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Final Technical Report on Aggressive Driving Behavior for the Revised Federal Test Procedure Notice of Proposed Rulemaking

U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources
Certification Division
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This technical report documents the need for certain proposed additions to the Federal Test Procedure(FTP) to ensure that it reflects current driving behavior. The first section provides background information on the current FTP driving cycle and discusses the need for the proposed modifications to the FTP. In section two, information is presented on the differences between in-use driving and the FTP. This is followed, in section three, by a summary of emission testing results, which quantify the emission impact of the non-FTP driving. Methods for controlling emissions from non-FTP driving are discussed in section four. This section also discusses the appropriate level of control, as well as adjustments for special cases. Section five reviews feasibility issues, followed by a cost and benefits discussion in section six. The final section presents a discussion of the required test procedures.

Section 1.Need for Controlling Emissions from Non-FTP Driving Behavior

1.1 Background on the FTP Driving Schedule

The FTP driving schedule is a principal component of the exhaust emission test. As designed, the FTP was intended to represent typical driving patterns in primarily urban areas. The driving cycle used for the FTP was derived to simulate a vehicle operating over a road route in Los Angeles believed to be representative of typical home to work commuting. The original road route was selected in the mid-1960s[1] by trial-and-error to match the engine operating mode distribution (based on manifold vacuum and rpm ranges) obtained in central Los Angeles using a variety of drivers and routes with the same test vehicle.

Using an instrumented 1964 Chevrolet, recordings were made of actual home-to-work commute trips by employees of the state of California's Vehicle Pollution Laboratory. By trial and error, a specific street route in the vicinity of the Lab was found that matched the average speed/load distribution on the commute trips. That 12 mile route was called the "LA4."

In a 1970 effort to develop an improved Federal Test Procedure (based on speed-time distributions rather than manifold

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[1] G.C. Hass, et. al., "Laboratory Simulation of Driving Conditions in the Los Angeles Area," SAE Paper No. 660546, August, 1966.

vacuum and rpm ranges), six different drivers from EPA's West Coast Laboratory drove a 1969 Chevrolet over the LA4 route. The six traces were analyzed for idle time, average speed, maximum speed, and number of stops per trip. The total time required for the six trips ranged from 35 to 40 minutes, with an average of 37.6 minutes. One of the six traces demonstrated much more speed variation than the other five and was discarded. The other five traces were surprisingly similar. Of those five, the trace with the actual time closest to the average was selected as the most representative speed-time trace. That trace contained 28 segments of non-zero speed activity separated by idle periods (these segments are commonly referred as hills, or microtrips) and had an average speed of 19.2 miles per hour (figure 1-1a).

Based on a 1969 report on driving patterns in Los Angeles,[2] the average trip length was estimated to be 7.5 miles. Several of the hills and portions of others were eliminated in order to shorten the cycle to 7.5 miles while maintaining the same average speed. The shortened route, designated the LA4-S3, was 7.486 miles in length with an average speed of 19.8 mph. Slight modifications to some of the speed-time profiles were also made in cases where the acceleration or deceleration rate exceeded the 3.3 mph/s limit of the belt-driven chassis dynamometers in use at the time. Mass emission tests comparing the shortened cycle to the full cycle showed very high correlation. The final version of the cycle was designated the LA4-S4 cycle and is 7.46 miles in length with an average speed of 19.6 mph.

This cycle is officially called the the Urban Dynamometer Driving Schedule (UDDS), but more commonly referred to as the LA4. (The remainder of this report will use the term LA4 when referring to the current FTP driving schedule). It has been the standard driving cycle for the certification of LDVs and LDTs since the 1972 model year. Beginning with the 1975 model year, the cycle was modified to repeat the initial 505 seconds of the cycle following a 10 minute soak at the end of the cycle. This allows emissions to be collected on a "hot" start (the engine is still warm) as well as after a cold start and during operation. The test then provides a more accurate reflection of typical customer service than running just one 7.46 mile cycle from a cold start.

1.2 Concerns with the FTP Driving Schedule

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[2] D.H. Dearm and R.L. Lamoureux, "Survey of Average Driving Patterns in the Los Angeles Urban Area," TM-(L)-4119/000/01, February 28, 1969.

The LA4 has been an critical component of EPA's strategy for reducing vehicle exhaust emissions; however, the driving schedule was developed over twenty-five years ago and EPA's initial review identified a number of concerns:

Speed. The maximum speed on the LA4 is 57 mph. Even in urban areas, limiting the speed to 57 mph is clearly missing a significant portion of in-use operation.

Acceleration. Acceleration rates on the LA4 were artificially reduced to accommodate the capabilities of the testing equipment. The LA4 was targeted to average driving, thus it fails to capture aggressive driving Current-technology dynamometers permit higher, more representative accelerations.

Road grade. There is no attempt to account for road grade in the LA4. In some urban areas, the extra load placed on the engine can be considerable.

Speed variation. The methodology used in the development of the LA4 led to a fairly smooth driving schedule and may not represent small timescale variation in vehicle speed.

The above concerns regarding the LA4's representativeness of in-use driving behavior is ultimately a concern that the emission control demonstrated by a vehicle when tested on the LA4 may not be translated into the same level of emission control in use.

1.3 CARB Testing

At the start of the FTP Review project, limited information existed on the emission impact of non-LA4 driving behavior. In 1990, the California Air Resources Board (CARB) conducted emission testing in order to get a preliminary assessment of the emission impact of high acceleration rates; acceleration rates greater than those on the LA4[3]. Ten late-model vehicles were tested over an engineered driving schedule consisting of nine acceleration modes developed to simulate various types of acceleration events. Relative to LA4-like accelerations, CO emissions increased very dramatically during most of the other accelerations. HC and NOx also showed large increases, although there was large variation in the emission response across vehicles and acceleration modes. It was calculated if the FTP

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[3] State of California Memorandum, from Mark Carlock to K.D. Drachand

was modified to add a single acceleration mode lasting only 16 seconds, CO emissions could double and HC emissions could increase by nearly 20%.

The CARB results provided preliminary evidence that non-LA4 operation can result in high emissions. However, the emission response of the 10 vehicles was extremely varied across the 10 acceleration modes and the CARB data did not address the in-use frequency of such behavior Thus, information was still needed to identify the range and frequency of non-LA4 driving which occurs in-use. At the start of FTP Review Project, EPA surveyed existing driving behavior data to access the importance of the above concerns. It quickly became apparent that very little information existed on the real world driving behavior. As a result, a major portion of the project involved conducting and analyzing results from a large scale in-use driving survey.

Section 2. In-use Driving Behavior

In a coordinated research effort, EPA collaborated with the American Automobile Manufacturers Association (AAMA), the Association of International Automobile Manufacturers (AIAM), and the California Air Resources Board (CARB) over the spring and summer of 1992 to conduct surveys of in-use driving and soak behavior in four major U.S. cities. [4]The Agency employed two survey methods to gather basic data on the speeds and accelerations found in actual in-use driving. In the "instrumented vehicle" approach, digital dataloggers were installed in private owner vehicles to record second-by-second speed and engine parameter data over a period of seven to ten days. Separate "chase car" studies used laser rangefinder technology in a "patrol" vehicle to calculate vehicle speed of targeted in-use vehicles operated over predetermined routes.

The instrumented vehicle surveys were conducted on a sample of 150 vehicles in Baltimore, Maryland, and 144 vehicles in Spokane, Washington. An additional 101 vehicles were instrumented in Atlanta, Georgia, in a cooperative effort between EPA's Office of Research and Development and the Georgia Institute of Technology. Chase car studies funded by EPA were conducted on 218 routes in Baltimore and 249 routes in Spokane; CARB-funded chase-car work was performed on 102 routes in Los

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[4] For a detailed description of the driving surveys and results, see "Federal Test Procedure Review Project: Preliminary Technical Report," May 1993, EPA 420-R-93-007

Angeles. The critical findings for the FTP review project are discussed below.

2.1 Speed and Acceleration

In May of 1993, EPA published its initial conclusions regarding aggressive driving behavior in the "Federal Test Procedure Review Project: Preliminary Technical Report."[5] These findings were largely based on the Baltimore, instrumented vehicle survey data; subsequent analysis has been completed on the larger, 3-city instrumented vehicle database, and the 3-city results were found to be consistent with the Baltimore only results(table 1-1a). The 3-city analysis showed that nearly 13 percent of vehicle operation time occurs at combinations of speed and acceleration that fall outside the matrix of speeds and accelerations found on the LA4. The maximum observed in-use speed in was 95.5 mph, compared to the LA4 maximum speed of 56.7 mph, and sightly more than 7 percent of in-use vehicle operation time was spect at speeds greater than 60 mph. Average speed from the 3-city in-use data was 25.9 mph compared to 19.6 mph over the LA4.

Table 1-1a
Comparison of Driving Behavior for Four Cities

Driving Behavior Measure	Balti-more instr. veh	Spokane instr. veh	Atlanta instr. veh	3-City instr. veh average	Los Angeles chase car
Speed (mph)					
Average	24.50	23.24	28.84	25.85	28.35
Maximum	94.46	77.55	96.48	96.48	80.30
Standard deviation	20.52	17.71	22.61	20.87	20.15

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[5] U.S. EPA, "Federal Test Procedure Review Project: Preliminary Technical Report," May 1993, EPA 420-R-93-007

Number of seconds	3,365,504	2,081,199	3,339,489	8,786,192	99,729
Acceleration (mph/sec.)					
Minimum	-19.49	-15.46	-18.57	-19.49	-15.00
Maximum	15.19	15.95	16.69	16.69	10.41
Standard deviation	1.50	1.46	1.54	1.50	1.74
Number of seconds	3,360,550	2,077,008	3,335,057	8,772,615	99,625
Power (mph^2/sec.)					
Average	46.02	40.14	51.99	46.97	58.97
Maximum	557.69	672.28	723.12	723.12	769.10
Standard deviation	42.96	40.82	48.06	44.79	49.11
Number of seconds	1,407,908	880,258	1,463,313	3,751,479	45,251
Average trip length (miles)	4.89	3.56	6.32	4.99	7.78
Average trip time (minutes)	12.03	9.18	13.16	11.59	16.45
Average distance b/w stops	0.87	0.81	1.08	0.88	1.26

Percent idle operation	21.12	17.91	17.47	18.97	11.78

Another speed-based measure, specific power[6], is useful when analyzing in-use driving behavior. Measures of power also indicated that in-use driving behavior was more aggressive than reflected in the LA4. Specific power in the 3-city sample ranged up to 723 mph2/sec and averaged 47.0 mph2/sec; the LA4 has maximum power of 192 mph2/sec and an average of 38.6 mph2/sec.

2.1.1 Microtransient Operation

The previous discussion of in-use speeds and accelerations presents a snapshot of driving behavior. While the acceleration measure, which looks at the change in speed from one second to the next, partially characterizes the transient nature of driving, there are other measures which expand the time interval to examine the small-scale deviations in speed (microtransients). One measure, referred to as jerk, is equal to the change in accelerations, Using speed data collected and averaged on a one second basis, the jerk measure expands the picture of driving out to three seconds. A related measure is change in specific power, which is second-to-second change in power. Conceptually, this measure captures the change in the power requirement imposed by the driving behavior.

EPA used the 3-parameter instrumented vehicle data from Baltimore, Spokane, and Atlanta, to calculate the microtransient measures for in-use driving behavior and compared the results to the LA4's representation on in-use driving behavior. The measures of jerk and change in power are shown below in the table 1-1b:

Table 1-1b

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[6] The power needed from an engine to move a vehicle is proportional to both the vehicle speed and the acceleration rate. Thus, neither variable, by itself, is a good measure of the load placed on the engine. The joint distribution of speed and acceleration is probably the best measure, but it must be examined in three dimensions, which is difficult to visualize and comprehend. The concept of specific power, calculated as the difference in the square of velocity from one second to the next, provides a two-dimensional measure which is roughly equal to 2*speed*acceleration and has the units of mph2/second.

Measures of microtransient driving behavior

Measure	Mean of the absolute values		Standard deviation	
	In-use	LA4	In-use	LA4
Jerk	0.47	0.36	0.89	0.63
Change in power	20.48	14.96	34.36	22.96

For both jerk and change in power, the mean of the absolute values were used in order to look at both the positive and negative values (the mean of the signed values of jerk is always equal to zero). The in-use means were higher than those for the LA4 indicating larger in-use changes in acceleration and power, as well as reflecting, in part, the LA4's acceleration rate cutoff of 3.3 mph/sec and the maximum speed of 57 mph. The standard deviations of jerk and change in power is probably a better measure of microtransient behavior. Again, in-use data show larger values for both measures. The greater variation around the mean demonstrated by the in-use data suggests that the LA4 does not adequately represent the microtransient nature of in-use driving behavior.

2.2 Road Grade

To properly evaluate the need to incorporate road into the existing FTP, information is needed regard in-use road grade and associated driving, as well as the emission impact of road grade. Ideally, the in-use data would include the fraction of in-use operation driven on roadways by level of grade. It is also important to understand the relationship between road grade and driving behavior. If driving behavior is independent of road grade, then the presence of road grade will increase the severity of the driving by increasing the engine load. If road grade affects driving behavior then the impact of road grade will be diminished or eliminated. It is likely that a severe grade will require an additional load on the engine even with "conservative" driving.

EPA's review of existing data found comprehensive information on road grade to be quite limited. A 1980 EPA report summarized Department of Transportation Data on the nationwide distribution of road gradient by the percent of vehicle-miles-travel (VMT).[7] From these data, the average positive road grade was 1.66 percent. Roughly 6 percent of VMT was spent on grades of 4 percent or higher. EPA did not find any information on road grade and driving behavior. As a result, the in-use driving survey included instrumentation to collect realtime road grade data. As part of the chase-car study, a gyroscope was installed to collect such data. Unfortunately, a combination of limited equipment precision and noise introduced by vehicle movement resulted in inadequate road grade data to evaluate the relationship between driving behavior and road grade. Thus, EPA has very limited in-use data for evaluating road grade.

2.3 Driving Behavior Determinants

There are a host of factors which can influence driving behavior; vehicle characteristics which may impact driving behavior need to be considered when looking at revisions to the FTP. In analyzing in-use driving behavior, EPA identified three important vehicle characteristics: transmission type (manual/automatic); vehicle performance(high/low powered); and vehicle type (ie. cars/trucks).

2.3.1 Transmission Type

Among the 166 vehicles from Spokane and Baltimore, 60 vehicles had manual transmissions and 106 vehicles had automatic transmissions. In looking at the in-use vehicles with aggressive driving, it appeared that the most of the vehicles which were driven aggressive were manual transmission vehicles. This finding suggested the need for a more detailed look at differences in manual and automatic transmissions. A comparison of aggressive driving for automatic and manual transmission vehicles was made using specific power. Specifically, for each vehicle we calculated fraction of vehicle operation above specific power of 200 (FTP maximum is 192). This was repeated using specific power of 300, as a somewhat arbitrary measure of extreme operation. Table 1-2 presents summary statistics for these two measures of aggressive driving. Manual transmissions had higher mean values for both measures than automatic transmission vehicles and manuals showed much more of a spread across vehicles as indicated by the larger standard deviations.

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[7] U.S. Environmental Protection Agency, "Passenger Car Fuel Economy: EPA and Road," Report No. EPA 460/3-80-010, September 1980, p.119.

Figures 1-1 and 1-2 present the frequency distributions for high power operation (power=300) for manual and automatic transmissions vehicles. These charts show this greater variation for manual transmission vehicles relative to automatic transmission vehicles, as well as showing the manual transmission vehicles with the largest fraction of high power operation.

2.3.2 Vehicle Performance

The performance of the in-use fleet of vehicles was measured by calculating the ratio of a vehicle's weight(W) to its peak horsepower (P). In general terms, performance relates to a vehicle's ability to deliver power from the engine when demanded by the driver, such as during an acceleration. A common performance measure is the time to accelerate from 0 to 60; the faster the time, the higher the performance. In using W/P as a performance measure, a low W/P value is associated with a high performance vehicle while a low performance vehicle would have a high W/P value. Weight to power ratios were calculated using information supplied by the vehicle manufacturers. The W/P is a good indicator of performance, although it does not account for differences in torque curves or aerodynamic design. Further, an in-use vehicle's performance is also determined by the physical condition of the vehicle--poorly maintained or malfunctioning vehicles will show a performance loss relative to the manufacturers specifications. Nonetheless, the ratio of weight to power is a useful indicator. The W/P measure also does account for performance differences of automatic and manual transmission. For a given W/P a manual transmission vehicle will show a higher performance(as measured by 0 to 60 times) than a comparable automatic transmission vehicle. The analysis below treats automatic and manual vehicles separately.

