 23 Mode 11 is the first mode of Phase 2 and if the 24th mode is completed the actual IM240 score would be used rather than the predicted score

Appendix C

IM240 REFERENCE DATA — **PKE VARIATION CUTPOINTS (miles/hr2)**

TIME	SPEED	CUM PKE (miles/hr2)	"BASE" DELTA	MULT FACTOR	VARYING DELTA	CUMULATIVE PKE LOW	CUMULATIVE PKE HIGH
0	0 0	0 0					
1	0 0	0 0					
2	0 0	0 0					
3	0 0	0 0					
4	0 0	0 0					
5	3 0	10,800 0					
6	5 9	14,080 4					
7	8 6	15,214 6					
8	11 5	16,417 2					
9	14 3	17,001 5					
10	16 9	17,079 7					
11	17 3	13,902 5					
12	18 1	12,336 8					
13	20 7	13,263 7					
14	21 7	12,284 1					
15	22 4	11,261 4					
16	22 5	9,964 5					
17	22 1	8,890 2					
18	21 5	8,046 4					
19	20 9	7,366 6					
20	20 4	6,805 5					
21	19 8	6,336 9					
22	17 0	5,983 3					
23	14 9	5,704 2					
24	14 9	5,450 1					
25	15 2	5,306 1					
26	15 5	5,171 6					
27	16 0	5,103 3					
28	17 1	5,213 3					
29	19 1	5,599 3					
30	21 1	5,990 0	342 3	4 000	1,369 3	4,621	7,359
31	22 7	6,242 3	356 7	3 986	1,421 8	4,820	7,664
32	22 9	6,014 8	343 7	3 971	1,365 1	4,650	7,380
33	22 7	5,745 3	328 3	3 957	1,299 3	4,446	7,045
34	22 6	5,500 0	314 3	3 943	1,239 3	4,261	6,739
35	21 3	5,287 2	302 2	3 929	1,187 0	4,100	6,474
36	19 0	5,110 8	292 1	3 914	1,143 3	3,968	6,254
37	17 1	4,961 9	283 6	3 900	1,105 9	3,856	6,068
38	15 8	4,831 8	276 1	3 886	1,072 9	3,759	5,905
39	15 8	4,708 3	269 1	3 871	1,041 7	3,667	5,750
40	17 7	4,937 5	282 2	3 857	1,088 4	3,849	6,026
41	19 8	5,220 8	298 4	3 843	1,146 5	4,074	6,367
42	21 6	5,450 3	311 5	3 829	1,192 5	4,258	6,643
43	23 2	5,638 2	322 2	3 814	1,229 0	4,409	6,867
44	24 2	5,685 3	324 9	3 800	1,234 6	4,451	6,920
45	24 6	5,592 5	319 6	3 786	1,209 9	4,383	6,802
46	24 9	5,481 7	313 3	3 771	1,181 5	4,300	6,663
47	25 0	5,332 7	304 8	3 757	1,145 0	4,188	6,478
48	25 7	5,321 5	304 1	3 743	1,138 2	4,183	6,460
49	26 1	5,245 9	299 8	3 729	1,117 8	4,128	6,364
50	26 7	5,216 3	298 1	3 714	1,107 2	4,109	6,323
51	27 5	5,230 2	298 9	3 700	1,105 9	4,124	6,336
52	28 6	5,307 9	303 3	3 686	1,118 0	4,190	6,426
53	29 3	5,298 0	302 8	3 671	1,111 6	4,186	6,410
54	29 8	5,246 1	299 8	3 657	1,096 4	4,150	6,343
55	30 1	5,155 0	294 6	3 643	1,073 2	4,082	6,228
56	30 4	5,068 3	289 6	3 629	1,051 0	4,017	6,119
57	30 7	4,985 6	284 9	3 614	1,029 8	3,956	6,015
58	30 7	4,848 3	277 1	3 600	997 5	3,851	5,846
59	30 5	4,719 2	269 7	3 586	967 0	3,752	5,686
60	30 4	4,597 2	262 7	3 571	938 3	3,659	5,535
61	30 3	4,481 7	256 1	3 557	911 1	3,571	5,393

