PROJECT E-37

Evaluation of the Effects of Air Conditioning Operation and Associated Environmental Conditions on Vehicle Emissions and Fuel Economy

Executive Summary

This Executive Summary provides an overview and introduction to the Coordinating Research Council E-37 Research Program, "The Effect of Air Conditioning on Regulated Emissions from In-Use Vehicles." This program was sponsored by the Coordinating Research Council (CRC), the California Air Resources Board (ARB), and the Texas Commission on Environmental Quality to evaluate the effects of air conditioning (AC) operation on vehicle emissions and fuel economy.

The detailed results from this program are presented in two laboratory test reports with associated data files and in 27 separate statistical analysis reports. A technical paper prepared for the Society of Automotive Engineers (SAE) [1] describes the full program and presents detailed results and conclusions of the statistical analyses. The technical paper is available for purchase from SAE. The laboratory reports and associated data files as well as the statistical analyses are available from the CRC.

SUMMARY OF RESULTS

The program results demonstrated that AC operation had a substantial impact on emissions and fuel consumption. Operation of the vehicle AC system over a range of environmental conditions resulted in consistent increases in vehicle emissions of nitrogen oxides (NO_x) and carbon monoxide (CO). NO_x increased by 0.1 to 0.6 g/mile, depending on the severity of the test cycle and ambient conditions. CO increased by 0.5 to 12 g/mile. Hydrocarbon emissions were not affected by air conditioning use except in a few, limited cases.

The application of solar load to the vehicle increased the impact of AC operation. The application of solar load increased NO_x emissions by 0.10 to 0.14 g/mile. Although this experiment was not designed to specifically address fuel economy, operation of the vehicle AC system caused substantial decreases in vehicle fuel economy, ranging from 2.5 to 4.5 miles/gallon. The addition of solar load increased the effect on fuel economy, primarily at less severe ambient conditions. Solar load caused a decrease of 1.3 miles/gallon at 80°F and moderate humidity.

The results of the program were intended to aid in the improvement of vehicle emissions inventory models. NO_x emission increases due to the use of AC ranged from 15% to 100% of baseline levels. CO increases due to the use of AC varied considerably depending on the test cycle and ambient conditions. The percentage increase in CO emissions from baseline levels ranged from 0% (no statistical effect) to as high as 200%. These effects indicate that AC use can have a significant effect on vehicle emissions and should be accounted for in the inventory models.

INTRODUCTION

On October 22, 1996, EPA revised the Federal Test Procedure to include a Supplemental Federal Test Procedure (SFTP). The SFTP addressed shortcomings with the FTP in the representation of aggressive driving behavior, rapid speed fluctuations, driving behavior following startup, and use of air conditioning. To limit exhaust emissions during AC operation the SFTP included a test procedure referred to as the SC03 cycle.

Development of the SC03 indicated that there was a larger emissions impact associated with AC operation than previously estimated. This raised the question of how well the effect of AC operation was accounted for in regional emissions inventories. These inventories are developed through the use of vehicle emissions models such as EPA's MOBILE model and the ARB EMFAC model.

MOBILE5b modeling and ARB test evaluations all indicated that the effects of AC operation on vehicle emissions were underestimated. As a result, the CRC determined that a program to more accurately quantify the effects of AC operation on exhaust emissions would be a valuable addition to the database used to construct vehicle emissions inventory models.

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[1] **J. Steve Welstand et al, "Evaluation of the Effects of Air Conditioning Operation and Associated Environmental Conditions on Vehicle Emissions and Fuel Economy," SAE Paper No. 2003-01-2247, June 23-25, 2003**

The primary objective of this project was to characterize the impact of AC use on tailpipe emissions from in-use vehicles. It aimed to delineate how AC use impacts vehicle emissions under a variety of test conditions, including multiple driving cycles, varying temperature and humidity, solar load settings, and different fuels.

CRC was the primary sponsor of the program. Additional funding was provided by the ARB. In addition, the Texas Commission on Environmental Quality provided support for the first phase of the program. The program was conducted by the Clean Air Vehicle Technology Center, located in Hayward, California, under contract with CRC. Testing was conducted from 1998 through 2001.

TEST PROGRAM

The test program was performed in two phases. The objective of Phase 1 was to determine the extent to which AC use impacted vehicle emissions. The effect of AC operation was determined for a variety of test cycles and ambient conditions. The results of Phase 1 indicated that additional testing would be useful in further defining the effect of AC operation on emissions.

The purpose of Phase 2 was to further define how environmental conditions – specifically temperature, humidity, and solar load – influenced emissions when the AC was operating. Phase 2 involved a broader range of test conditions and a more refined test protocol.

In order to simulate the true effects of AC operation on exhaust emissions, the test program was conducted using a test cell that provided full temperature and humidity controls. In addition, solar load was also applied to the vehicle to further represent real world operation. This was done by placing a large array of solar lamps above the vehicle during testing.

PHASE 1 TEST PROGRAM

Phase 1 focused on determining the effects of AC operation on four specific test cycles. These test cycles were the EPA-75 or FTP (used for light-duty new vehicle emissions certification), the SC03 (EPA AC test cycle), the Unified Cycle (ARB inventory test cycle), and the IM240 (EPA short test cycle for state and local vehicle Inspection and Maintenance programs).

Tests were run at various combinations of three environmental conditions: temperature, humidity, and solar load. For each of the test cycles, at least one of the environmental combinations was run both with and without the AC operating. These tests provided a direct measure of the impact of the AC load on emissions. Fourteen passenger cars and light-duty trucks, representing two age groups, were tested in Phase 1. Seven of the vehicles were 1985-1988 make/model vehicles that were matched to similar 1995-1997 vehicles.