The analysis looked at differences in driving behavior as a function of vehicle performance. Specifically, the analysis tried to answer the question of whether higher performance vehicles are driven more "aggressively" than lower performance vehicles. Driving aggressiveness was measured by first calculating, for each vehicle, the fraction of time spent at or above specific power values, using intervals of ten. The next step was to rank the vehicles according to their percent time spent in each of these categories. Finally, in each category, the vehicles were separated into three groups: the bottom ten percent(least aggressive); the middle 80 percent (normal); and the top ten percent (most aggressive). Once the vehicles were categorized as either high, middle or low, the average W/P for each group in each power category was obtained.

For manual transmission vehicles, figure 1-3 shows that the most aggressive vehicles consistently had a lower mean W/P than the normal vehicles, for operation in the non-FTP operation (the intervals above 200). The least aggressive manual transmission vehicles had a higher mean W/P than the normal vehicles and spent no time at all at power values above 200. For automatic transmission vehicles, there was only a small difference in mean W/P between most aggressive and normal vehicles (figure 1-4). The mean W/P for the least aggressive vehicles, however, was substantially higher than the normal vehicles

For manual transmission vehicles these results indicate that W/P, as a proxy for vehicle performance, is correlated with driving behavior, higher performance vehicles (low W/P) tend to be driven more aggressively than lower performance vehicles (high W/P). The in-use data for automatic transmission does suggest that lower performance vehicles (high W/P) are driven less aggressively than "normal" vehicles, but the vehicles driven most aggressive aren't necessarily high performance vehicles. The results suggest that the driver is an important, but unquantifiable, factor in the driving behavior.

EPA considers the conclusions on vehicle performance to be preliminary. The Spokane/Baltimore database had a very limited number of high performance vehicles. There were only 3 vehicles with a W/P below 20--two automatic and one manual transmission. To increase the sample of high performance vehicles, EPA is updating the analysis to include vehicles from the Atlanta in-use driving survey.

2.3.3 Heavy, light-duty Trucks

The initial analysis presented in the Preliminary Technical Report (footnote) showed very little difference between cars and trucks. As a result of the vehicle test program (discussed in section 3), additional analysis of the in-use data was conducted using a further categorization of trucks since the light duty-truck classification covers a broad range of vehicles. EPA classifies light duty trucks into light, light-duty(LLDT) and heavy, light-duty(HLDT). It became apparent during the test program discussed below that the HLDT may need to be treated in a different manner than LLDTs and LDVs.

The in-use data provided a limited data set to examine the in-use behavior of HLDTs. For this analysis, eight vehicles from the in-use data set were identified as HLDTS (gross vehicle weight > 6,00lbs.). It is important to note that there is no information of the physical load these vehicles carried. It is possible some or all of the vehicles, for some or all of the time, were subject to extra load which may impact the driving behavior.

The speed/acceleration distribution of the HLDTs were compared to the speed/acceleration distributions for all vehicles. The fraction of time spent at speeds above 50 mph was much smaller for the HLDTs compared to the rest of the fleet. This difference increases with increasing speeds above 50 mph. In terms of acceleration, there was one HLDT which was driven very aggressively, but only at speeds below 50 mph Thus, the acceleration distribution by speed range was fairly similar for the two groups up to 50 mph. However, above 50 mph, the distribution at higher acceleration rates dropped off faster than the overall decrease for the speed range, indicating that HLDTs were also driven less aggressively during the limited time spent at higher speeds. This limited data suggests that the driving behavior of HLDTs is likely to be different than the fleet at large.

In summary, high performance, manual transmission vehicles were driven in a more aggressive manner than the broad, mid-performance category. At the other end, the low performance vehicles were driven somewhat less aggressively. EPA also found that the heavy, light-duty trucks(HLDTs) tended to be driven at lower speeds than other light-duty vehicles, and when driven at higher speeds, their accelerations were typically less severe.

Section 3. Emission Impact of Non-FTP Driving

After analyzing the driving patterns data, the next step is to assess the resulting exhaust emissions. This section discusses the vehicle emission test programs carried out by EPA, ARB, and the vehicle manufacturers. A fleet of vehicles were tested on new cycles developed from the in-use driving survey data. The testing served two objectives: a quantitative assessment of the emission impact of non-FTP driving, and an evaluation of alternative control cycles.

3.1 Cycle Development

The first step in assessing the emissions impact of the non-LA4 driving, is the reduction and synthesis of the driving data into representative driving cycles for use in vehicle testing. EPA's approach to cycle development involved the selection of actual segments of in-use driving which best matched the joint distribution of in-use speed and acceleration. In order to maintain a high level of coordination between the EPA and CARB, the data set used in developing the in-use cycles was the driving survey data from EPA's Baltimore instrumented vehicle study and data from the ARB's Los Angeles chase car study.[8] EPA developed separate cycles for start driving and aggressive driving(non-LA4), and to complete the representation of in-use driving behavior for emission assessment purposes, a third cycle, the Remnant cycle, was developed to characterize in-use driving behavior not represented by either the start or aggressive driving cycle. EPA developed individual cycles rather than a single "representative" cycle in order to evaluate EPA's areas of concern independently. This is most critical in the case of aggressive driving where both capturing the diversity of aggressive driving behavior and representing it proportionally in a single cycle covering all in-use operation would lead to a very long cycle.

Under contract with EPA, Sierra Research developed driving cycles intended to represent the range of in-use vehicle operation. In generating a cycle, entire micro-trips (idle-to-idle) were the basic building blocks used to match the "target surface" of the joint distribution of speed and acceleration. The cycle generation software developed for this task uses an iterative technique to find the combination of microtrips which best match the target surface. The first step involves the random selection of a specified number of microtrips. Their speed-acceleration surface is computed and compared to the target surface. The software then searches for the microtrip which provides the best incremental fit to the target surface. This micro-trip is then added to the cycle and the process is repeated until the desired cycle length is reached. In this manner, a large number of cycles were generated (several thousand). The candidate cycles were then ranked according to how well they matched speed-acceleration distribution of the target surface i order to select the best cycle.[9]

3.1.1 Start Driving (ST01)

For the Start (ST01) cycle, three target surfaces were developed from the database, representing three successive 80-second segments of in-use driving immediately following the

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[8] .A follow-up analysis compared the Baltimore/Los Angeles database to the 3-city, instrumented vehicle database. The differences were not large and EPA does not believe they would materially effect the cycles.

[9] For a detailed discussion of the cycle development see the contractor report, "Development of Driving Cycles to Represent Light-Duty Vehicle Operation in Urban Areas."

initial idle. The combinations of speed and acceleration found in these distributions could largely be found in the LA4, but with different percentages and in a different sequence. The microtrips that produced the best fit to these surfaces, together with an initial idle period that best matched in-use initial idles, generated a start cycle that was 257 seconds long (figure 1-5). Testing using ST01 allowed separate determination of start driving emissions; ST01 was also used to quantify the emissions effects of varying soak duration.

3.1.2 Aggressive Driving (REP05)

The second cycle, characterizing aggressive driving, was the Representative Non-LA4 cycle (REP05). This cycle targeted speeds and accelerations, as well as microtransient effects, not covered by the current LA4. The in-use data points used in developing the REP05 target surface were those with combinations of speed and acceleration that were <u>not</u> represented on the LA4 cycle (non-LA4) and, in addition, were not part of the ST01 target surfaces. These points tended to be either high-speed or high-acceleration (or both). By assembling the cycle from actual idle-to-idle driving segments, however, the cycle necessarily included some speed/acceleration combinations that were represented on the LA4, amounting to about 30 percent of the cycle's 1400 seconds. The average speed of REP05 is 51.5 mph, the maximum speed is 80.3 mph, and the maximum acceleration rate is 8.5 mph/sec (figure 1-6a).

3.1.3 Remnant Cycle

The Remnant cycle was intended to represent the balance of in-use driving not already covered by ST01 or REP05. Thus, the Remnant target surface was obtained by using the remaining speed/acceleration distribution after subtracting that found in the in REP05 and STO1. Though much of the 1237 seconds in the Remnant cycle is LA4-like driving, there are some non-LA4 segments (at low speeds, with high acceleration rates) which were not captured by the REP05 cycle (figure 1-6b). In addition, the Remnant cycle has greater speed variation than is found on the LA4.

3.1.4 Representation of Microtransients

The three in-use cycles had in common a representation of microtransient operation. Table 1-2b summarizes the characteristics of the cycles as well as the LA4's characteristics.

Table 1-2b
Microtransient characteristics of in-use driving cycles

	Start	**Remant**	**REP05**	**LA4**
Mean:				
speed	19.37	18.87	51.50	19.60
power	21.59	17.66	35.54	15.30
jerk	0.56	0.49	0.64	0.36
change in power	19.45	17.25	54.97	14.96
Standard deviation:				
speed	13.49	16.93	20.16	14.70
power	37.82	57.17	57.92	27.47
jerk	0.88	0.98	1.02	0.63
change in power	28.92	30.26	78.07	22.96

3.1.5 Other cycles: HL07 and ARBO2

The ARB02 cycle (figure 1-7) was developed by CARB based on data from their Los Angeles chase car study. The purpose of the cycle is to test vehicles over in-use operation outside the boundary of the LA4, including extreme in-use driving events. The HL07 (figure 1-8) is an engineered cycle developed by EPA in coordination with the auto manufacturers. The purpose of this cycle is to test vehicles on a series of acceleration events over a range of speeds. The severity of the accelerations are such that most vehicles will go into wide open throttle.

3.2 Vehicle Testing

The coordinated effort developed in the driving survey program carried over to the vehicle testing phase. Beginning in the Spring of 1993, EPA, ARB, and the vehicle manufacturers worked together to develop a cooperative vehicle test program. Emission testing was conducted at each of the agencies' facilities while all of the testing sponsored by the vehicle manufacturers' was carried out at GM's Milford facility.

3.2.1 EPA Test Program

The principal objective of EPA's FTP Test Program was to assess the emissions from well-maintained, current technology vehicles over the in-use cycles. Nine, 1991-1993 model year vehicles representing a range of vehicle and engine types were selected for the test program. Table 1-3 describes the eight vehicles which completed the program (one vehicle was lost due to malfunctions). Baseline FTP tests were run first to ensure vehicles met current standards. All of the in-use testing was designed to test the vehicle in a hot, stabilized condition--both the engine and catalyst are stabilized at their normal (hot) operating condition. These conditions were selected in order to look at emissions, and differences in emissions, associated with driving behavior. Replicate tests were run for each cycle. Testing was conducted on EPA's in-use cycles (REP05, REM01), ARB's ARB02 cycle, and the HL07 cycle. Vehicles were also tested on the LA4, again in a hot stabilized condition, in order to compare emissions from LA4 driving to emissions from in-use driving. EPA completed the base testing in August of 1993.

Figures 1-9 and 1-10 presents a summary of the emission results for the 8 vehicles in EPA's test program. The large differences seen between the non-FTP emissions and the LA4 emissions must be placed in the proper context by applying appropriate weighing factors to reflect the fraction of in-use operation represented by the specific cycle. The weights shown in table 1-4 correspond to the fraction of in-use miles represented by the cycles; these weights were developed from the in-use driving survey data as part of the cycle development effort.. The weighted emission results are shown in table 1-5. The weighted "in-use" emissions are significantly higher than the weighted, warm, stabilized FTP emissions. NMHC increased by 0.04 grams/mile, CO rose by 2.8 grams/mile, and NOx rose by 0.08 grams/mile. This increase in in-use emissions relative to the FTP cannot be attributed to a single driving mode or condition. In evaluating the relative significance of the in-use components, their contribution to the increase was calculated as:

(In-use component - warm, stabilized FTP) x in-use component weighing factor

The total difference between in-use and hot, stabilized FTP emissions is the sum of the weighted differences.

Table 1-6 shows each in-use component's contribution as a percent of the total increase. The results suggest that while

"REP05" driving accounts for a large fraction of the increase (31 to 58%), the other in-use driving modes also make significant contributions, with more for HC and NOx than CO. Some of the observed emission increases were unexpected. For example, substantial emission increases for all three pollutants were observed on the Remnant cycle; such increases were not predicted given the Remnant cycle's similarity to the FTP in speed and acceleration.

3.2.2. Vehicle Manufacturer Test Program

Vehicle testing sponsored by the American Automobile Manufacturers Association (AAMA) and the Association of International Automobile Manufacturers (AIAM) greatly enhanced the EPA's database on off-cycle emissions. The manufacturer's program included 26 late model vehicles representing 7 vehicle manufacturers. Testing included real-time measurement of engine-out and tailpipe emissions, as well as various engine parameters. The second-by-second data were helpful in understanding off-cycle emissions. This program also provided a unique opportunity to look at a potential strategy for controlling offcycle emission. A subset of 15 vehicles went through a second phase of testing after each vehicle's calibration was changed to eliminate commanded enrichment. Much was learned in the comparison of emissions from the production and "stoich" (no commanded enrichment) configurations of these vehicles. The vehicle manufacturers' program began shortly after the completion of EPA testing and was completed by the Spring of 1994.

The program's emphasis was the testing of potential control cycles. Testing was conducted on REP05, ARB02, FTP, and HL07 cycles; very little testing was done on the REM01 due to the fact that it was principally thought of as an emission assessment cycle(to assess the amount of emissions generated in use), not a control cycle (to control in-use emission as part of a test procedure). Unfortunately, this omission makes it impossible to do a full in-use emission assessment with the manufacturer data, and thus, a direct comparison cannot be made with EPA's results on the difference between in-use and FTP emissions. However, two comparisons can be made. First, the average results from the two programs over the REP05 and ARB02 cycles are compared to see if the levels of off-cycle emissions are in general agreement. Second, to look at the increase between offcycle and hot, stabilized FTP emissions, a comparison can be made of the difference of REP05 and hot stabilized FTP emissions from the two test programs.

Table 1-7 provides a summary of the results from EPA's and the vehicle manufacturers' test programs. The average emissions by vehicle type are pretty consistent of the two programs. For LDVs, average NMHC emissions are slightly higher for the manufacturers test program, while EPA testing showed higher average CO emissions and a slightly larger difference between REP05 and FTP emissions. Average NOx emissions were substantially higher for the vehicle manufacturers' tested vehicles, as was the REP05 and FTP difference.

A comparison of light- duty truck results shows somewhat larger average differences between the two programs. Over the REP05 and ARB02 cycles, NMHC emissions are pretty similar for the two programs; however, EPA testing showed much lower emissions for hot FTP driving and as a consequence, the REP05 and FTP difference is higher for EPA testing than manufacturer testing. The two programs had similar average CO emissions for LDTs. In contrast, NOx emissions were much higher for the vehicles tested by the manufacturers, as was the difference between REP05 and FTP emissions. Only the manufacturer test program tested heavy light duty trucks.

On average, the two programs showed consistent emission results. The largest discrepancy was found for NOx emissions, in which case EPA vehicles had substantially lower emissions. The consistency of the two programs' average emissions gives support to EPA's emission assessment based on the 8 vehicles tested by EPA.

3.2.2.1 Load- adjusted Testing

In addition to the testing discussed above, a subset of vehicles were tested after making adjustments to the dynamometer load settings. These adjustments were made to vehicles which fell more than 1.5 seconds behind the speed-time trace of the REP05, HL07, or ARB02 cycles. The auto manufacturers were concerned that portions of the high speed/load cycles were too aggressive and "unrepresentative" for some vehicles, such as lower performance vehicles. The adjustment was intended to allow the vehicle to follow the trace within the 1.5 second tolerance band. Two of the three dynamometer load coefficients were candidates for adjustment. If the out of tolerance event occurred at speeds less than 50 mph, the inertia, or A coefficient, was adjusted. For such events with speeds above 50 mph, the aerodynamic drag, or C coefficient was adjusted. For some vehicles and some cycles, adjustments were necessary on both coefficients. The load adjustment was applied to the entire driving cycle, not just the portions where the out of tolerance event occurred. Thirteen of the 28 vehicles in the manufacturers' test program required an adjustment on at least one cycle. The EPA program saw only one vehicle with the need for a load adjustment and that was on the HL07 cycle.

In practice, the determination of the percent adjustment was an iterative and an imprecise process. The adjustment was successful in allowing the vehicle to meet the 1.5 second tolerance band. It is impossible, however, to evaluate whether the specific adjustments were the appropriate amount or whether they were excessive. Further, adjusting the inertia for the entire cycle decreases the severity for the entire cycle, while only a very small portion of the cycle "needed" the adjustment.

3.2.3 CARB Test Program

The nature and scope CARB tested paralleled the EPA and AAMA\AIAM programs. One significant difference was CARB's use of a twin-roll dynamometer instead of a large, single-roll dynamometer. EPA has limited its analysis to data collected using the single-roll dynamometer; future testing by CARB will be on a single-roll dynamometer and EPA will consider such data, as is appropriate.

3.3 Emissions associated with Road Grade

Road grades affect on emissions results from the increased engine load above that which is associated with the driving behavior alone. The higher mass flow associated with the increased load will produce higher emission for all three pollutants. The extra load associated with road grade can also increase the frequency or extend the duration of enrichment resulting in large increases in CO, and to a lesser extent HC. While EPA lacked the in-use information necessary to conduct a full emission assessment, emission testing with simulated road grade was conducted on several vehicles to get a sense of the emissions increase associated with road grade. EPA tested 3 vehicles over the in-use driving cycles with a 2 Percent road grade added by means of increasing the inertia load of the dynamometer.