IM240 REFERENCE DATA			PKE VARIATION CUTPOINTS (miles/hr2)				
		CUM PKE	"BASE"	MULT	VARYING	CUMULATIVE PKE	
TIME	SPEED	(miles/hr2)	DELTA	FACTOR	DELTA	LOW	HIGH
62	30 4	4,389 2	250 8	3 543	888 7	3,501	5,278
63	30 8	4,352 1	248 7	3 529	877 6	3,474	5,230
64	30 4	4,250 1	242 9	3 514	853 6	3,397	5,104
65	29 9	4,154 4	237 4	3 500	831 0	3,323	4,985
66	29 5	4,064 1	232 3	3 486	809 6	3,255	4,874
67	29 8	4,022 9	229 9	3 471	798 1	3,225	4,821
68	30 3	4,013 3	229 3	3 457	792 9	3,220	4,806
69	30 7	3,988 8	228 0	3 443	784 8	3,204	4,774
70	30 9	3,935 5	224 9	3 429	771 1	3,164	4,707
71	31 0	3,869 4	221 1	3 414	755 0	3,114	4,624
72	30 9	3,791 8	216 7	3 400	736 8	3,055	4,529
73	30 4	3,718 5	212 5	3 386	719 5	2,999	4,438
74	29 8	3,649 2	208 5	3 371	703 1	2,946	4,352
75	29 9	3,595 5	205 5	3 357	689 8	2,906	4,285
76	30 2	3,569 2	204 0	3 343	681 9	2,887	4,251
77	30 7	3,569 2	204 0	3 329	678 9	2,890	4,248
78	31 2	3,569 3	204 0	3 314	676 0	2,893	4,245
79	31 8	3,582 2	204 7	3 300	675 6	2,907	4,258
80	32 2	3,569 2	204 0	3 286	670 2	2,899	4,239
81	32 4	3,531 2	201 8	3 271	660 2	2,871	4,191
82	32 2	3,469 8	198 3	3 257	645 9	2,824	4,116
83	31 7	3,411 4	195 0	3 243	632 2	2,779	4,044
84	28 6	3,360 3	192 0	3 229	620 0	2,740	3,980
85	25 1	3,316 8	189 5	3 214	609 3	2,708	3,926
86	21 6	3,280 2	187 5	3 200	599 9	2,680	3,880
87	18 1	3,250 2	185 7	3 186	591 7	2,658	3,842
88	14 6	3,226 3	184 4	3 171	584 7	2,642	3,811
89	11 1	3,208 4	183 4	3 157	578 9	2,630	3,787
90	7 6	3,196 3	182 7	3 143	574 1	2,622	3,770
91	4 1	3,189 8	182 3	3 129	570 3	2,619	3,760
92	0 6	3,188 9	182 2	3 114	567 5	2,621	3,756
93	0 0	3,188 9	182 2	3 100	564 9	2,624	3,754
94	0 0	3,188 9	182 2	3 086	562 3	2,627	3,751
95	0 0	3,188 9	182 2	3 071	559 7	2,629	3,749
96	0 0	3,188 9	182 2	3 057	557 1	2,632	3,746
97	0 0	3,188 9	182 2	3 043	554 5	2,634	3,743
98	3 3	3,203 1	183 0	3 029	554 4	2,649	3,757
99	6 6	3,250 7	185 8	3 014	560 0	2,691	3,811
100	9 9	3,331 3	190 4	3 000	571 1	2,760	3,902
101	13 2	3,443 8	196 8	2 986	587 6	2,856	4,031
102	16 5	3,587 2	205 0	2 971	609 1	2,978	4,196
103	19 8	3,760 1	214 9	2 957	635 4	3,125	4,396
104	22 2	3,892 7	222 5	2 943	654 7	3,238	4,547
105	24 3	4,013 3	229 4	2 929	671 7	3,342	4,685
106	25 8	4,090 8	233 8	2 914	681 3	3,409	4,772
107	26 4	4,093 0	233 9	2 900	678 3	3,415	4,771
108	25 7	4,045 3	231 2	2 886	667 1	3,378	4,712
109	25 1	3,999 9	228 6	2 871	656 4	3,344	4,656
110	24 7	3,956 1	226 1	2 857	646 0	3,310	4,602
111	25 2	3,951 8	225 8	2 843	642 0	3,310	4,594
112	25 4	3,924 1	224 3	2 829	634 3	3,290	4,558
113	27 2	4,024 3	230 0	2 814	647 2	3,377	4,672
114	26 5	3,979 2	227 4	2 800	636 7	3,342	4,616
115	24 0	3,939 2	225 1	2 786	627 1	3,312	4,566
116	22 7	3,902 0	223 0	2 771	618 0	3,284	4,520
117	19 4	3,870 9	221 2	2 757	609 9	3,261	4 481
118	17 7	3,842 9	219 6	2 743	602 4	3,241	4,445
119	17 2	3,816 0	218 1	2 729	595 0	3,221	4,411
120	18 1	3,834 3	219 1	2 714	594 8	3,240	4,429
121	18 6	3,832 2	219 0	2 700	591 3	3,241	4,423
122	20 0	3,879 0	221 7	2 686	595 4	3,284	4,474
123	20 7	3,887 7	222 2	2 671	593 5	3,294	4,481