PHASE 2 TEST PROGRAM

The focus of Phase 2 was on determining the influence of varying environmental conditions on the effect of AC use on emissions and fuel economy. The conditions evaluated were temperature, humidity, and solar load. The hot operating portion (Bag 2) of the Unified Cycle was selected as the primary test cycle because it was specifically designed to incorporate the full range of driving patterns that characterize California vehicle fleet operation. FTP and SCO3 tests were also run for reference.

One objective of the Phase 2 test program was to incorporate temperature and humidity levels that systematically varied the demand (load) on the AC system. To achieve this objective, the psychrometric enthalpy was used as a surrogate for AC load. Enthalpy is the internal heat energy of a system, expressed as BTU/pound of dry air (BTU/lb). The greater the enthalpy, the more the AC system will have to work to achieve a comfortable passenger environment. Correspondingly, it was assumed vehicle emissions – with AC on – would be directly related to the enthalpy value for each test. Therefore, a test protocol was developed to conduct tests at various temperature and humidity levels to evaluate the validity of the enthalpy premise.

Twelve in-use vehicles representing three technology groups were tested in Phase 2. Four were certified to ARB Low Emissions Vehicle (LEV) or Ultra Low Emissions Vehicle (ULEV) standards. These vehicles represented the emissions performance of advanced technologies. Four of the vehicles were the same make and model as those used in the Phase 1 program with two drawn from each of the 1985-1988 and 1995-1997 age categories. The remaining four vehicles represented a diverse variety of other types of vehicles. One of these vehicles in the last group, a 1996 model SUV, was a high emitting vehicle. Popular model pickup trucks and minivans were well represented.

The temperatures incorporated in the test program ranged from 70ºF to 110ºF. Humidity levels varied from 40 grains to 100 grains per pound of air. The enthalpy range was 15 to 35 BTU/lb.

STATISTICAL ANALYSES AND RESULTS

The data generated in the Phase 1 and Phase 2 programs were subjected to analyses to identify statistically valid results. A series of reports prepared for CRC document the analyses and results. Results were considered statistically significant if the p-values of the tests were less than or equal to <u>0.05</u>. The results for each phase were analyzed separately. In addition, analyses were also conducted with combined data from both phases where there were common tests. These analyses provided assessments of the influence of AC operation (AC on vs. AC off), solar load (with AC operating), and enthalpy (heat load) on exhaust emissions and fuel economy.

PROGRAM CONCLUSIONS

The results of the Phase 1 and Phase 2 test programs and statistical analyses led to the following conclusions.

- Operation of the vehicle AC system resulted in consistent increases in vehicle emissions of CO and NO_x. CO increases varied from 0.5 to 12 g/mile, depending on the severity of the test cycle and ambient conditions. NO_x increases varied from 0.1 to 0.6 g/mile. Besides depending on the severity of the test cycle and somewhat on ambient conditions, NO_x increases were strongly affected by vehicle type. In Phase 2 the highest NO_x emissions increase due to AC operation (Unified Cycle, constant enthalpy conditions, with solar load) was 0.60 g/mile for the group that represented larger vehicles with pre-LEV emissions control systems. In Phase 1 the older, mid-1980s vehicles had higher NOx increases than the newer vehicles. This occurred for each of the test cycles/temperature conditions tested, with an average increase of 0.53 g/mile.

- Application of solar load increased the emissions response to AC operation. NO_x consistently increased due to the application of solar load over the range of increasing enthalpy levels. The solar load impact on NO_x, at 0.10 to 0.14 g/mile, was modest compared to the AC effect alone.

- A substantial influence of enthalpy on the impact of AC operation on CO emissions was indicated for the Unified Cycle. As enthalpy was increased from 20.1 to 34.5 BTU/lb, CO increased 14 grams/mile with the solar load off and 19 grams/mile with the solar load on. However, additional analyses indicated there was a similar (independent) CO response related to the increase in ambient temperature incorporated in the enthalpy values evaluated (80ºF to 110ºF). Therefore, the increase in temperature is indicated to be the primary cause of increased CO rather than the increase in enthalpy.

- Operation of the vehicle AC system caused substantial decreases in vehicle fuel economy, ranging from 2.5 to 4.5 miles/gallon, depending on the severity of the test cycle and ambient conditions.

- The AC effect on fuel economy was further increased, i.e., degraded, due to application of solar load. This influence was apparent primarily at the lower enthalpy condition. At the lowest enthalpy condition (80°F/55 grains), the solar load impact on fuel economy was a decrease of 1.3 miles/gallon.

- The response of fuel economy to AC operation was strongly influenced by increasing enthalpy on a fleet-wide basis. This effect was apparent only in the absence of the application of the solar load. Increasing enthalpy, across the range evaluated, caused fuel economy to decrease 2.7 miles/gallon with the Unified Cycle. When evaluated using the FTP, the impact was a decrease of 3.4 miles/gallon.

The relationship of emissions and, to some extent, fuel economy to AC operation is a complex issue. It has been demonstrated that the relationship is influenced by temperature, humidity, and solar load. The direct effect of temperature on emissions is a confounding factor. The response of specific vehicle AC systems to AC loads is a factor in this response and most likely adds to this complexity. An evaluation of AC system design factors was not within the scope of this program. A more definitive assessment than was conducted in this program would be required to account for all of these factors.