The HC increase was consistent across the three vehicles averaging only .04 grams/mile. The CO increase avenged 3.2 grams/mile, with significant differences in the level of increase among the vehicles tested. The vehicles averaged a 0.19 g/mile NOx increase, with most of the increase accounted for by one vehicle, the Crown Victoria.

Section 4. Controlling Emissions from non-FTP Driving Behavior

High load events (hard accelerations), and high speed and transient driving behavior were all components of non-LA4 driving behavior which showed the potential for large emissions increases relative to FTP, controlled emissions. The results of the test program established a need to control these emissions. This section considers alternative methods of controls and the feasible levels of emission control.

4.1 Causes of Emission Increases

There are several causes for exhaust emissions that resulted from high speed and load, and transient, non-FTP driving behavior, as found over the ARB02 and REP05 cycles. Commanded and transient enrichments had a significant impact on HC and CO emissions; while high combustion chamber temperatures resulting from high speed and load operation, and poor catalyst conversion efficiency levels, caused high NOx emissions.

4.1.1 Commanded Enrichment

Commanded enrichment is any extra fuel, beyond what is necessary to maintain a stoichiometric air-fuel ratio, that is deliberately delivered to the engine via a command from the engine calibration through the electronic engine control system to the electronic fuel injection system. It is analogous to the acceleration enrichment that was used for carburetored fuel systems. Commanded enrichment is typically used whenever the engine is under high loads, such as those that occur during hard accelerations or pulling a loaded trailer. The extra fuel provides the engine with a power gain and is also used to cool the engine and catalyst.

Emission data from the EPA/CARB/AAMA/AIAM cooperative test program indicates that hydrocarbon (HC) and carbon monoxide (CO) emissions are very sensitive to commanded enrichment. Engine-out CO emissions increase as the air-fuel ratio is richened from stoichiometric levels, due to the lack of oxygen available to complete the combustion process to CO2. Engine-out HC emissions are simply unburned fuel that result from wall quenching, deceleration misfire, rich operation, and by hiding in combustion chamber and piston wall crevices. As hydrogen reactions are favored over carbon reactions and tend to continue to occur even in a rich environment, engine-out HC emissions show relatively little sensitivity to air-fuel ratio as compared to CO emissions. Catalyst conversion efficiency levels for both HC and CO emissions are very sensitive to air-fuel ratio. In a rich environment, the lack of oxygen causes the oxidation of HC and CO into CO2 and water vapor, to drop off very quickly, causing catalyst conversion efficiency to be reduced, especially for CO. Air-fuel ratios during commanded enrichment events can be as rich as 11.7:1, compared to the normal stoichiometric A/F level of approximately 14.7:1.

4.1.1.1 Impact of Commanded Enrichment

Figure 1-11 provides an example of the impact of a commanded enrichment event on CO emissions. For an 8-second segment of an acceleration event , the figure compares CO emission and the A/F ratio for vehicle 304 (Oldsmobile 98), tested in the production configuration and in the stoich (no commanded enrichment configuration. The commanded enrichment event lasted approximately eight seconds and changed the air-fuel ratio from 14.7:1 to 13.0:1, and increased maximum engine-out CO about an order in magnitude.

As part of the manufacturers test program, a subset of approximately 15 vehicles were tested with stoichiometric (referred to as "stoich") calibrations as well as with the original production calibrations. The manufacturers eliminated the commanded enrichment strategies for the stoich calibrations, but made no attempt to reduce any other enrichments, such as starting or transient, or to optimize spark timing or other strategies as a result of eliminating commanded enrichment.[10] In fact, some of the vehicles still ran slightly rich under high loads with the stoich calibrations. Therefore, it should be kept in mind that while the stoich calibrations demonstrate the reductions in HC and CO emissions that can be achieved by eliminating commanded enrichment, they have not been optimized for overall emission control or impacts on driveability and performance. Thus, without directly proving feasibility, they do demonstrate the approximate improvement in high speed and load off-cycle HC and CO emissions that can be achieved.

The effects of commanded enrichment on CO and HC emissions is further illustrated in table 1-8. Table 1-8 shows the HC and CO tailpipe emissions results of eight vehicles over an acceleration event on the ARB02 cycle with the production and stoich calibrations. The production calibrations use commanded enrichment during this acceleration whereas commanded enrichment has been removed for the stoich calibrations. By comparing the emissions generated during this acceleration for those calibrations with and without commanded enrichment, the impact of commanded enrichment can be clearly demonstrated. This acceleration was chosen because it is one of the most aggressive accelerations found on the cycle and almost every vehicle in the

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[10] Transient enrichmentis used to compensate for lean spikes that typically accompany sudden throttle opening or momentary accelerations that occur during microtransient operation. "Starting Enrichment" is used during cold and hot engine start-up. It is required to overcome poor atomization of fuel droplets that occur during extreme ambient conditions.

test program went into commanded enrichment when operated over it[11]. The average duration of the commanded enrichment events for these vehicles over this acceleration was 8.3 seconds with an average change in air-fuel ratio of 14.61:1 to 12.45:1.

Table 1-8
Impact of commanded enrichment on HC and CO tailpipe emissions
Initial acceleration of hill 19 of ARB02 cycle

Vehicle	HC (g/sec)			CO (g/sec)		
	Prod	Stoich	Increase	Prod	Stoich	Increase
Escort	0.390	0.048	0.342	30.58	2.67	27.91
Supreme	0.250	0.008	0.242	20.78	0.39	20.39
GPrix	0.275	0.020	0.255	16.38	0.43	15.95
Olds 98	0.146	0.027	0.119	14.83	2.60	12.23
Seville	0.643	0.029	0.614	28.76	0.74	28.02
Saturn	0.268	0.020	0.248	22.55	1.50	21.05
Metro	0.411	0.110	0.031	19.71	4.12	15.59
GrandAm	0.364	0.032	0.332	22.02	3.98	18.04
Average	**0.343**	**0.037**	**0.306**	**21.95**	**2.05**	**19.89**

For HC emissions, the average tailpipe levels were 0.037 g/sec with the stoich calibration **(no commanded enrichment)** and 0.343 g/sec with the production calibration **(commanded enrichment)**, with an average increase of 0.306 g/sec. The average CO tailpipe emission levels were 2.05 g/sec with the stoich calibration and 21.95 g/sec with the production calibration, for an average increase of 19.89 g/sec. The

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[11] The Mercedes 420 SEL does not use commanded enrichment. Mercedes is currently the only manufacturer that produces some vehicle models that do not utilize commanded enrichment.

increase in HC and CO tailpipe emissions for these vehicles due to commanded enrichment, is about one order of magnitude, 1000%.

4.1.1.2 Comparison of Production and Stoich Bag Results

Figure 1-12 compares the production and stoich HC and CO emission results for the REP05 cycle. The stoichiometric calibration reduces CO emissions dramatically; HC emissions decrease in almost all cases. The stoich. calibration tends to increase NOx emissions. This potential trade-off between CO/ HC emission reduction and NOx control is an important issue which is explored more fully in section 5.

4.1.2 Transient Fuel Control

EPA and manufacturers have long believed that slight changes in throttle movement can impact HC and CO emissions. Data from the EPA/CARB/AAMA/AIAM test programs support this theory for HC and CO emissions during non-FTP driving operation. There is not one clear explanation for the increase in emissions. The data does point to one possible cause: rich spikes in the air-fuel ratio. These rich spikes do not appear to be caused by commanded enrichment since they were observed in results from both, production and stoich calibrations. Rather, they seem to occur for two different reasons, either from a series of short, abrupt throttle openings that happen during rapid throttle movement or from moderate to heavy deceleration events.

4.1.2.1 Throttle Movement

The rich air-fuel ratio spikes that occur from short, abrupt throttle openings during periods of significant throttle movement, appear to be related to enrichment strategies . When the throttle is initially opened, there is a lag between the air entering the cylinder and the fuel being injected into the cylinder. The air enters the cylinders instantaneously whereas the injection of the fuel cannot occur until the fuel control system (i.e., control module) senses that the throttle has been opened; calculates how much fuel is necessary; and sends the proper voltage signals to the injectors to release the fuel. This results in a momentary period of enleanment or a lean spike. A very common calibration strategy for minimizing the length and depth of these lean spikes is to use extra fuel, known as transient enrichment, as soon as the control system senses that the throttle is being opened. Unfortunately, it is common for the transient enrichment calibration to use too much fuel and result in an unwanted rich spike.

A good example of transient enrichment is shown by the Mercedes 420 SEL; a vehicle which was included in both the EPA and vehicle manufacturer testing. A unique feature of this Mercedes is that it does not use any commanded enrichment strategies, yet it demonstrated an emissions sensitivity to variability in the amount of throttle movement from one test to another. Over a given cycle, a driver that drove with more fluctuation in the throttle generated higher emissions than a driver with less throttle variation , or a more "steady foot." Table 1-9 presents emissions results and throttle movement measures for three runs over the REM01 cycle, using 3 different drivers. The change in throttle (DTP) was calculated as the change in the measured throttle position from one second to the next. The sum of the DTP shows driver C to be the smoothest driver. This driver also had the lowest HC and CO emissions. The results suggest that there are some vehicles which show HC and CO emission sensitivity to the amount of throttle movement.

4.1.2.2 Throttle Movement Modelling

As a follow-up to the analysis of the Mercedes', EPA used data from the vehicle manufacturers test program to analyze the emission impact of throttle movement. Only stoich tests were used in order to eliminate the impact of commanded enrichment, and the test data were limited to the two non-FTP cycles: ARB02 and REP05 (note: the manufacturers test program did not include testing on REM01). A simple tailpipe emissions regression model was developed to look at the determinants of the emission differences. After controlling for vehicle and cycle, the model looked at impact of throttle variation, measured as the sum of the one-second change in throttle (DTP). As shown in table 1-10, DTP is statistically significant (factor,) at the 10% level for both HC and CO emissions.

The movement of the throttle is the vehicle's response to the driver's demands to achieve or maintain a particular speed. In following a driving schedule, the changes in throttle are associated with changes in the driving behavior; a speed-based measure that relates well with the throttle change is the sum of the change in power (dpwrsum). Table 1-10 suggests that dpwrsum shows a similar 10% significance for explaining marginal variation in HC and CO emissions.

Table 1-10
Marginal Effects of Change in Throttle (DTP)
and Change in Specific Power (DPWRSUM)
Stoich Tests, ARB and REP Cycles
with no load adjustment (n=58)

	Pollutant	Full model R^2	Coefficient (x1000)	t statistic	prob.>t
DTP					
	CO	0.875	13.044	1.90	0.064
	HC	0.883	0.315	2.68	0.011
	NOX	0.980	-0.064	-0.18	0.855
DPWRSUM					
	CO	0.873	3.016	1.74	0.089
	HC	0.882	0.076	2.55	0.015
	NOX	0.980	0.014	0.16	0.876

4.1.2.3 Heavy Deceleration Enrichment

Increases in HC and CO emissions during heavy deceleration events is due to the potentially large slugs of raw fuel that are drawn into the combustion chamber during quick closures of the throttle that usually occur during sudden deceleration events. As fuel flows through the intake system into the combustion chamber, a fuel boundary layer is formed, where liquid fuel is "stored" along the surfaces of the intake manifold, port area, combustion chamber, and cylinder walls. The thickness of the fuel boundary layer is inversely proportional to the manifold vacuum. When a vehicle suddenly decelerates, the manifold vacuum decreases dramatically in response to closure of the throttle blade. This results in the simultaneous drop of air to very low levels, due to the throttle closing, and a surge of fuel being drawn off the intake and combustion surfaces, due to the increase in manifold vacuum. For most vehicles equipped with port fuel injection (PFI) systems, the amount of extra fuel drawn is usually small. However, the extra fuel that is drawn into the combustion chamber stays in a liquid form and doesn't properly mix with the rest of the fuel-air mixture and is passed through the engine in a raw uncombusted state, raising engine-out HC emissions.

This phenomenon was the most apparent for vehicles equipped with throttle-body fuel injection (TBI) during heavy decelerations. This is most likely due to the fact that more fuel is "stored" along the intake manifold walls for TBI vehicles than for PFI vehicles since the fuel injector is located in the throttle-body where air and fuel are combined, and then must flow along the length of the intake runners to the combustion chambers. For PFI vehicles, the fuel injector is located in the intake manifold runner as close to the valves in the combustion chamber as possible. When the fuel is injected into the combustion chamber, there is considerably less intake runner surface for fuel to adhere to, thus, less liquid fuel is drawn into the combustion chamber. While this phenomenon was the most prevalent with TBI vehicles, there were some PFI vehicles that also experienced increases in HC emissions due to heavy decelerations. This is probably a result of poor calibration strategy, due to either a lack of the proper strategy needed to anticipate when a heavy deceleration will occur, or poor calibration technique of the existing deceleration strategies.

Most of the heavy decelerations that caused HC increases over the various cycles were aggressive, i.e., instantaneous throttle closing combined with braking for several seconds, that typically occurred at the end of a hill. However, the test data revealed that even relatively short, but abrupt throttle closings that occurred during the middle of a hill, not in an attempt to stop the vehicle but rather as a result of excessive or even erratic throttle behavior on the part of the test driver to maintain the driving trace, can cause similar HC increases.

The increases in HC and CO emissions due to enrichment occurring during heavy deceleration events were small. This is most likely due to the fact that even though air-fuel ratios were very rich (approximately 13:1) during heavy deceleration events, the exhaust mass flow is very low, thus, only generating relatively low emission levels.

4.1.3 High Combustion Temperatures

The NOx emissions resulting from the ARB02 and REP05 cycles were significantly higher than warm, stabilized FTP levels. This is due to the fact that NOx emissions are temperature sensitive.   Excessively high temperatures in the combustion chamber cause free oxygen and nitrogen from the air-fuel mixture to combine and create NOx. During high speed and load operation, more fuel and air are burned in the combustion chamber. As the amount of combustion increases, temperatures also increase. The temperatures in the combustion chamber are considerably higher during high speed and load operation than during typical FTP operation, thus causing the significant increase in engine-out NOx emissions.

Figure 1-13 illustrates the increase in NOx emissions from bag 2 of the FTP to the REP05 cycle. Bag 2 emission results were chosen, rather than overall FTP emission results, because bag 2 results are warm, stabilized results without any start-up emissions, similar to REP05 cycle results.

As discussed in Section 4.1.1., commanded enrichment is used to reduce combustion temperatures. During stoichiometric operation, combustion is much more complete than during rich or lean operation, where there is an excess of fuel or air. The more complete the combustion process is, the more heat that is given off as a byproduct. Commanded enrichment reduces combustion temperatures from those observed at stoichiometry because the extra fuel in the air/fuel mixture, above stoichiometry, is not combusted and dampens or absorbs the heat from the combustion process, keeping combustion temperatures lower than what would occur during stoichiometric operation. Thus the removal or reduction of commanded enrichment causes an increase in combustion temperatures and consequentially, engine-out NOx emissions. The effects of removing commanded enrichment over the ARB02 and REP05 cycles is illustrated in Table 1-11.

Table 1-11
Impact on engine-out NOx emissions from removal of commanded enrichment over ARB02 and REP05 cycles

Vehicle	ARB02 Cycle			REP05 Cycle		
	Prod	Stoich	Increase	Prod	Stoich	Increase
Escort	4.83	5.61	0.78	4.11	4.74	0.63
Cruiser	2.03	2.68	0.65	1.85	2.22	0.37
Seville	3.11	3.68	0.57	2.56	2.69	0.13
Supreme	3.89	4.37	0.48	3.20	3.54	0.34
Olds 98	4.02	4.28	0.26	3.67	3.81	0.14
Saturn	2.16	2.41	0.25	1.92	2.18	0.26
Average	**3.34**	**3.84**	**0.50**	**2.89**	**3.19**	**0.30**

Table 1-11 shows that for both, the ARB02 and REP05 cycles, that as commanded enrichment was removed, engine-out NOx levels increased. The average increase over the ARB02 cycle was 0.50 g/mi, while the average increase for the REP05 cycle was 0.30 g/mi. The difference in the average engine-out increase between the two cycles is most likely due to the fact that the ARB02 cycle contains more aggressive acceleration events than the REP05 cycle.