IM240 REFERENCE DATA

TIME	SPEED	CUM PKE (miles/hr2)
124	21 7	3,914 4
125	22 4	3,923 5
126	22 5	3,895 8
127	22 1	3,863 1
128	21 5	3,831 7
129	20 9	3,801 8
130	20 4	3,772 9
131	19 8	3,745 4
132	17 0	3,722 1
133	17 1	3,703 4
134	15 8	3,682 2
135	15 8	3,661 2
136	17 7	3,720 0
137	19 8	3,794 6
138	21 6	3,860 2
139	22 2	3,863 3
140	24 5	3,964 6
141	24 7	3,943 1
142	24 8	3,915 9
143	24 7	3,883 2
144	24 6	3,851 1
145	24 6	3,819 6
146	25 1	3,817 5
147	25 6	3,815 4
148	25 7	3,789 6
149	25 4	3,758 6
150	24 9	3,728 8
151	25 0	3,704 9
152	25 4	3,698 2
153	26 0	3,702 8
154	26 0	3,673 1
155	25 7	3,644 1
156	26 1	3,637 9
157	26 7	3,643 0
158	27 3	3,648 1
159	30 5	3,812 6
160	33 5	3,978 0
161	36 2	4,133 0
162	37 3	4,172 3
163	39 3	4,282 5
164	40 5	4,330 6
165	42 1	4,412 1
166	43 5	4,477 8
167	45 1	4,561 4
168	46 0	4,584 2
169	46 8	4,598 2
170	47 5	4,603 2
171	47 5	4,546 8
172	47 3	4,492 0
173	47 2	4,438 6
174	47 2	4,386 5
175	47 4	4,352 1
176	47 9	4,343 2
177	48 5	4,342 6
178	49 1	4,342 0
179	49 5	4,324 9
180	50 0	4,316 3
181	50 6	4,316 0
182	51 0	4,299 3
183	51 5	4,291 0
184	52 2	4,299 3
185	53 2	4,332 3

PKE VARIATION CUTPOINTS (miles/hr2)

"BASE" DELTA	MULT FACTOR	VARYING DELTA	CUMULATIVE PKE LOW	HIGH
223 7	2 657	594 4	3,320	4,509
224 2	2 643	592 6	3,331	4,516
222 6	2 629	585 2	3,311	4,481
220 8	2 614	577 1	3,286	4,440
219 0	2 600	569 3	3,262	4,401
217 3	2 586	561 8	3,240	4,364
215 6	2 571	554 4	3,219	4,327
214 0	2 557	547 3	3,198	4,293
212 7	2 543	540 9	3,181	4,263
211 6	2 529	535 1	3,168	4,239
210 4	2 514	529 1	3,153	4,211
209 2	2 500	523 1	3,138	4,184
212 6	2 486	528 4	3,192	4,248
216 9	2 471	535 9	3,259	4,330
220 6	2 457	542 1	3,318	4,402
220 8	2 443	539 3	3,324	4,403
226 6	2 429	550 2	3,414	4,515
225 3	2 414	544 0	3,399	4,487
223 8	2 400	537 1	3,379	4,453
221 9	2 386	529 4	3,354	4,413
220 1	2 371	521 9	3,329	4,373
218 3	2 357	514 5	3,305	4,334
218 2	2 343	511 1	3,306	4,329
218 0	2 329	507 7	3,308	4,323
216 6	2 314	501 2	3,288	4,291
214 8	2 300	494 0	3,265	4,253
213 1	2 286	487 1	3,242	4,216
211 7	2 271	480 9	3,224	4,186
211 3	2 257	477 0	3,221	4,175
211 6	2 243	474 6	3,228	4,177
209 9	2 229	467 8	3,205	4,141
208 3	2 214	461 1	3,183	4,105
207 9	2 200	457 4	3,181	4,095
208 2	2 186	455 0	3,188	4,098
208 5	2 171	452 7	3,195	4,101
217 9	2 157	470 0	3,343	4,283
227 3	2 143	487 1	3,491	4,465
236 2	2 129	502 8	3,630	4,636
238 4	2 114	504 1	3,668	4,676
244 7	2 100	513 9	3,769	4,796
247 5	2 086	516 2	3,814	4,847
252 1	2 071	522 3	3,890	4,934
255 9	2 057	526 4	3,951	5,004
260 7	2 043	532 5	4,029	5,094
262 0	2 029	531 4	4,053	5,116
262 8	2 014	529 3	4,069	5,127
263 1	2 000	526 1	4,077	5,129
259 8	1 986	516 0	4,031	5,063
256 7	1 971	506 1	3,986	4,998
253 7	1 957	496 4	3,942	4,935
250 7	1 943	487 0	3,899	4,874
248 7	1 929	479 7	3,872	4,832
248 2	1 914	475 1	3,868	4,818
248 2	1 900	471 5	3,871	4,814
248 1	1 886	467 9	3,874	4,810
247 2	1 871	462 5	3,862	4,787
246 7	1 857	458 1	3,858	4,774
246 7	1 843	454 5	3,861	4,771
245 7	1 829	449 3	3,850	4,749
245 2	1 814	444 9	3,846	4,736
245 7	1 800	442 3	3,857	4,742
247 6	1 786	442 1	3,890	4,774