4.1.4 NOx Catalyst Conversion Efficiency

In addition to increased combustion temperatures, data from the test programs indicated that high NOx emission levels also appear to be related to not having tight enough air-fuel ratio control (i.e., numerous rich and lean spikes, and a lean bias for the fuel control system during this type of operation). Analyses done by EPA showed that vehicles from the manufacturer test program that had high NOx emissions during high speed and load operation, also had erratic NOx catalyst conversion efficiency levels[12]. Those vehicles that had low NOx emissions during high speed and load operation, had almost continuous high catalyst conversion efficiency levels. Further examination revealed that the vehicles that had erratic conversion efficiency levels also had erratic air-fuel ratio levels, with numerous rich and lean spikes, while the vehicles with high conversion efficiency had very tight air-fuel ratio control. In addition, the vehicles with high catalyst conversion efficiency levels appeared to use a rich bias; their air-fuel ratios averaged around 14.4:1 to 14.5:1, whereas the vehicles with the erratic conversion efficiency seemed to have more of a lean biased or unbiased fuel control strategy with the average air-fuel ratio centering around 14.6:1 to 14.7:1.

Vehicles 201 (Escort) and 306 (Custom Cruiser) both used a control strategy known as lean-on-cruise (LOC). The purpose of this strategy is to enhance fuel economy by operating at an air-fuel ratio of approximately 17:1

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[12] Memorandum from Ted Trimble to John German, titled "Nox emissions on REP05", dated April 8, 1994

during steady-state cruises. For both of these vehicles, LOC only occurred during relatively high speed cruises. Table 1-11b shows the time spent in LOC and the grams/second emissions resulting from LOC over the FTP and REP05 cycles for both vehicles with production calibrations. The Custom Cruiser spent no time in LOC during the FTP, but averaged 351 seconds of LOC operation over the REP05 cycle, and the Escort averaged 34.5 seconds on the FTP and 358.5 seconds during the REP05 cycle. Over the REP05 cycle, the contribution of LOC operation to total NOx emissions was 52.5% for the Custom Cruiser and 71.5% for the Escort.

Table 1-11b
Lean-On-Cruise Operation for Vehicles 201 & 306 with Production Calibrations (grams/sec.)

Veh	Test	Lean-On-Cruise			Total			% of Total			Time
		HC	CO	NOx	HC	CO	NOx	HC	CO	NOx	(sec)
201	FTP	.004	.59	.92	2.73	32.32	5.83	4.0	1.5	15.5	34.5
	REP05	.130	.58	24.74	2.70	156.3	34.72	5.0	0.4	71.5	358.5
306	FTP	0	0	0	n/a	n/a	n/a	0	0	0	0
	REP05	.585	6.10	7.28	3.81	203.5	13.82	15.0	3.0	52.5	351.0

4.2 Approaches to Compliance Testing for Non-FTP Driving Behavior

In examining alternative control methods, EPA's basic premise is that the better the representation of in-use driving the better the control of in-use emissions. While this premise has to be balanced by practical considerations such as cost and feasibility, the importance of trying to accurately reflect actual in-use conditions cannot be lost.

4.2.1. Air-Fuel control cycle

The HL07 cycle is an engineered cycle designed to drive a vehicle through a series of high acceleration/load events covering a range of severity and speeds. The cycle also includes a two and half minute cruise at 65 mph. Prior to starting the test program manufacturers' suggested that a cycle like the HL07 could be used to develop a air-fuel based emission standard. In general, this approach would eliminate commanded enrichment by establishing an air-fuel band around stoichiometry. This option would place standards on the duration or magnitude of deviations from stoichiometry., measured over the short HL07 cycle. Such an approach would likely eliminate much of in-use, commanded enrichment, thus greatly reducing CO emissions, and also achieving HC reductions. The ability to control offcycle NOx and HC emissions caused by poor transient fuel control is less certain. A very tight band would be necessary to ensure NOx control, while this may not be entirely appropriate or feasible. However, drawbacks to this approach include the following: the lack of control for microtransient enrichment; lack of a suitable methodology for achieving NOx control; difficulties in devising an A/F standard for vehicles operating on alternative fuels, like diesel or compressed natural gas (CNG); and reduced manufacturer flexibility in designing a control strategy. This option effectively mandates a control system strategy, while an emission performance standard provides manufacturers the flexibility to determine, case-by-case, the most cost effective way to achieve the desired emissions result.

4.2.2. Representative cycle

A second method for controlling non-FTP emissions, a representative cycle, stands in sharp contrast to the HL07 cycle. As a control cycle representing the full range of non-FTP operation, it can be argued that a representative cycle is the best method for ensuring that the emission control achieved in testing will fully translate to in-use emission control.

The principal difficulty in implementing such an approach is that a such cycle must try to represent speed, acceleration, the interaction of speed and acceleration, as well as the change in accelerations. All these variables lead to the need for a very long cycle. EPA developed REP05 expressly to represent the range of non-FTP operation, and as a consequence the cycle is 1400 seconds (over 23 minutes) in duration. A large fraction of the representative cycle will be high speed cruise operation, since this is the predominant mode of non-FTP operation. The extra testing and facility time to include all the cruise operation is hard to justify of a cost/benefit. It is reasonable to assume that control of emissions during high speed cruise operation can be achieved without having to match its exact in-use representation.

4.2.3 High speed/load transient control cycle (US06)

A third control approach involves a hybrid cycle that shares characteristics of both the air-fuel control approach and the representative cycle approach. The new cycle, US06, is 600 seconds in duration and is comprised of segments of CARB's ARB02 cycle and EPA's REP05 cycle. Similar to the air-fuel control method, this method targets specific high emission, non-FTP operation. And like the representative cycle, the US06 is based on actual segments of in-use driving.

Through a concerted, coordinated effort, staff from the two agencies (with helpful manufacturers' comments) developed the US06 based largely on a review of the second-by second emissions over the REP05 and ARB02 cycles, from the vehicle manufacturer's test program. From the two driving cycles, staff identified segments which they felt would provide control emissions from aggressive driving and transient operation. The US06 includes the range of non-FTP driving operation including all of the more severe acceleration events and includes representative high speed cruise operation, while reducing the cycle time to 10 minutes.   The US06 cycle is shown in figure 1-14.

4.2.4 Justification for selecting US06 as preferred option

US06 is EPA's preferred method for establishing control of emissions from non-LA4 driving behavior. The US06 covers the range of non-LA4 driving, while targeting severe, high emission events. Because the driving modes generating the highest emissions differed widely across vehicles, it is very important to include a variety of high load events representing actual aggressive driving behavior. In addition, the US06 cycle achieves the objectives of both EPA and CARB, thus eliminating issues or costs associated with the respective agencies having two different control An important CARB objective is to make sure outer bounds of in-use aggressive driving is represented and controlled; this is achieved with the inclusion of the ARB02 high-speed micro-trip. A second, ARB02 high-speed microtrip was rejected due to an extended, high-speed acceleration which might result in excessive catalyst temperatures in vehicles which are controlling commanded enrichment. Thus, the US06 provides for control of short-duration commanded enrichment events associated with aggressive driving. As discussed in the feasibility section which follows, the duration of commanded enrichment control needs to be limited due to catalyst temperature concerns. EPA's analysis of catalyst temperature data from the manufacturer's test program concluded that the ARB02 high speed microtrip used in US06 provides for a reasonable duration of control.

4.2.4.1 Road Grade

The severe driving events contained within US06 also help provide for some control over the emission impact of road grade. As discussed in section 2.2, the extra load placed on the engine by road grade is analogous to the load from an acceleration, and thus, if sufficient, can result in a sharp emission increases as a result of commanded enrichment. The in-use frequency and duration of commanded enrichment events are a function of the combined effects of driving behavior, road grade, and vehicle loading. To the extent that US06 contains driving which is more aggressive than that called for by a representative cycle, this "safety margin" provides for some control of commanded enrichment resulting from road grade or vehicle loading. For example, commanded enrichment events associated with aggressive driving on a road grade (such as an entrance ramp) would be controlled--up to the control duration established by US06.

4.2.5 US06 adjustments

As a control cycle, the US06 is appropriate for a large fraction of light-duty vehicles and light-duty trucks. However, inasmuch as the cycle is intended to control emissions during severe, high speed and load operation, the severe operation characterized by the cycle may exceed some vehicles' capabilities. Section 2.2 discussed differences in in-use driving behavior as a function of vehicle performance, transmission type, and vehicle type. These differences need to be considered in judging the appropriateness of the control cycle for all vehicles.

4.2.5.1 Vehicle Performance and Transmission Type

In-use driving patterns data indicate that for manual transmission vehicles, high and low performance vehicles (performance based on W/P) are driven differently than the broad range of mid-performance vehicles (see section 2.2.1.). High performance vehicles were driven in a more aggressive manner, while the low performance vehicles were typically driven less aggressively. For automatic transmission vehicles, it appears that low performance vehicles are driven less aggressively than middle and high performance vehicles. The US06 cycle is a hybrid of the REP05 and ARBO2 cycles, and it is intended to be represent the vehicle fleet as a whole. The portions of the REP05 cycle used in the US06 cycle are identified below in table 1-12, along with a description of the vehicle which actually generated the driving segment. The W/P for the vehicles' which comprise the REP05 cycle cover the full performance spectrum; one segment, R5, came from a high performance vehicle. It is not possible to identify the vehicle's which generated the driving for the Los Angeles chase car data.

Table 1-12

Segment	In US06	Veh. #	Description	Transmission	W/P
R1	**yes**	B163	1988 Honda Accord Lxi	manual	25.00
R2	no	B467	1986 Honda Accord	automatic	28.75
R3	**yes**	B287	1979 Chevrolet Monte Carlo	automatic	27.78
R4	no	B419	1980 Buick Regal	automatic	25.83
R5	**yes**	S224	1988 Ford Thunderbird	manual	19.33
R6	no	B368	1988 Hyundai Excel	automatic	36.76
R7	**yes**	B389	1982 Toyota Corolla	automatic	37.50

The in-use driving survey results suggest that it would be unrepresentative and inappropriate to require low performance vehicles to drive portions of the US06, such as R1 and R5, without adjustments.

4.2.5.2 HLDTs

Evidence from the in-use driving survey data points to the need for adjustments over the US06 cycle for HLDTs. The case for HLDTs is analogous to that for high and low performance vehicles. The US06 and predecessors were developed to represent non-FTP driving behavior for the fleet as a whole. As discussed in section 2.2.2, HLDT driving behavior appears to be different than the rest of the light- duty vehicles' behavior. Determining the appropriate testing for HLDTs is complicated by the current method of testing HLDTs at adjusted load vehicle weight (1/2 payload). The driving segments found in US06 are from LDVs, and the load they were subjected to while exhibiting such behavior in not known. It can be assumed, however, that these vehicles were not loaded to the extent that HLDTs are loaded when tested at 1/2 payload.

4.2.5.3 Adjustment approach

The tailoring of the cycle to meet the needs of each individual vehicle is impractical. As is the case for the FTP driving schedule, there will always be some vehicles for which the US06 will be "easier" than it is for others. However, it is desirable to have the US06 broadly representative for all vehicles. To achieve this objective, EPA feels it is appropriate to make adjustments for low performance vehicles and HLDTs (to reduce the cycle's severity where it appears overly severe). Again, the adjustments are to make the cycle more representative of actual vehicle operation and to ensure that the emission control demonstrated on the test procedure results in in-use emission reductions.

One approach would involve making adjustments to the test procedure, by modifying the actual US06 driving cycle. This would lead to a proliferation of cycles and would greatly increase the cost and complexity of testing. An alternative to modifying the speed-time trace is to make adjustments to the dynamometer inertia settings. An adjustments to the inertia load can have the same effect as a modification to the cycle, as the engine can't tell the difference between an inertia load and an acceleration load. This approach was tested during the emission test programs with general success (see section 3.2.2.1) EPA believes adjustments to dynamometer load settings is a reasonable and practical method for handling the need for modifications to the cycle. Section 7 proposes refinements to the dynamometer load adjustment approach used in the emission test program. The proposed adjustments to low performance vehicles are intended to bring these vehicles toward the mid-performance vehicles. The HLDT adjustments serve to reduce the severity of the cycle to be more consistent with their in-use operation.

4.3 Potential Strategies for Controlling Emissions from Non-FTP Driving Behavior

The Agency has determined that significant reductions in emissions, resulting from aggressive driving and microtransient operation, can be achieved by improved fuel control through optimization of engine calibrations and some slight hardware modifications. Significant reductions in HC and CO emissions can be gained by reducing or eliminating commanded enrichment and optimizing transient fuel control strategies to better maintain stoichiometric air-fuel ratio operation. In order to realize these reductions, some vehicles may have to also switch from synchronous-fire port fuel injection systems to sequential-fire port fuel injection systems. Large reductions in NOx emissions can be achieved by improving NOx catalyst conversion efficiency levels through tight closed-loop fuel system control of an air-fuel ratio with a slightly rich bias during high speed and load operation.

Emissions could be further reduced by using "drive-by-wire" technology and going to larger catalysts with higher noble metal loadings. However, these would be very costly and the level of emission reductions would be small compared to what can be achieved through the calibration optimization discussed above. Therefore, EPA feels that the emission benefits that could be gained by using "drive-by-wire" systems and larger catalysts are not sufficient to require vehicle manufacturers to incur the costs of using such control strategies.

4.3.1 Improved Fuel Control Through Calibration

4.3.1.1 Commanded Enrichment

As previously discussed in Section 4.2.3, the vehicle operation simulated by the US06 cycle is considerably more aggressive than that found on the FTP. For example, the Geo Metro equipped with a 1.0 liter three cylinder engine, had an average throttle opening of only 7.5% over the FTP with a maximum throttle opening of 42.4%. On the US06 cycle, the Metro had an average throttle opening of 22.0% with a maximum opening of 100%. The Metro was the lowest performing vehicle in the test program with a weight-to-power ratio of 38.6 (2125 ETW/55hp), and yet it never needed to exceed a throttle opening of 50% over the FTP.

Because of the relatively low power requirements on the FTP, especially when considering accelerations, only a few vehicles in the test program ever went into commanded enrichment over the FTP. This greatly contrasts with the observations for the US06 cycle. All of the vehicles in the test program, except the Mercedes, went into commanded enrichment during the US06 cycle. The actual level of enrichment, or the amount of additional fuel added, during commanded enrichment events varies from vehicle to vehicle. The amount of commanded enrichment necessary, and the strategy for when it is utilized, is dependent on vehicle design constraints and calibration refinement. For some high performance vehicles the additional power generated by commanded enrichment may not be as important as the cooling effect the extra fuel has on the engine and catalyst. Typically, these vehicles have more concern over engine and catalyst durability because of the higher exhaust throughput generated by the large engines, and their frequent use of small close-coupled warm-up catalysts. Smaller low performance vehicles may have a greater need for the extra power that is generated by commanded enrichment. These vehicles often have small displacement, in-line 3 and 4 cylinder, high revving engines that typically run hotter than larger 6, 8, and 10 cylinder V-type engines. Because of this, a common strategy among manufacturers is to keep engine temperatures down by using commanded enrichment during high load operation.

In addition to optimizing commanded enrichment for specific engine/vehicle configuration constraints, there is the impact of calibration sophistication. Unfortunately, not all development engineers who calibrate the engine and emission control systems, have the same level of skill or experience. It has been suggested by various manufacturers that the occasional discrepancy in test data or occurrence of an unexplained phenomenon may be the result of poor calibration technique.

Fuel control calibrations are currently not calibrated to control exhaust emissions that occur during heavy load operation. There are several reasons for this: 1) Commanded enrichment calibrations have been intended to meet specific performance and durability criteria, such as enhancing power and/or to cool the catalyst; 2) Lack of sufficient high load operation over the FTP necessary to engage commanded enrichment: 3) No emission standards for off-cycle emissions; and 4) The occasional lack of calibration sophistication. As previously demonstrated, the commanded enrichment events that occur during the US06 cycle have significant effects on HC and CO emissions. The vast majority of vehicles sold in the United States utilize some level of commanded enrichment. It is therefore apparent that the relationship between commanded enrichment and exhaust emissions from heavy load operation, have not been an area of focus for manufacturers. The results from the various vehicles tested with stoich calibrations over the US06 cycle, demonstrate the large reduction in HC and CO emissions that can be obtained by reducing or eliminating commanded enrichment. It is apparent then, that one of the most important control strategies that will have to be implemented by manufacturers in order to comply with proposed HC and CO emission levels, will be the reduction or, in some cases, the elimination of commanded enrichment. The potential effects of reducing or eliminating commanded enrichment on vehicle performance and engine and catalyst durability is discussed in section 5.

4.3.1.2 Transient Enrichment

Another potential strategy for reducing HC and CO emissions during non-FTP driving behavior is to maintain tight stoichiometric air-fuel ratio control during transient operation, or more specifically, during rapid throttle movement where there is a series of short, abrupt throttle openings. This could be achieved by optimizing transient enrichment calibrations. As discussed in Section 4.1.2.1, transient enrichment is used to compensate for brief periods of enleanment that occur immediately following throttle opening due to time lags in the fuel control system. By optimizing transient enrichment calibrations such that the amount of enrichment is minimized and throttle opening is better anticipated, HC and CO emissions resulting from transient operation should be greatly reduced.

Unlike the reduction or elimination of commanded enrichment, this strategy will not be necessary for all vehicles. Several vehicles from the test program, such as 303 (Pontiac Grand Prix) and 305 (Cadillac Seville) had very tight air-fuel ratio control and low HC and CO emissions over all of the high speed and load cycles. The tight air-fuel ratio control and low emissions indicate that transient enrichment is not a problem for these vehicles. Therefore, EPA believes optimization of transient enrichment calibrations can be readily applied to all vehicles that have high non-FTP HC and CO emissions resulting from poor transient fuel control.

4.3.1.3 Heavy Deceleration Enrichment

As previously mentioned, the emission impact of heavy deceleration enrichment on HC and CO emissions are minimal. However, there still is some merit in discussing the elimination of rich air-fuel ratio spikes that occur during heavy deceleration events as a potential control strategy for the reduction of HC and CO emissions. As discussed in Section 4.1.2.3, the enrichment that causes rich air-fuel ratio spikes during deceleration events is not the result of programmed enrichments like commanded or transient. Rather, it is the result of poor transient fuel control strategies, and the natural phenomenon of fuel being stored on the surfaces of the intake manifold wall, valves, etc., and then being drawn into the engine during sudden throttle closure. However, the later cause is the most prominent. Therefore, calibration enhancements will only be part of the potential control strategy. The most viable calibration technique that can be used to control heavy deceleration enrichment is a control strategy known as decel fuel shut-off. During moderate to heavy decelerations, fuel is shut off, thus greatly reducing HC and CO emissions. This strategy has been used on numerous vehicle models by various manufacturers for several years. It has been typically used to eliminate the heavy deceleration event rich spikes for increased fuel economy. Vehicles 304 (Oldsmobile 98) and 314 (Pontiac Grand-Am) were both equipped with decel fuel shut-off and never experienced any rich spikes due to heavy decelerations during any of the high speed and load cycles.

4.3.1.4 NOx Catalyst Conversion Efficiency

There are several potential strategies for controlling NOx emissions from non-FTP driving behavior. An analysis by EPA examining NOx catalyst conversion efficiency levels, engine-out NOx emissions, and tailpipe NOx emissions, appear to indicate out that control of engine-out NOx levels were not as significant in reducing tailpipe emissions as maximizing NOx conversion efficiency levels over the various high speed and load cycles. The two vehicles with the highest tailpipe emissions, 306 (Custom Cruiser) and 305 (Seville), also had some of the lowest engine-out levels. Consequentially, these two vehicles also had the some of the lowest conversion efficiency levels at 62.8% and 74.8%, respectively, over the REP05 cycle.

Therefore, one of the main control strategies available for controlling non-FTP NOx emissions is to raise NOx catalyst conversion efficiency levels during high speed and load operation. The above mentioned analysis suggests that this can be accomplished by incorporating very tight fuel control around a slightly rich biased air-fuel ratio (14.5:1-14.6:1). At least four vehicles from the manufacturers test program, 314 (Grand-Am), 401 (Civic), 601 (Mirage), and 801 (Camry) experienced catalyst efficiency levels over 95% and had very low tailpipe NOx emission levels over the REP05 cycle. All four vehicles used a slight rich bias and had very tight fuel control. However, it is possible that the use of a rich air-fuel ratio bias could cause CO emissions to increase. This issue has not been fully evaluated by EPA.

Another control strategy, the elimination of the lean-on-cruise fuel strategy, will have less impact on NOx emissions for the vast majority of vehicles since only a small percentage of vehicles utilize it. Lean-on-cruise is typically used during high speed cruise operation to improve fuel economy. During the 65 mph cruise at the end of the HL07 cycle, the air-fuel ratio was maintained at approximately 17:1. Corresponding to this enleanment, the rate of NOx emission generation rises dramatically. Therefore, the elimination of this strategy will cause a significant reduction in NOx emissions.

An additional control strategy would be to concentrate on lowering engine-out NOx emissions through the use of exhaust gas recirculation (EGR) and reducing spark advance. Both of these strategies have been used extensively for years throughout the auto industry as a means to reduce engine-out NOx emissions by lowering combustion temperatures. These strategies would still be very beneficial in lowering NOx emission levels and EPA expects that they will used by most manufacturers. However, based on the above discussions, it appears that solely concentrating on lowering engine-out NOx levels through the use of EGR or reducing spark advance, may not be as effective of a control strategy as improving catalyst conversion efficiency levels.

4.3.2 Improved Fuel Control Through Sequential-Fire Port Fuel Injection

The ability to fire each fuel injector individually rather than simultaneously firing several injectors, as in synchronous-fire systems, allows even greater control of the air-fuel mixture for each cylinder. Each cylinder is assured of getting the complete fuel injector pulsewidth-worth of fuel. For synchronous-fire systems, if two injectors are fired simultaneously, only one of the injectors is being fired into a cylinder where the intake valve(s) is open and ready. The other cylinder is at a different point in the firing cycle and may not have the intake valve(s) fully open yet, thus fuel is injected onto the valve instead of into the cylinder. While some of the fuel may get into the cylinder, it's not the amount of fuel that was intendd to go in, nor is the same as what went into the other cylinder. This can also cause an excess of fuel to "puddle" on the valve so that when the valve is fully open, this excess fuel is drawn in with the injected fuel, causing the cylinder to receive too much fuel.

The type of fuel injection system used by a vehicle is moot when the potential control strategy is the reduction or elimination of commanded enrichment. However, for tighter air-fuel ratio control, which is one of the main potential control strategies available for controlling all three pollutants, the difference between fuel injection systems can be important. The type of fuel injection system used by a vehicle can help reduce the vehicle's sensitivity to throttle movement and improve the NOx catalyst conversion efficiency. Systems that utilize throttle-body (TBI) fuel injection systems will typically have more difficulty maintaining tighter air-fuel ratio control because of poorer distribution of the air-fuel mixture and the greater lag in the air-fuel mixture arriving to the combustion chamber, than those vehicles equipped with PFI systems. However, as demonstrated by the Mercedes, even a PFI system can still have poor air-fuel ratio control during rapid throttle movement. As discussed above, sequential-fire PFI systems can offer fuel control advantages that may be necessary for the level of air-fuel control required to reduce HC and CO emissions and increase NOx catalyst conversion efficiency levels for those vehicles that are unable to accomplish this through calibration strategies and synchronous-fire PFI systems.

The use of PFI fuel control systems (synchronous or sequential) should also eliminate the majority of HC emissions that result from unburned HC's ingested by the engine during moderate-to-heavy deceleration events.

Manufacturers have indicated that the current direction for fuel injection systems throughout the industry is to have all vehicles equipped with sequential-fire PFI systems. EPA believes that prior to implementation of this regulation (1998 model year) TBI fuel systems will be eliminated and there will be few synchronous-fire PFI systems.

EPA feels that the main strategies that will be required for controlling emissions from non-FTP driving will be calibration-related. The incidence of vehicle models needing to go to sequential-fire PFI systems in order to control non-FTP emissions should be low. This is a moot point since the vast majority of the vehicle fleet will already be equipped with sequential-fire PFI systems by the time this regulation takes effect.

4.3.3 Drive-by-Wire Systems (Electronic Throttle Control)

The term "drive-by-wire" refers to an electronic throttle control system. For most current vehicles, the accelerator pedal is connected to the throttle blade by a metal linkage or cable. The engine control module measures throttle movement by means of a variable resistor, known as the throttle position sensor (TPS), located on the shaft of the throttle blade. Unfortunately, there is some time lag between when the driver moves the accelerator pedal and the control module receives the information and is able to process it into necessary fuel or spark levels. Drive-by-wire systems eliminate the physical connection between the accelerator pedal and the throttle blade. Instead, the accelerator pedal is electronically connected directly to the control module. The throttle blade is operated by an electronic servo motor and the accelerator pedal has a variable resistor connected to it, similar to the TPS. When the accelerator pedal is moved, the variable resistor on the pedal sends a voltage signal, indicating the driver's desired throttle opening, to the control module. In turn, the control module processes the signal and sends a voltage signal to the servo motor on the throttle blade and opens the throttle accordingly. This greatly improves the ability to anticipate when the throttle will be opened or closed and allow for optimization of fuel to address rich and lean spikes that typically occur during throttle movement.

This technology was originally developed for vehicles utilizing all-wheel drive, as a means for controlling wheel slippage. This technology currently exists on a few relatively expensive luxury vehicles. The cost of utilizing such a system would be considerable due to the additional and complex hardware that is required. EPA believes that the vast majority of emission reductions that can be gained from better air-fuel control can be achieved by optimization of engine calibrations along with sequential-fire PFI systems. The additional level of emission reduction that could be achieved by using drive-by wire systems is small. The cost of using drive-by-wire systems outweigh the emission benefits to be gained by utilizing drive-by-wire. EPA does not believe that drive-by-wire technology will be necessary to comply with proposed HC emission levels. Therefore, to achieve the level of reduction in emissions desired by the Agency, EPA does not believe that drive-by-wire systems will be necessary.

4.3.4 Improved Catalysts

Analysis of the test data indicates that the use of larger catalysts with higher noble metal loading would not further reduce HC emissions from the levels achievable from the reduction or elimination of commanded enrichment; the optimization of transient enrichment; and use of sequential-fire PFI systems. However, further reductions in CO and NOx emissions could be realized for some vehicles by using larger catalysts and higher noble metal loading due to catalyst breakthrough that can occur at high speeds. Catalyst breakthrough is the inability of the catalyst to oxidize HC and CO, or reduce NOx in the face of high exhaust mass flow, despite the likely presence of sufficient oxygen to sustain catalysis. No catalyst breakthrough was observed for HC control.

The increase in CO and NOx emissions from high speed catalyst breakthrough is very small compared to the increases resulting from commanded enrichment and poor NOx catalyst conversion efficiency levels. The only vehicles that would likely experience breakthrough are those vehicles with large displacement engines that would have a very high exhaust mass flow rate during high speed operation. Increasing catalyst size and noble metal loading is expensive. The additional reductions in CO and NOx emissions beyond what can be achieved by eliminating commanded enrichment; optimizing transient enrichment; increasing NOx catalyst conversion efficiency levels; and using sequential-fire PFI systems, are very small and would not be cost effective due to the high cost of larger sized catalysts and high noble metal loading.

4.3.5 Reasonable Conclusion

As discussed in Section 4.1, the vast majority of HC, CO, and NOx emissions that occur during high speed and load non-FTP driving behavior result from commanded enrichment; poor transient fuel control; and inadequate NOx catalyst conversion efficiency levels. The potential control strategies for these causes in emission increases, as discussed in the above sections, should reduce emissions substantially. The two other potential control strategies; drive-by-wire and larger catalysts, are very costly and would only result in a very small additional reduction in emissions. Therefore, EPA feels that the achievable levels of emission control should be based on the reduction or elimination of commanded enrichment; optimization of transient fuel control; and the improvement of NOx catalyst conversion efficiency levels.

4.4 Level of Control

Section 4.3 identified recalibrations as the emission control strategy EPA believes will be the most cost effective. Thus, recalibration was the emission control strategy assumed in determining the appropriate levels of control and the most cost-effective control program for aggressive driving. The discussion below assumes the US06 as the control cycle, thus, the discussion on appropriate emission levels are specific to the US06 cycle.

EPA's conceptual approach to establishing the appropriate level of control is based on the premise that it is reasonable and feasible to expect off-cycle air/fuel calibration and the associated emissions to be consistent with calibration and emissions found on FTP. The level of control that these strategies can achieve over aggressive driving is pollutant specific, reflecting the different impact on the pollutant levels of factors like engine load and air/fuel calibration. As discussed above, this level of control can be attained by the elimination of commanded enrichment and improved air-fuel control. EPA accepts that there are exceptions, such as high load events of an extended nature--towing a trailer up a long grade. Trying to control emissions to FTP levels under these severe, infrequent, events would likely lead to the undesirable effect of catalyst deterioration.

4.4.1 HC Control

In establishing HC tailpipe emission levels for US06, EPA began with the hot, stabilized emission levels on the FTP; this corresponds to bag 2 of the FTP, as bags 1 and 3 include start-up emissions. The US06 emission data were simulated by splicing together the appropriate seconds of emission data from the US06 "parent" cycles, REP05 and ARB02. (Both of the latter cycles were also tested in a hot stabilized condition.) In the following tables, emission results for both production and stoich configurations are presented for US06, while for bag 2 of the FTP and the full FTP, only the production emissions are shown, as a baseline.

EPA believes that because engine-out hydrocarbon emissions vary directly with load on the engine, it should be possible to achieve comparable per-mile HC emissions over two cycles of comparable average load, as long as similar catalyst conversion efficiencies are maintained. Comparisons of the fuel economy results from the US06 and bag 2 of the FTP indicate that the US06 cycle, although clearly more aggressive in the speed and acceleration of its individual events, actually has a slightly lower average load (on a per mile basis) than bag 2 of the FTP. These results are presented in figure 1-15a. In nearly all cases the US06 fuel economy (miles per gallon) is above that for bag 2 of the FTP. The average load equivalency established by the fuel economy results is supported by a comparison of engine-out emissions. Figure 1-15a compares engine-out HC for bag 2 of the FTP and US06, and the full FTP. The data indicate that in both the production and stoich calibration, US06 engine-out emissions were lower than the vehicle's corresponding bag 2 emissions. For tailpipe emissions, figure 1-16 suggests that while production calibrations show large differences between the US06 and the FTP cycles, vehicles using the stoich calibration had US06 emissions which were comparable to FTP bag 2 emission with the exception of 312(Saturn). The Saturn uses throttle body fuel injection, a relatively old technology, and demonstrated poor transient fuel control and thus EPA feels it should be discounted. Overall, EPA feels it is reasonable to expect that with proper calibration to maintain good catalyst conversion efficiency, US06 HC levels can be controlled to the equivalent of bag 2, FTP levels.

4.4.2 CO Control

Tailpipe CO emissions in the production calibration are extremely high on the US06, as shown in figure 1-17. With stoich calibrations, five vehicles had the same or lower emissions on the US06 compared to the full FTP, while three vehicles were higher. In the stoich calibration, only vehicle 305(Seville) had US06 emissions that were lower than FTP bag 2 emissions. The Seville was one of the high performance vehicles in the test program and rarely got into high throttle openings even on the US06, and thus, spent little time in commanded enrichment.

The sensitivity of CO emissions to the drive cycle is further illustrated in figure 1-18. In the stoich calibration, the relationship between engine-out US06 CO emissions and FTP emissions is similar to the corresponding tailpipe relationships; the same vehicles tend to be higher or lower than the FTP. This indicates that catalyst conversion efficiency plays a minor role in the difference between HC and CO emission response on the US06; rather, most of the effect is due to the extreme sensitivity of engine-out CO emissions to any minor excursion in air/fuel ratio. Such excursions are likely the result of incomplete control of commanded enrichment or transient enrichment. These results lead EPA to conclude that holding US06 CO emissions to full FTP levels instead of bag 2 FTP levels is more appropriate. At this level it still will achieve a large reduction in offcycle CO emissions without forcing expensive control systems, such as drive-by-wire.

4.4.3. NOx Control

In contrast to engine-out HC which increases linearly with load, engine out NOx increases exponentially. While the average load on the US06 is similar to bag 2 of the FTP, the high instantaneous loads during the hard accelerations of US06 result in a nonlinear increase in engine-out NOx emissions. Figure 1-19 shows large differences between US06 NOx emissions and the FTP emissions--bag 2 as well as the full FTP. For nearly all vehicles on every test, the NOx emissions during for the stoich tests are higher than those for the production tests. As discussed earlier, the elimination of commanded enrichment has the undesirable effect of increasing NOx emissions due to higher engine temperatures

The comparison of tailpipe NOx emissions suggests a problem in trying to control US06 emissions to bag 2, FTP levels (figure 1-20). In the production configuration, among the 16 LDVs, only two vehicles (314 and 401) had US06 emissions below the bag 2, FTP levels; three other vehicle were below the full FTP levels. In addition, the stoich NOx levels ran higher than the production levels for every vehicle except the Saturn and this vehicle had high HC emissions, as discussed above. However, that fact that with the stoich calibration, tailpipe NOx increased proportionally far more than engine-out NOx on every vehicle suggests that mediocre NOx conversion efficiency accounts for most of the NOx increase between production and stoich, and it indicates that most vehicles are not calibrated for optimal NOx catalyst conversion efficiency. Evaluation of the catalyst conversion efficiency impacts, for each vehicle tested, indicated that the vehicles with large drops in NOx conversion efficiency in stoich configuration also had fuel control which allowed significant lean A/F episodes.