IM240 REFERENCE DATA

TIME	SPEED	CUM PKE (miles/hr2)
186	54 1	4,356 8
187	54 6	4,347 7
188	54 9	4,322 3
189	55 0	4,280 9
190	54 9	4,232 4
191	54 6	4,185 2
192	54 6	4,139 1
193	54 8	4,109 5
194	55 1	4,088 2
195	55 5	4,075 0
196	55 7	4,046 6
197	56 1	4,034 0
198	56 3	4,006 4
199	56 6	3,986 7
200	56 7	3,952 4
201	56 7	3,911 4
202	56 3	3,871 4
203	56 0	3,832 5
204	55 0	3,795 0
205	53 4	3,759 3
206	51 6	3,725 4
207	51 8	3,704 9
208	52 1	3,691 1
209	52 5	3,683 7
210	53 0	3,682 8
211	53 5	3,682 0
212	54 0	3,681 1
213	54 9	3,705 8
214	55 4	3,704 7
215	55 6	3,684 4
216	56 0	3,677 1
217	56 0	3,644 6
218	55 8	3,612 7
219	55 2	3,581 7
220	54 5	3,551 6
221	53 6	3,522 5
222	52 5	3,494 5
223	51 5	3,467 4
224	50 5	3,441 2
225	48 0	3,416 8
226	44 5	3,394 4
227	41 0	3,374 0
228	37 5	3,355 6
229	34 0	3,339 0
230	30 5	3,324 3
231	27 0	3,311 4
232	23 5	3,300 3
233	20 0	3,290 9
234	16 5	3,283 1
235	13 0	3,277 1
236	9 5	3,272 7
237	6 0	3,269 9
238	2 5	3,268 7
239	0 0	3,268 7
Cycle Sums		3,268 7

PKE VARIATION CUTPOINTS (miles/hr2)