Calibration changes can greatly reduce the engine out NOx; but the EPA believes that above results suggest that level is some margin above the levels found on bag of the FTP. Figure 1-21 presents the hypothetical NOx conversion efficiency that would be required on US06 in order to bring US06 NOx emissions down to full FTP levels. While these rates of efficiencies are high, there is evidence to suggest they are achievable. The required conversion rates are, in fact, less than or equivalent to the actual NOx conversion efficiency achieved on the FTP, bag 2 for 10 of 16 vehicles in the production configuration. In addition, although it is not shown on the graph, the Grand Am in production calibration achieved an overall US06 NOx conversion efficiency of 96.4%, well above the efficiency required to bring US06 emissions down to full FTP levels. In fact, there were 5 vehicles with actual NOx conversion efficiencies greater than 95 percent. On this basis, EPA believes that with adequate attention to A/F control, manufacturers can attain NOx conversion efficiencies during US06 operation that are on par with levels over the bag 2 of the FTP, and in the process control NOx emissions to the levels found on the full FTP.

One issue EPA has not fully evaluated is possible correlations between NOx and CO emissions. It is likely that the optimal control of NOx emissions would involve slight rich biasing of the A/F ration to improve NOx conversion efficiency, and/or limited amounts of commanded enrichment to control engine-out NOx emission levels. Either strategy, if needed, could increase CO emissions.

In summary, EPA believes that US06 emissions can be greatly reduced by manufacturer recalibration to eliminate or greatly reduce commanded enrichment, and to tighten A/F control to increase HC and NOx conversion efficiency. HC emissions on US06 can be reduced to the same level as a vehicle's FTP, bag 2 emissions. For CO and NOx, the US06 control level is the full FTP emission level. No explicit gram per mile emission levels are presented here. Rather, as discussed in the preamble, these vehicle-specific control levels are converted into a numerical standard as part of a composite standard.

Section 5. Technological Feasibility

This section discusses EPA's assessment of the effects on vehicle performance and durability of using these feasible technological controls to comply with the proposed emission levels over the US06 cycle. Specifically, this section will focus on the impact on performance and driveability, and catalyst and engine durability.

5.1 Impact on Performance

Automotive manufacturers have indicated that in today's society, automotive performance has become very important. The motoring public has come to expect a certain level of performance out of their vehicles. Vehicles today have the greatest combination of fuel economy and power in history. Fuel economy is at an all time high, while 0-60 mph times for the average vehicle continues to decrease. There are a number of factors that contribute to this: improvements in aerodynamics; lighter materials; better tire designs; advanced electronic engine management with multiport fuel injection; electronic four speed transmissions; improved, more sophisticated engine calibrations; and more efficient, higher output engines, to name just a few.

The mix of vehicle types today is more diverse than in the past. Coupes, sedans, 2-seaters, station wagons, convertibles, recreational vehicles, sport utilities, mini-vans, full size vans, small pick-up trucks, and large pick-up trucks are just some of numerous categories of motor vehicles available on the market. Manufacturers have indicated that there are two common requirements that the motoring public demands from all of these different vehicle types: good fuel economy and vehicle performance. One of the main reasons that vehicles have been able to achieve high fuel economy and good vehicle performance is that over the past decade, engine displacements have been slowly getting smaller while still maintaining excellent power. There are more four and six cylinder engines than ever, and the number of eight and ten cylinder engines has been slowly increasing from an all-time low, although their displacements have dramatically decreased over the past 10-20 years.

Two factors that are essential for good vehicle performance are power and driveability. Power is the ability of the engine to perform work, while driveability is how well the engine performs that work. Power is defined as the engine's ability to perform work in a given time. For example, the rate at which a vehicle is able to accelerate at, or the ability to pull a trailer up a mountain pass, are functions of power. Driveability is defined as how well a vehicle operates and performs; i.e., how well the engine starts, how smooth the vehicle accelerates, a steady imperceptible idle, whether the engine stalls, or if the vehicle surges, hesitates, or stumbles. It's possible to have good power with poor driveabity and to also have the opposite, poor power with good driveability. The two are not directly related.

5.1.1 Power

One of the most important factors in vehicle performance is engine power output. Power is the ability of the engine to perform work. The best examples of power are the rate at which a vehicle is able to accelerate at, and/or the ability to pull or carry heavy loads, such as a pulling a camper or carrying a load of lumber in the bed of a pick-up truck. In addition to power output, there are many other factors that contribute to overall vehicle performance: aerodynamic drag, transmission type, gear ratio, final drive ratio, vehicle weight, and tire size and type. Another important factor in vehicle performance is the vehicle weight-to-power ratio (W/P). Light vehicles with engines that have high power outputs have far better vehicle performance than heavy vehicles equipped with low power output engines.

Even though there are a number of factors that influence performance, this discussion will focus on power output. Not only is power output one of the most important factors in vehicle performance, as stated above, but it is also the factor that is the most directly affected by trying to control emissions over the US06 cycle. Vehicle manufacturers have been concerned that in order to control emissions, especially HC and CO, over a high load/high speed cycle, it would mean the elimination of any commanded enrichment which is typically used during heavy load operation, such as aggressive accelerations or pulling trailers, for increases in power output and for catalyst and engine cooling. They have even expressed concern that any loss in power, especially for smaller vehicles with high W/P ratios, would result in unsatisfactory and even dangerous vehicle performance and may require the replacement of small displacement, fuel efficient engines with larger displacement four and six cylinder engines that could have poorer fuel economy. Because of these concerns, EPA feels that the issue of power loss due to the reduction or elimination of commanded enrichment, is a very important issue for the feasibility of technological control of the proposed emission levels over the US06 cycle.

There are a number of factors that contribute to engine power output. Engine design parameters, such as combustion chamber type, compression ratio, cylinder bore and stroke, and exhaust and intake manifold configurations, are essential to maximum power output. Another important factor is the management of specific engine control systems, such as the spark timing and metering of air and fuel. The metering of air and fuel, or more specifically, the control of the air-fuel ratio, has the greatest effect on tailpipe exhaust emissions and is also the most affected by operating over the US06 cycle.

Data from the test program indicates that, over the FTP, approximately 96%[13] of all fuel control operation for most vehicles occurs at a stoichiometric air-fuel ratio. Stoichiometry is typically in the range of 14.6:1 to 14.7:1. Only about 0.2% of total fuel control operation over the FTP is commanded enrichment. The frequency of commanded enrichment over the FTP was extremely low; in fact, the vast majority of vehicles never went into commanded enrichment over the FTP. For those rare occasions where a vehicle did go into commanded enrichment on the FTP, the enrichment duration was very

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short, on the order of 1-2 seconds. Air-fuel ratios as rich as 12:1 were observed for some vehicles, but only for a very short period. Over the US06 cycle, the average air-fuel ratio was very similar to that for the FTP, however, the rich excursions resulting from commanded enrichment were much more frequent and of a longer duration. Approximately 92% of all fuel control operation over the US06 cycle was at stoichiometry, while approximately 3.5% was commanded enrichment[14]. The average air-fuel ratio for a commanded enrichment event over the US06 cycle was approximately 12.5:1 with some vehicles having events as rich as 11.5:1. The average duration of commanded enrichment events over the US06 cycle was 5.0[15] seconds.

Information gathered from literature and the manufacturers have indicated, that for most engines, maximum horsepower occurs at an air-fuel ratio rich of stoichiometry (typically between 12:1 to 13:1). It should be noted that the extra power gained with enrichment used to be much more than they are today, due to fuel distribution problems. The use of PFI has virtually eliminated fuel distribution problems, allowing higher power levels without the need for extra fuel. The air-fuel ratios experienced by vehicles in the test program over US06 typically feel between 12:1 and 13:1. In discussions with EPA, several vehicle manufacturers indicated that operating the engine at a steady stoichiometric air-fuel ratio, rather than at the air-fuel ratio for maximum power of approximately 12:1 to 13:1, during an extended acceleration or during heavy engine load operation (i.e., pulling a trailer up a hill) would result in a 3%-10% loss in horsepower depending on the engine and vehicle application.

The impact of a 3-10% loss in power is relative to the specific vehicle model and the horsepower of the particular engine in that model. For example, if the Dodge Viper, with a rated power of 400hp and a weight-to-power ratio of 8.5, experienced a 3-10% loss in power, it would result in a loss of 12 to 40hp, leaving the vehicle with a rated power of 360 to 388hp and weight-to-power ratios of 9.4-8.8. While this may cause some concern to the marketing people, the performance of the vehicle should still be excellent and not cause any safety concerns. On the other hand, the Geo Metro has a power rating of 55hp with a weight-to-power ratio of 38.6. A loss of 3-10% in power would result in a loss of 2.0 to 5.5hp, leaving the vehicle with a rated power of 49.5 to 53hp and weight-to-power ratios of 42.9-40.1. It's much less clear whether this type of power reduction for this vehicle would result in unsatisfactory performance or even be a safety issue.

Unfortunately, EPA was unable to measure the power loss that resulted from removing commanded enrichment from the production calibrations to the stoich calibrations. Due to logistical and timing constraints, neither EPA nor the manufacturers were able to operate the vehicles with stoich calibrations on the road to determine the effect eliminating commanded enrichment had on vehicle performance. Therefore, in an attempt to find a way to evaluate the effect that eliminating commanded enrichment had on power

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[14] Memorandum from Phil Enns to John German, dated December 6, 1993 and titled "Enrichment Event Analysis."

[15] Memorandum from Phil Enns to John German, dated December 6, 1993 and titled "Enrichment Event Analysis."

output and vehicle performance, EPA compared the differences in wide open throttle (WOT) times for the production and stoich calibrations over various accelerations from the US06 cycle. The general approach was to see whether or not any significant differences in WOT times occurred for the vehicles when operating with the stoich calibrations, which had no commanded enrichment, compared with the production calibrations that had commanded enrichment. If WOT times were significantly different, then an argument could be made that the elimination of commanded enrichment would indeed influence vehicle performance. However, if the difference in times were small, it could be argued that the impact on vehicle performance was minimal and any reduction in power output should be insignificant for most vehicles. It should also be noted that the stoich calibrations simply had the commanded enrichment strategies removed, while other fuel and spark strategies were left alone. They were not optimized for performance or emissions and therefore, do not represent optimized production-level calibrations with commanded enrichment eliminated. Thus the results should represent a scenario worse than what might end up in production.

EPA realizes that this method for analyzing effects on vehicle performance may be overly simplistic and does not convincingly prove or disprove that the feasible technological controls proposed by EPA to comply with the proposed US06 cycle emission levels will not affect vehicle performance. However, without any other mechanism to accurately measure power loss or quantify performance effects, EPA believes that this approach will provide a general understanding as to whether or any negative effects on vehicle performance will tend to occur as a result of complying with the proposed US06 cycle emission levels.

EPA evaluated the WOT times for 11 vehicles that had been tested with both production and stoich calibrations. The maximum continuous WOT time that occurred during any particular acceleration and the total amount of WOT time that occurred over the cycle for each vehicle was examined. While total WOT time can be a good indicator for the frequency of WOT for a given vehicle, it is hard to make any assessments as to the impact on vehicle performance. For example, 20 seconds of total WOT time could consist of two WOT events lasting 10 seconds each or 20 one second WOT events spread throughout the cycle. Maximum continuous WOT time is better for assessing effects on performance since that represents the worst case scenario for each vehicle. For the purpose of this analysis, WOT was defined as any throttle opening greater than 90%.

Table 1-13 shows the increase from production to stoich calibrations in average maximum continuous and total WOT times for all 11 vehicles over the US06 cycle. These increases demonstrate the effect of eliminating or reducing commanded enrichment on WOT times.

Table 1-13
Average WOT Time Increase From Production to Stoich Calibrations for Individual Vehicles

Vehicle	Max Prod	Max Stoich	Max Increase	Total Prod	Total Stoich	Total Increase
Suburban	9	10	1.0	26.0	38.5	12.5

Metro	6.5	7.5	1.0	31.5	38.0	7.5
C10 P/U	4	5	1.0	16.5	22.0	5.5
Supreme	3	4	1.0	6.5	11.5	5.0
Grand-Am	5.5	5.5	0.0	11.5	16.0	4.5
Sonoma	1.5	1.5	0.0	1.5	2.0	0.5
Escort	7	8	1.0	36.0	35.5	-0.5
Grand Prix	2.5	3.5	1.0	8.0	5.5	-2.5
Olds 98	1.5	2	0.5	5.5	3.0	-2.5
Seville	3	0	-3.0	4.0	0.0	-4.0
F250 P/U	3	3.5	0.5	14.0	9.0	-5.0
Average	**4.2**	**4.6**	**0.4**	**14.6**	**16.5**	**1.9**

The average increase in maximum continuous WOT time for all of the vehicles was 0.4 seconds, while the average increase in total WOT time was 1.9 seconds. These increases appear to be minimal. EPA feels that such minimal increases would seem to illustrate that any losses in power output and consequentially vehicle performance, would be negligible.

Three of the vehicles had no increase in maximum continuous WOT time and only marginal increases in total WOT time. In fact, the Cadillac Seville had a decrease in WOT time. This brings up an interesting observation that was made on all 11 vehicles. The way the vehicle was driven over the cycle had an impact on WOT times. For example, on the initial acceleration of the third hill of the cycle, the Seville had an of average of 3.0 seconds continuous WOT operation in the production calibration but never went above 80% throttle with the stoich calibration over the same acceleration. To illustrate this behavior, figure 1-22 presents the drive trace data for one of production tests. It appears that the driver got behind the speed trace and had to go WOT for 3.0 seconds to catch back up with the trace. On one of the stoich tests(figure 1-23), in contrast, although the driver got behind the trace, the speed was still within the speed tolerances, and it appears that the driver didn't attempt to catch back up. Thus, the vehicle did not go into WOT. This particular observation seems to distort the results for the Seville to some extent, but not entirely. Chances are good that if the driver had behaved the same way for all of the stoich tests as they did for the production tests, the WOT time results would have been very similar. Thus for this vehicle, the effect on vehicle performance over the cycle seems to be negligible.

The Escort, Grand Prix, Olds 98, and F250 P/U all had total WOT times that decreased. Again, examination of the driving trace data for the individual tests revealed that, for all of these vehicles, there were situations, where on certain accelerations, the driver attempted to follow the trace very closely and would occasionally go into WOT for a period of time, whereas on other occasions over the same accelerations, the driver could avoid WOT operation by not following the trace as closely but still staying within the speed tolerances. From the perspective of affecting power output and vehicle performance, these observations suggest that driver behavior was more important than any power change from production to stoich calibrations. This would seem to further enforce the position that the difference in performance between the production and stoich calibrations is minimal and the effect on vehicle performance is negligible.

The vehicles with the highest WOT time increases were the Chevy Suburban and Geo Metro. The Suburban had an average maximum continuous WOT time increase of 1.0 second and a total WOT time increase of 12.5 seconds. Examination of the drivers traces indicated that the same driving phenomenon that occurred for the Seville also occurred for the Suburban. There were numerous instances where the driver attempted to follow the trace very closely and went into WOT, and cases where the driver didn't follow the trace as closely but still remained within the speed tolerances and subsequential didn't go into WOT.

The Geo Metro had an average maximum continuous WOT time increase of 1.0 second and a total WOT time increase of 7.5 seconds. The Metro's WOT performance also seemed to be influenced by how it was driven over the cycle, but not nearly as much as the rest of the vehicles. The Metro was equipped with a manual transmission which would typically give it an advantage in performance over a similar vehicle equipped with an automatic transmission. The Metro had a W/P ratio of 38.6 and was the worst case vehicle for W/P ratio in the test program. As discussed in section 3, EPA will allow load adjustments for low W/P vehicles so that they will not be penalized by the aggressiveness of the cycle that it is more apparent for these type of vehicles. The Metro was tested in both the production and stoich calibrations with load adjustments made. Reductions were made to the inertia weight and aerodynamic drag coefficient. When retested over the US06 cycle in the production and stoich calibrations with the load adjustments, the Metro actually had a reduction in maximum continuous WOT time of 0.5 second and a reduction in total WOT time of 1.0 second. The average maximum continuous and total WOT times were 5.0 seconds and 13 seconds, respectively, for the production calibration and 4.5 seconds and 12 seconds for the stoich calibrations. It would appear that these differences also support the assumption that the differences in WOT time are insignificant and that the effect on power loss and vehicle performance is negligible.

Another factor that may have influenced WOT times was automatic transmission shift schedules. Comments received by EPA test drivers and test engineers were that automatic transmission shift schedules for several vehicles were obviously not calibrated for the US06 cycle because they shifted either too early or too late and made it difficult for the vehicles to maintain the speed trace. This further illustrates that the way the vehicle was operated over the cycle had a greater impact on WOT times than the elimination of commanded enrichment.

As stated earlier, the real concern about losses in vehicle performance resulting from control strategies necessary to comply with proposed US06 cycle emission levels have centered around lower performance vehicles. Moderate to high powered vehicles seem to have a sufficient combination of power and available gearing that proposed control strategies such as the reduction or elimination of commanded enrichment should have negligible effects on vehicle performance. The results of EPA's analysis on WOT time comparisons seems to indicate that even for low powered vehicles the effects on performance should be negligible, especially since they will be designed to reflect operation that occurs over the FTP and the lowest performance vehicles will have load adjustments over the cycle that should put them on an even par with the moderate performance vehicles.

EPA believes that some vehicles may inevitably suffer some losses in engine power and vehicle performance as a result of complying with proposed US06 cycle emission levels. However, EPA expects that for the vast majority of vehicles, the loss in power and vehicle performance will be negligible.

5.1.2 Driveability

There are numerous definitions of driveability used throughout the automotive industry. EPA views driveability as how well a vehicle operates. How well it starts, idles, accelerates, decelerates, and cruises. Does it have spark knock, surge, or any hesitations when accelerating? Does the idle quality deteriorate when the rear defroster is on or can the driver feel the air conditioning compressor engaging? All of these are part of driveability. Driveability, unlike vehicle performance, is very subjective. There are very few measurements of driveability that can be quantified like rated horsepower, torque, or 0-60mph times. Because of this, it is very hard to assess the effect that proposed feasible technologies and control strategies for complying with the proposed US06 cycle emission levels will have on driveability. Adding to this complication is the fact that the only operation of the test vehicles occurred on the chassis dynamometer (referred to as the rolls) during emission tests. No vehicles were operated on the road and evaluated for driveability issues. It is very difficult to make driveability evaluations on the rolls. The somewhat harsh ride that occurs on the rolls tends to mask many driveability problems. Neither EPA nor manufacturer test personnel were prepared to evaluate driveability. Drivers and test operators typically report any unusual vehicle behavior. The manufacturers never reported any driveability problems to EPA.

All of the proposed control strategies and technologies for complying with the proposed emission levels should further enhance driveability. Control strategies, such as tighter air-fuel ratio control over the majority of off-cycle high speed and load operation, and technologies, such as PFI systems, sequential-fire PFI systems, or drive-by-wire systems, are all geared towards improved open and closed-loop operation and should be valuable assets in improving driveability. None of these strategies or technologies should have adverse effects on driveability. The only item that could potentially be an issue is the reduction or elimination of commanded enrichment. However, EPA believes that the removal of commanded enrichment is a performance issue rather than a driveability issue.

EPA feels that the effect of complying with proposed US06 cycle emission levels on driveability should be minimal. Although no evaluation on the subject was performed by EPA or the manufacturers, good engineering judgement supports EPA's assumption. The control strategies and technologies that should be necessary to comply with the proposed emission levels should help rather than hinder driveability. The lack of any obvious driveability concerns reported during the test program indicates that operation with the stoich calibrations, which were not optimized for driveability, had no blatant driveability problems.

5.2. Impact on Durability

One of the greatest concerns over the control strategies and technologies analyzed as feasible to comply with the proposed US06 cycle emission levels, is the impact on catalyst and engine durability.

5.2.1 Catalyst Durability

The discussion on catalyst durability will focus on the following areas:

- Catalyst thermal degradation
- Production catalyst temperatures over the US06 cycle
- Stoich catalyst temperatures over the US06 cycle
- Temperature differences between production and stoich calibrations
- Summary

5.2.1.1 Catalyst Thermal Degradation

The catalytic converter is the single most important part of any vehicle's emission control system. Because it is the last element in the emission control system, it provides the final means to decrease the level of undesirable tailpipe emissions. The catalyst's function is to initiate two different types of chemical conversions, oxidation and reduction. The products of incomplete combustion, i.e. hydrocarbons and carbon monoxide, are oxidized into carbon dioxide and water vapor, and the nitrogen oxides are reduced to molecular nitrogen and other products depending on the reducing agent. Catalyst deterioration due to thermal exposure can cause these two types of conversion to occur with reduced efficiency, allowing more pollutants generated upstream to be emitted into the atmosphere.

A major cause of catalyst deterioration is thermal degradation, which results from excessive catalyst temperature. Prolonged exposure to excessive temperatures results in washcoat surface area loss and/or sintering of the noble metals. Extreme cases can lead to monolith meltdown. During stoichiometric operation, the ratio of reducing agents (i.e., HC, CO, H, etc.) and oxygen is optimum for promoting oxidation of HC and CO and the reduction of NOx. However, these reactions can be thought of as simply finishing the combustion process in the catalyst. These processes burn up the HC and CO, which dramatically raises the catalyst temperature. Under normal FTP type operation, the mass flow rate of emittants entering the catalyst is fairly low, thus the exotherm (or heat generated) doesn't typically raise catalyst temperatures to high levels. Under high load accelerations, the mass flow rate of the emittants is much greater, which has two effects: The temperature of the exhaust gases entering the catalyst tend to be higher, and the higher mass of emittants increases the exotherm. This combination produces higher temperatures that could potentially damage the catalyst. A common strategy for avoiding these high temperatures, is to use a rich strategy during these high load accelerations. The additional fuel acts as a heat sink in the engine, lowering exhaust temperatures, and restricts the amount of oxygen available for oxidation and lowers the exotherm, thus lowering the catalyst temperature.

It is generally accepted throughout the automotive industry that vehicle operation which results in catalyst temperatures below 900 C will not result in thermal degradation of catalyst conversion efficiency for catalysts containing platinum (Pt) and rhodium (Rh) .[16] For palladium (Pd) catalyst,

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[16] C.D. Tyree, "Emission Levels and Catalyst Temperatures as a Function of Ignition Misfire," SAE Technical Paper 92098

this temperature may be as high as 950°C. Coplete failure of the catalyst could be expected when the ceramic substrate reaches 1093 C.

5.2.1.2. Production Catalyst Temperatures

Table 1-14 shows the average of the maximum catalyst temperatures, time at temperatures greater than 816 C (1500 F), and continuous time at temperatures greater than 816 C, for 13 of the vehicles tested in the production and stoich calibrations over the ARB02, REP05, and US06 cycles. These vehicles represent a fairly wide range of vehicles; 9 passenger cars, 2 light-heavy-duty trucks, and 2 light-duty trucks.

Table 1-14
US06 Production Catalyst Temperatures

Vehicle	Type	Time @ > 816 C (secs)	Cont. Time (secs)	Time @ > 872 C (secs)	Cont. Time (secs)	Max Temp (C)	Cycle
Escort	LDV	70	20.5	0	0	864	REP05
Olds 98	LDV	24	23	0	0	843	US06
GranAm	LDV	19	19	0	0	832	US06
Metro	LDV	6	6	0	0	825	ARB02
Camry	LDV	3	3	0	0	817	US06
F250	LHDT	0	0	0	0	783	ARB02
C10	LDT	0	0	0	0	773	US06
Supreme	LDV	0	0	0	0	766	US06
Saturn	LDV	0	0	0	0	753	ARB02
Gran Prix	LDV	0	0	0	0	739	ARB02
Cruiser	LDV	0	0	0	0	732	US06
Sonoma	LDT	0	0	0	0	697	US06
Seville	LDV	0	0	0	0	692	ARB02
Suburban	LHDT	0	0	0	0	670	ARB02
Avg		**8.7**	**5.1**	**0**	**0**	**770**	

The average of the maximum catalyst temperatures was 770°C. The range of temperatures was 194°C. Five vehicles, the Escort, Olds 98, Grand-Am, Camry, and Metro experienced temperatures over 816° C (1500° F). The Escort and Camry were the only vehicles equipped with close-coupled three-way catalysts. The Escort had a single three-way catalyst, while the Camry had a light-off catalyst followed by a three-way underfloor catalyst. The rest of the catalyst temperatures were for three-way underfloor catalysts that were not close-coupled.

It is important to examine the maximum catalyst temperatures over all three cycles: ARB02; REP05; and US06, because all three of these cycles consist of actual in-use driving events. Any catalyst temperature experienced over these cycles could also occur in-use. Therefore, it can be assumed that the catalysts for these vehicles are already designed to withstand such temperatures.

5.2.1.3. Stoich Catalyst Temperatures

Table 1-15 displays the same information as table 1-14 for the stoich catalyst temperatures.

Table 1-15
US06 Stoich Catalyst Temperatures

Veh	Type	Time @ > 816 C (secs)	Cont. Time (secs)	Time @ > 872 C (secs)	Cont. Time (secs)	Max Temp (C)	Cycle
Escort	LDV	136.5	47.5	48.5	20.5	920	US06
GranAm	LDV	58.5	19.5	1.5	1	872	US06
Olds 98	LDV	37	24.5	0	0	851	US06
Metro	LDV	18	11	0	0	843	US06
F250	LHDT	30	26	0	0	826	US06
Cruiser	LDV	0	0	0	0	820	US06
Supreme	LDV	0	0	0	0	812	US06
C10	LDT	0	0	0	0	788	US06
Saturn	LDV	0	0	0	0	782	US06
Gran Prix	LDV	0	0	0	0	776	US06
Seville	LDV	0	0	0	0	732	US06
Sonoma	LDT	0	0	0	0	708	US06
Suburban	LHDT	0	0	0	0	686	US06
Avg		**21.5**	**9.8**	**3.8**	**1.6**	**801**	

The average of the maximum catalyst temperatures with the stoich calibration was 801° C. Seven vehicles had maximum catalyst temperatures exceeding 800°C. The range of temperatures was 234°C, ranging from the Escort which had the highest maximum temperature at 920°C to the Suburban which had the lowest at 686°C. The Escort was the only vehicle to exceed the 900°C threshold. Figure 1-23b shows that for one test, the Escort spent as much as 11 consecutive seconds over 900°C as a result of the acceleration in the middle of the third hill of the US06 cycle that simulates a high speed passing maneuver.

All of the maximum stoich catalyst temperatures found in table 1-15 are those that occurred over the US06 cycle. This is because manufacturers will only be required to design their catalysts to withstand temperatures that occur over this cycle rather than temperatures that could result from any in-use accelerations or loads more severe than those occurring on the US06 cycle. Manufacturers will try to optimize the amount of enrichment they will be able to use for catalyst cooling by determining how long they will have to operate at or near stoichiometry during the WOT conditions that will be implemented by the US06 cycle. For example, if the most aggressive acceleration on the cycle requires a vehicle to operate at WOT for five seconds, then that is the amount of time that they will have to operate at stoichiometry. For any WOT operation that occurs in-use that is greater than five seconds, the manufacturer will be allowed to use some cooling enrichment for however much WOT operation occurs after the five seconds has surpassed.

5.2.1.4. Temperature Differences Between Production and Stoich Calibrations

Table 1-16 illustrates the increase in the average of the maximum catalyst temperatures for the vehicles when tested with the production and stoich calibrations.

Table 1-16
Increase in average of maximum catalyst temperatures between production and stoich calibrations

Vehicle	Type	W/P	Stoich temp	Prod temp	Increase
Cruiser	LDV	26.4	820	732	88
C10	LDT	23.8	788	773	15
Escort	LDV	31.3	920	864	56
Supreme	LDV	22.0	812	766	46
F250	LHDT	25.0	826	783	43
Saturn	LDV	30.9	782	753	29
Grand-Am	LDV	21.0	872	832	40
Metro	LDV	38.6	843	825	18

Seville	LDV	15.7	732	692	40
Grand Prix	LDV	19.4	776	739	37
Olds 98	LDV	23.5	851	843	8
Suburban	LHDT	28.6	686	670	18
Sonoma	LDT	17.3	708	697	11
Average			**801**	**767**	**34**

The average increase in maximum catalyst temperature between the production and stoich calibrations was 34°C. The largest increase was 88°C for the Cruiser, while the lowest increase was for 8°C for the Olds 98. The increase in catalyst temperature between production and stoich calibrations is very important. The average and maximum catalyst temperatures experienced over the US06 cycle are higher than those for the FTP. This is not any surprise since the loads and speeds for the US06 cycle are much higher than those found on the FTP. While there is an obvious increase in catalyst temperatures between the cycles, the increased temperatures are not a concern, since this type of operation exists in the real world and vehicle manufacturers have had to design their catalyst systems to withstand this type of operation. However, in order to comply with proposed emission levels over the US06 cycle, manufacturers will have to reduce or even eliminate the extra fuel from commanded enrichment that they have traditionally relied on to keep catalyst temperatures down. As the above table shows, without commanded enrichment, catalyst temperatures increase beyond the production levels which utilized commanded enrichment.

If the increase in temperature is too large, there is a strong possibility that the catalyst could suffer thermal degradation and catalytic conversion efficiency would deteriorate at a faster rate. In addition to the increase in catalyst temperatures resulting from the elimination of commanded enrichment, the level of the maximum temperature for the production calibration is important. For example, the maximum production temperature for the Escort is 864°C. With an average increase of 56°C, the maximum stoich temperature is 920°C, which is over the 900°C threshold that has been traditionally acknowledged as the upper limit temperature before thermal degradation starts to occur. But, for the Cruiser, which had an increase in temperature of 88°C and a maximum production temperature of 732°C, the maximum stoich temperature is only 820°C, which is well below the 900°C threshold. As previously stated, the average increase in maximum catalyst temperature for all of the vehicles was 34°C while the average maximum catalyst temperature in the stoich calibration was 801°C. While the maximum stoich catalyst temperatures and the increases in maximum catalyst temperature between production and stoich calibrations are high, they are lower than what the Agency thought they would be at the onset of the test programs. An interesting fact is that all of the stoich catalyst temperatures for the rest of the vehicles were lower than the Escort's production temperature. Since all of the other catalyst temperatures were for "underfloor catalysts," that is, catalysts located downstream of the exhaust manifold, rather than right next to it, this would seem to indicate that catalyst technology exists that should allow most underfloor catalysts to withstand the temperature increases that would result from eliminating commanded enrichment.

5.2.1.5 Summary

The evidence from the test program indicates that catalyst temperatures will rise during high load operation as a result of reducing or eliminating commanded enrichment. Obviously any increase in catalyst temperatures beyond current design tolerances are a concern to both EPA and industry. However, EPA believes that the catalyst temperatures experienced by the vehicles tested in the stoich configuration are generally low enough that thermal degradation should not be a concern.

5.2.1.5.1 Underfloor Catalysts

For underfloor catalysts, the average maximum stoich catalyst temperatures experienced over the US06 cycle was 791°C. The vehicle with the highest maximum stoich underfloor catalyst temperature was the Olds 98 with a temperature of 851°C. However, this was only 8°C higher than it's maximum production temperature! Several vehicles, such as the Suburban (686°C) and Seville (732°C), had temperatures considerably lower than the average. EPA believes that these temperatures are low enough that thermal degradation should not be a concern. As previously mentioned, 11 out of 13 vehicles equipped only with underfloor catalysts, had stoich temperatures less than the Escort's (close-coupled catalyst) production temperatures. It is apparent that the technology exists to make underfloor catalysts more thermally durable. One potential technology that could be used to improve underfloor (and close-coupled) catalyst thermal resistance would be to use the noble metal palladium rather than platinum, since palladium is more thermally durable than platinum.[17]

5.2.1.5.2 Close-Coupled Catalysts

Close-coupled catalyst temperatures were measured and recorded for only two vehicles ; the Escort and Camry. The Camry was tested in the production configuration only, while the Escort was tested in both the stoich and production configurations. The Escort had a maximum production temperature of 864°C, while the Camry had a maximum production temperature of 817°C. The Escort had the highest production temperature of the 13 vehicles. The Camry was not only lower than the Escort, but it was also lower than three of the vehicles equipped with underfloor catalysts only. The Escort was equipped with a single close-coupled three-way catalyst that was located as close to the exhaust manifold as possible. The Camry was equipped with a single close-coupled three-way light-off catalyst followed by a single three-way underfloor catalyst. Over the US06 cycle, the Camry operated considerably more rich than the Escort. This may be responsible for the differences in the close-coupled catalyst temperatures between the Escort and Camry.

Figures 1-24 and 1-25 compare the production and stoich catalyst

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[17] J.C. Summers, W.B. Williamson, and J.A. Scaparo, "The Role of Durability and Evaluation Conditions on the Performance of Pt/Rh and Pd/Rh Automotive Catalysts," SAE Technical Paper 900495

temperature profiles of the Escort with the Saturn over the REP05 and ARB02 cycles. The Saturn is compared with the Escort because it used an underfloor catalyst and had the same engine displacement as the Escort and was also similar in weight. These figures clearly illustrate the higher temperatures experienced by the close-coupled Escort. In fact, the close-coupled Escort catalyst saw higher catalyst temperatures than all of the other vehicles, including the Camry. The maximum catalyst temperature experienced over the US06 cycle for the Escort in the stoich configuration was 920°C. Over this cycle, the Escort averaged a total of 10 seconds over 900°C. All of this time was continuous and occurred during the high speed passing maneuver found in the middle of hill 3. EPA feels that the length of duration and maximum catalyst temperatures experienced by the Escort could result in some catalyst thermal degradation. Based on just this one vehicle, EPA cannot claim that all close-coupled catalyst applications will experience catalyst thermal degradation during high load operation resulting from the reduction or elimination of commanded enrichment, especially since the production catalyst temperatures for the Camry's close-coupled light-off catalyst was 47°C lower than the Escorts temperature. However, EPA also has no reason to believe that the close-coupled catalyst found on the Escort does not represent typical close-coupled catalyst technology, and that it's catalyst temperature profiles should not be fairly representative of other close-coupled catalyst applications. Therefore, EPA acknowledges that for close-coupled catalyst applications, there is the possibility that the reduction or elimination of commanded enrichment could cause some thermal degradation of the catalyst during high load operation.