"BASE" DELTA	MULT FACTOR	VARYING DELTA	CUMULATIVE PKE LOW	CUMULATIVE PKE HIGH
249 0	1 771	441 0	3,916	4,798
248 5	1 757	436 6	3,911	4,784
247 0	1 743	430 5	3,892	4,753
244 6	1 729	422 9	3,858	4,704
241 9	1 714	414 6	3,818	4,647
239 2	1 700	406 6	3,779	4,592
236 5	1 686	398 7	3,740	4,538
234 9	1 671	392 5	3,717	4,502
233 6	1 657	387 2	3,701	4,475
232 9	1 643	382 6	3,692	4,458
231 3	1 629	376 6	3,670	4,423
230 5	1 614	372 1	3,662	4,406
229 0	1 600	366 3	3,640	4,373
227 8	1 586	361 3	3,625	4,348
225 9	1 571	354 9	3,597	4,307
223 5	1 557	348 1	3,563	4,259
221 2	1 543	341 3	3,530	4,213
219 0	1 529	334 8	3,498	4,167
216 9	1 514	328 4	3,467	4,123
214 8	1 500	322 3	3,437	4,082
212 9	1 486	316 3	3,409	4,042
211 7	1 471	311 5	3,393	4,016
210 9	1 457	307 4	3,384	3,998
210 5	1 443	303 7	3,380	3,987
210 5	1 429	300 7	3,382	3,984
210 4	1 414	297 6	3,384	3,980
210 4	1 400	294 5	3,387	3,976
211 8	1 386	293 5	3,412	3,999
211 7	1 371	290 4	3,414	3,995
210 6	1 357	285 8	3,399	3,970
210 1	1 343	282 2	3,395	3,959
208 3	1 329	276 7	3,368	3,921
206 5	1 314	271 3	3,341	3,884
204 7	1 300	266 1	3,316	3,848
203 0	1 286	261 0	3,291	3,813
201 3	1 271	255 9	3,267	3,778
199 7	1 257	251 1	3,243	3,746
198 2	1 243	246 3	3,221	3,714
196 7	1 229	241 6	3,200	3,683
195 3	1 214	237 1	3,180	3,654
194 0	1 200	232 8	3,162	3,627
192 8	1 186	228 6	3,145	3,603
191 8	1 171	224 6	3,131	3,580
190 8	1 157	220 8	3,118	3,560
190 0	1 143	217 1	3,107	3,541
189 2	1 129	213 6	3,098	3,525
188 6	1 114	210 2	3,090	3,510
188 1	1 100	206 9	3,084	3,498
187 6	1 086	203 7	3,079	3,487
187 3	1 071	200 7	3,076	3,478
187 0	1 057	197 7	3,075	3,470
186 9	1 043	194 9	3,075	3,465
186 8	1 029	192 1	3,077	3,461
186 8	1 014	189 5	3,079	3,458
			3,079	3,458

Appendix D

Original Scott Laboratories Data Used in Regression Analysis						
Vehicle	Temperature (°F)	Humidity Grains H2O per pound of dry air	Measured NOx (grams/ mile)	NOx from Regression with T & H (grams/mile)	NOx from Regression with H only (grams/mile)	NOx from Regression without T or H (grams/mile)
1	59	20	7 62	6 78	7 19	5 65
1	59	40	6 81	6 14	6 60	5 65
1	59	60	6 54	5 56	6.05	5 65
1	71	20	6 92	7 15	7 19	5 65
1	71	40	6 90	6 47	6 60	5 65
1	71	60	6 48	5 86	6 05	5 65
1	71	80	5 39	5 30	5 55	5 65
1	83	20	7 42	7 54	7 19	5 65
1	83	60	5 26	6 18	6 05	5 65
1	83	80	6 06	5 60	5 55	5 65
1	83	100	4 24	5 07	5 09	5 65
1	83	120	3 39	4 59	4 67	5 65
1	83	140	3 35	4 15	4 28	5 65
1	95	40	7 51	7 20	6 60	5 65
1	95	60	7 04	6 52	6 05	5 65
1	95	80	4.69	5 90	5 55	5 65
1	95	100	5 34	5 34	5 09	5 65
1	95	140	4 62	4 38	4 28	5 65
1	95	180	4 94	3 59	3 60	5 65
2	59	20	8 21	6 72	7 14	5 66
2	59	40	5 92	6 09	6 55	5 66
2	59	60	5 60	5 51	6 01	5 66
2	71	20	6.69	7 09	7 14	5 66
2	71	40	6 60	6 42	6 55	5 66
2	71	60	6 46	5 81	6 01	5 66
2	71	80	5 15	5 26	5 51	5 66
2	83	20	7 12	7 48	7 14	5 66
2	83	40	6 37	6 77	6 55	5 66
2	83	60	6 44	6 13	6 01	5 66
2	83	80	4 26	5 55	5 51	5 66
2	83	100	4 94	5 02	5 05	5 66
2	83	120	4 61	4 55	4 64	5 66
2	83	140	3 94	4 12	4 25	5 66
2	95	40	7 26	7 14	6 55	5 66
2	95	60	6 80	6 47	6 01	5 66

Original Scott Laboratories Data Used in Regression Analysis						
Vehicle	Temperature (°F)	Humidity Grains H2O per pound of dry air	Measured NOx (grams/ mile)	NOx from Regression with T & H (grams/mile)	NOx from Regression with H only (grams/mile)	NOx from Regression without T or H (grams/mile)
2	95	80	5 42	5 85	5 51	5 66
2	95	100	5 59	5 30	5 05	5 66
2	95	140	4 38	4 34	4 25	5 66
2	95	180	3 84	3 56	3 58	5 66
3	59	20	8 31	8 99	9 55	7.56
3	59	40	7 74	8.14	8 76	7 56
3	59	60	7 89	7 36	8 03	7 56
3	71	20	8 33	9 48	9 55	7.56
3	71	40	8 89	8 58	8.76	7 56
3	71	60	5 82	7 77	8.03	7.56
3	71	80	5 58	7 03	7 37	7 56
3	83	20	10 60	10.00	9 55	7 56
3	83	40	8 45	9 05	8 76	7 56
3	83	60	9 34	8 19	8 03	7 56
3	83	80	9 08	7 42	7 37	7 56
3	83	100	7 36	6 72	6 76	7 56
3	83	120	6.61	6 08	6 20	7 56
3	83	140	5 86	5 50	5 68	7 56
3	95	40	9 84	9 55	8 76	7 56
3	95	60	9 28	8 64	8 03	7 56
3	95	80	7 17	7 82	7 37	7.56
3	95	100	7 12	7 08	6 76	7 56
3	95	140	5 83	5 80	5 68	7 56
3	95	180	5 20	4 76	4 78	7 56
4	59	20	7 12	7 22	7 68	6 01
4	59	40	5 98	6 54	7 04	6 01
4	59	60	6 08	5 92	6 46	6 01
4	71	40	8 06	6 90	7 04	6 01
4	71	60	7 65	6 24	6 46	6.01
4	71	80	4 96	5 65	5 92	6 01
4	83	20	8 04	8 04	7 68	6 01
4	83	40	6 02	7 28	7 04	6 01
4	83	60	7 70	6 59	6 46	6 01
4	83	80	6 46	5 96	5 92	6 01
4	83	100	5 56	5 40	5 43	6 01
4	83	120	4 86	4 89	4 98	6 01
4	83	140	4 57	4 42	4 57	6 01
4	95	40	9 50	7 67	7 04	6 01
4	95	60	7 77	6 95	6 46	6 01

Original Scott Laboratories Data Used in Regression Analysis

Vehicle	Temperature (°F)	Humidity Grains H2O per pound of dry air	Measured NOx (grams/ mile)	NOx from Regression with T & H (grams/mile)	NOx from Regression with H only (grams/mile)	NOx from Regression without T or H (grams/mile)
4	95	80	6 67	6 29	5 92	6 01
4	95	100	6 24	5 69	5 43	6 01
4	95	140	3 93	4 67	4 57	6 01
4	95	180	3 85	3 82	3 84	6 01
5	59	20	8 01	8 84	9 39	7 43
5	59	40	7 74	8 00	8 61	7 43
5	59	60	7 89	7 24	7 90	7 43
5	71	20	9 97	9 32	9 39	7 43
5	71	40	9 22	8 44	8 61	7 43
5	71	60	6 44	7 64	7 90	7 43
5	71	80	7 39	6 91	7 24	7 43
5	83	20	9 71	9 83	9 39	7 43
5	83	40	9 35	8 90	8 61	7 43
5	83	60	7 74	8 06	7 90	7 43
5	83	80	7 60	7 29	7 24	7 43
5	83	100	6 89	6.60	6 64	7 43
5	83	120	6 21	5 98	6 09	7 43
5	83	140	5 62	5 41	5 59	7 43
5	95	40	10 40	9 39	8 61	7 43
5	95	60	8 89	8 50	7 90	7 43
5	95	80	7 34	7 69	7 24	7 43
5	95	100	6 70	6 96	6 64	7 43
5	95	140	4 97	5 71	5 59	7 43
5	95	180	4 28	4 68	4 70	7 43
		Mean NOx	6 67			
		NOx Standard Deviation	1 68			
		NOx total sum of squares	275 40			
			Number of data points	98	98	98
			Number of regression parameters	7	6	5
			Degrees of freedom	91	92	93
			Standard Error of NOx estimate for original data.	0 74	0 84	1 49
			Residual sum of squares for original NOx data	49 51	65 38	205 88
			R^2 for original NOx data	0 82	0 76	0 25
			Difference in sum of squares from column to left	15 87	140 50	
			Additional parameters for reduced sum of squares	1	1	
			Mean square for added parameter	15 87	140 50	
			F ratio for added parameter	29 17	197 71	
			Probability that added parameter is not significant	5 25x10^{-7}	1 21x10^{-24}	