However, EPA believes that in-use driving modes that would result in elevated catalyst temperatures such that thermal degradation would occur, will be so infrequent that the occurrence of thermal damage should be minimal. Based on in-use survey data on enrichment activity, aggressive driving accounts for less than 2 percent of in-use operation. Because commanded enrichment can be used in-use for catalyst cooling during any accelerations or high load conditions that occur <u>beyond</u> the maximum acceleration event found on the US06 cycle, maximum catalyst temperatures should not be any higher in-use than over the US06 cycle. EPA is in the process of assessing the loss of catalyst conversion efficiency over a typical vehicle's life as a result of increased temperature exposure resulting from the reduction or elimination of commanded enrichment. A similar methodology exists in Section IX, part E of the Preamble, where a projection of conversion efficiency losses was made for the insulation of catalysts. Based on these projected losses, and the preliminary work being done for losses due to the reduction of commanded enrichment using the same methodology, EPA expects that losses in catalyst conversion efficiency over useful life resulting from the reduction or elimination of commanded enrichment should be very low.

Given that the temperature increases associated with control at this level are within design limits, and the deterioration impacts of the increases should be low, the Agency believes that additional catalyst system modifications solely to address catalyst deterioration will be unnecessary.

5.2.2. Engine Durability

Actual engine temperatures were not recorded as part of the test program. Instead, exhaust temperatures were measured as a surrogate. Vehicle manufacturers have indicated that material temperature restraints for exhaust manifolds, exhaust valves, turbo chargers, and oxygen sensors range from 720°C to 850°C depending on the item and the material used. Maximum exhaust temperatures for vehicles tested with stoich calibrations over the US06 cycle ranged from 641°C to 816°C. The average maximum temperature for all of these vehicles was 705°C. Only two vehicles out of 16 had maximum exhaust temperatures greater than 800°C. They were the Ford F250 pick-up truck and the Ford Escort. The maximum temperatures for the F250 and Escort were 816°C and 856°C, respectively. The escort utilized a control strategy known as lean-on-cruise that controls the air-fuel ratio at very lean levels during high speed cruises as a means of fuel economy. The maximum production exhaust temperatures for the Escort were 805°C. Examinations of exhaust temperature profiles for this vehicle over hill 3 of the US06 cycle, clearly show that during the lean-on-cruise operation, the exhaust temperatures raised significantly. For the stoich calibrations, this strategy made the situation worse. Immediately following a high speed cruise portion of hill 3, where lean-on-cruise is active, the vehicle must accelerate through an aggressive high speed acceleration. The exhaust temperature is already high and still rising during the lean-on-cruise operation, when the vehicle suddenly accelerates without the benefit of any commanded enrichment. The combination of rising high exhaust temperatures from the lean-on-cruise operation and the sudden large engine load, resulting from the aggressive acceleration, at a stoichiometric air-fuel ratio caused the exhaust temperature to rise to 856°C.

The proposed NOx emission standards for the US06 cycle will prohibit the use of lean-on-cruise strategies. Therefore, the exhaust temperatures experienced by the Escort are not representative of what can be expected as a result of complying with the proposed emission levels, thus that it why the Escort was not included in the range of maximum temperatures for the stoich vehicles, mentioned above.

There is no explanation for the relatively high exhaust temperatures experienced by the F250 pick-up truck. However, its temperatures fall right into the middle of the range listed by the manufacturers and it's possible that the material temperature restraints for this particular model is higher than 805°C.

EPA feels that for the vast majority of vehicles, exhaust temperatures resulting from control strategies necessary to comply with proposed US06 cycle emission levels, will not have any negative impacts on engine durability.

5.3 Excessive Temperatures and Road Grade

Section 4.2 discusses the way in which the US06 cycle implicitly controls for the effect of road grade on emissions. The duration of control for road grade is determined by the duration of commanded enrichment control over the US06. Thus, emission control will be limited for extended road grade, or other extended high-load events (such as certain acceleration events while trailer towing). EPA had concluded that it is not feasible to control enrichment beyond the US06 duration due to temperature concerns associated with stoichiometric control of the air-fuel mixture during high load events (see section 5.2.1). EPA believes the infrequent nature of these extended high load events does not justify expanding control to address these events given the potential for significant catalyst degradation and/or the increased hardware cost.

5.4. Projected Vehicle Modifications

5.4.1. Modifications Necessary to Comply with Proposed Standards

To comply with the proposed US06 cycle standards, nearly all manufacturers will need to optimize engine calibrations. These optimization will involve the reduction or elimination of commanded enrichment during heavy accelerations and WOT found on the US06 cycle, improvements to air-fuel control strategies such that air-fuel ratio is tightly controlled in order to reduce transient emissions, and increasing catalyst NOx conversion efficiency levels through tighter air-fuel control during high speed operation.

In addition to the above control strategy modifications, some vehicles may also have to make hardware modifications or additions. Some vehicles may have to incorporate sequential-fire port fuel injection systems. Currently, there are several different types of fuel injection systems being used in production. The current trend is a fairly even mixture of different types of port fuel injection systems. There are synchronous-fire, synchronous double-fire, and sequential-fire systems. The primary difference is that synchronous-fire systems fire multiple injectors simultaneously, whereas sequential-fire systems fire each injector separately. This guarantees that each cylinder is getting the proper amount of fuel at the right time. There are also some vehicles that still use throttle-body fuel injection systems. Vehicle manufacturers have indicated to EPA that throttle-body and synchronous-fire injection PFI systems are being phased-out and the vast majority of vehicles will already use sequential-fire injection PFI systems by the time this rule is effective.

EPA feels that modifications to control strategies (calibrations) should be all that's necessary for the majority of vehicles. For a small percentage of vehicles, a combination of control strategy modifications along with sequential-fire port fuel injection, may be required to comply with the proposed emission standards.

5.4.2. Modifications Necessary to Offset Performance and Durability Impacts

The Agency feels that there should be no modifications necessary to offset performance and durability impacts resulting from complying with the proposed emission standards. EPA believes that any impacts on vehicle performance will be minimal and will not require any hardware modifications.

Section 6. US06 Test Procedures

6.1 Preconditioning

The US06 driving schedule and the associated level of emission control were developed for a test in which the vehicle in a hot, stabilized condition. Thus, sufficient driving is required prior to the test to achieve the hot, stabilized condition. EPA believes running a vehicle on the 505 driving cycle (bag 1 of the FTP) or the new start cycle (ST02) is sufficient if the prior soak period is 2 hours or less. If the soak period in longer, a complete LA4 driving cycle is necessary. To address potential adaptive memory concerns, EPA believes it is appropriate to drive the vehicle on the US06 driving cycle, using certification fuel, prior to the actual certification emission test.

6.2 Sequencing

The only sequencing requirement for the US06 cycle is the preconditioning discussed above. The US06 cycle can run in conjunction with the air conditioning test requirement.

6.3 Dynamometer Procedure

The characteristics of the US06 driving cycle require the cycle be tested on a single-roll, large diameter dynamometer, or its equivalent. EPA believes a large-capacity constant volume sampler(CVS) will be necessary for properly testing vehicles on the US06. The FTP test program used a large-capacity CVS (700 cfm) during the FTP test programs. This was necessary due to the high-volume exhaust flow produced by the larger-displacement vehicles as they were tested on the driving cycles which served as the basis for the US06.

6.3 Manual transmission shift points

The US06 cycle and the FTP driving cycle represent very different types of driving behavior, thus, it is not reasonable to expect that manual transmission shift points will be identical for the two cycles. The higher rates of acceleration found on the US06 requires a fairly aggressive shift pattern (shifting at high RPM) in order to properly follow the driving schedule. Further, it is expected that these shift points will be vehicle-specific and it would be inappropriate to prescribe pre-determined shift points. EPA is proposing to allow the vehicle manufacturer to determine appropriate shift points on a case by case basis. The shift points should be consistent with the recommendations specified in the owner's manual with respect to the maximum RPM for each gear. In general, EPA will allow manufacturers to specify upshift points, but downshifting will not be permitted unless the vehicle is unable to stay within the driving tolerance on the speed trace in the existing gear.

6.4 Adjustments for vehicle performance

As discussed in section 4.3, adjustments to US06 for differences in vehicle performance are necessary. EPA proposes to account for vehicle performance differences through adjustments to the dynamometer inertia load.

6.4.1 Performance Criteria

The objective of the performance criteria is to classify vehicles into three vehicle performance categories: high, medium, and low. The boundaries of these categories are established from the in-use driving survey data, separately for automatic and manual transmission vehicles. As appropriate, dynamometer adjustments will be made for the vehicles in the high and low performance categories. Two alternatives measures of vehicle performance were considered by EPA: the ratio of vehicle weight to peak horsepower, and the number of seconds for a vehicle to accelerate from 0 to 60 mph.

6.4.1.1 W/P measure

To date, all analysis of in-use data has used the ratio of vehicle weight to peak horsepower (W/P) as a proxy of vehicle performance. This measure provides a good indication of vehicle performance; however, it fails to take in account several factors. The W/P measure fails to account for differences in torque curves, aerodynamic design, and the performance difference between manual and automatic transmissions. The separate treatment of automatic and manual transmissions addresses this last concern.

6.4.1.2 Measure based on 0 to 60 acceleration time

A vehicle's 0 to 60 acceleration time is a direct measure of performance and as such, it is a preferred over W/P, an indirect measure. The use of such a measure takes into account all the vehicle variables which were unaccounted for by the W/P criteria; however, there are a number of practical concerns with using 0 to 60 times.

1. High and low performance cut-off points based on 0-60 times need to be established from the in-use driving survey data. This will require going back to the in-use driving survey database and trying to establish 0 to 60 times for each of the vehicles. This will be a time consuming task and the consistency and accuracy of the historical data is likely to be a problem.

2. A new test procedure will need to be developed to obtain 0 to 60 times for new vehicles; these results will need to correlate with the existing in-use data.

3. The 0 to 60 times do not take into account vehicle performance for speeds between 60 and 80 mph, an area of vehicle operation characterized on the US06.

While EPA feels the use of 0 to 60 times is the best vehicle performance measure, the lack of information and the technical difficulties identified above preclude EPA from proposing it as the preferred option.

6.4.2. Performance categories

The vehicle performance categories are established from the in-use survey data. Analyses in section 2.1 identified a correlation between aggressive driving and vehicle performance; however, the analysis did not identify specific boundaries for low, middle, and high performance vehicles. To establish these categories, EPA went back to the in-use survey data for Baltimore and Spokane to look for natural breakpoints in aggressive driving based on the W/P measure. For each vehicle, two measures of aggressive driving were used in the analysis: the fraction of time spent above power values of 200 (roughly equal to non-FTP operation), and fraction of time above power values of 300(very aggressive operation). The high performance category was defined by W/P, starting at WP <20, and the category was expanded by increments of one; the low performance category was fixed at W/P >32.

For manual and automatic transmission vehicles separately, table 1-17 compares the two measures of aggressive driving for the alternative high performance categories. Among the automatic transmission vehicles, the high performance vehicles were driven less aggressively than the mid-performance for all possible high performance categories. In contrast, for manual transmission vehicles, there appears to be distinct differences between the high and mid-performance vehicles, and the data show a WP of 21 to be the upper value for the high performance category. These results are based on a very limited number of vehicles for the high performance category, and as mentioned earlier, EPA plans to add the data from the Atlanta in-use driving survey to the Spokane and Baltimore in-use survey database.

The in-use survey data provides a good sample of mid- and low performance vehicles. Table 1-18 compares alternative thresholds for low performance vehicles. For manual transmission vehicles, there is very little difference between middle and low performance categories for the fraction of time above 200 until you get to the W/P >34, thus EPA feels the most appropriate is W/P >34, the corresponding value for automatic transmission vehicles in W/P >31, as the data shows a sharp drop-off in the fraction of operation above 200 going from the W/P >30 to the W/P >31 category. Thus, the low performance cutoff point for manual transmission vehicles in W/P of 31, while automatic transmission vehicles would have a cutoff point of 34 W/P.

6.4.2 Adjustment Calculation

For testing purposes, a vehicle's W/P will be calculated as the ratio of its estimated test weight (ETW) and its maximum rated horsepower. The adjustment calculation is best shown by example. If a manual transmission vehicle has a W/P value of 40, then the adjustment would be 34/40 or 0.85. The dynamometer inertia load would be set to 85 percent of vehicle weight, thereby implicitly bringing the 40 W/P vehicle down to a 34 W/P vehicle. EPA proposes an adjustment cap of 50%, although EPA expects the 50% cap to impact few, if any, low performance vehicles.

EPA proposes to apply the load adjustment only during the high load portions of US06. Figure 1-26 illustrates the segments of US06 subject to adjustment; these points represent 43 seconds or 7 percent of the cycle. This contrasts with the earlier application of load adjustment carried out in the vehicle manufacturers test program. In that program the entire cycle was modified, in large part because dynamic adjustment was not a viable option at the time. EPA feels dynamic adjustment is more consistent with the objective of modifying only the high load portions of the cycle which are not appropriate for some vehicles. Special programming is required to have the dynamometer provide a dynamic adjustment of load, and further test work is planned to identify any feasibility issues.

6.4.3 Requirement for high performance vehicles

The limited in-use data indicate high performance, manual transmission vehicles are driven more aggressively than the rest of fleet and as such, the US06 may not appropriate. Also, the testing of several high performance, automatic transmission vehicles, indicated that the US06 may not be sufficiently aggressive to force these vehicles to wide open throttle (WOT) operation. EPA believes it is necessary to ensure some WOT emission control for all vehicles, including high performance vehicles. Thus, for these vehicles, manufacturers would be required to provide a demonstration of stoichiometric A/F control for wide open throttle events of two seconds or less. EPA proposes high performance cutoff point of 18 W/P, based on a conservative evaluation of the in-use data.

6.5. Adjustments for Heavy, Light-duty Trucks

For the US06, HLDTs will be tested at curb weight + 300 lbs instead of adjusted loaded vehicle weight((1/2 payload). HLDTs will continue to be tested at 1/2 payload during the FTP driving schedule. By bringing the load down to curb + 300 for the US06, HLDTs would be tested in the same manner as LDVs. This is more in line with the underlying assumptions used in developing US06. US06 was developed to represent a broad spectrum of driving behavior in both cars and trucks. As most of the data used in developing this was from cars and smaller trucks--probably lightly loaded-- it does not seem appropriate to require heavy, light-duty trucks to drive the same cycle with the additional load.

6.6 Driving Schedule Tolerances

The discussion in section 4.1.2.2 demonstrated the emission sensitivity of vehicles to how they are driven over a prescribed driving schedule, such as US06. The emissions for some vehicles are particularly sensitive to the amount of throttle variation. Given that a principal objective of the US06 is to provide a more representative driving cycle, it is important that the test procedure ensures that the minor speed deviations characteristic of in-use operation, and the resulting throttle movement, are preserved. The current FTP regulations (section 86.115-78 b) require that "the driver should attempt to follow the target schedule as closely as possible." To accomplish this, the regulation specifies a speed tolerance band and associated requirements for a valid test. The regulations also suggest that minimum throttle action should be used to maintain the proper speed-time relationship. EPA believes that the speed tolerance band does not ensure that the microtransient components of the driving schedule are preserved, and the current minimum throttle action language in the regulations exacerbates the problem of microtransient representation.

A throttle-based measure which establishes an acceptable range of throttle variation would appear to be most desirable; however, such a measure is not practical. The change in throttle required to follow a driving schedule will be determined in part the performance of the vehicle. If two vehicles were driven identically over a driving schedule, it is to be expected that a low performance vehicle would show greater throttle variation than a high performance vehicle. In addition, differences in throttle design can result in physical differences in the effect on the engine for identical throttle angles.

EPA proposes an additional trace tolerance criteria for all FTP driving cycles using the speed-based measure, the sum of change in specific power (DPWRSUM). EPA's analysis in section 4.1.2.2 showed this measure to correlate with change in throttle as well as emissions. Unlike a throttle-based measure, DPWRSUM is independent of the physical characteristics of the vehicle and there exists a unique value corresponding to the nominal driving schedule. A test run which exactly matches the nominal driving schedule, and thus matches the microtransient behavior of the driving schedule, would have a sum of change in power equal to the nominal DPWRSUM. Tests runs in which the DPWRSUM is less than the nominal value indicate that the exact trace was not maintained. Test runs where the DPWRSUM is greater than the nominal suggest excessive changes in power, and most likely, excessive throttle action. A test with a DPWRSUM value greater than the nominal DPWRSUM value would be invalid. A DPWRSUM value equal to 50 percent of the nominal value would offer a conservative lower threshold; however, EPA's analysis for establishing a lower DPWRSUM threshold is incomplete and we will seek input and data on a appropriate method for doing so.