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Technical Report

Carbon Balance and Volumetric Measurements of Fuel Consumption

by

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I. Introduction/Background

A recently completed EPA test program investigated the effects on emissions and fuel consumption of different types and brands of tires. In that program, fuel consumption was measured using both the carbon balance and volumetric methods. The number of tests conducted provided adequate data for a comparison of the results obtained by these different methods.

A previously conducted investigation into the differences between carbon balance and volumetric measurements of fuel consumption concluded that a consistent difference exists between them. Fuel consumption measured volumetrically was found to average three percent higher than when measured by the carbon balance method.1/ This report presents another analysis of this question. Further background information on carbon balance vs volumetric fuel consumption measurements can be found in the earlier report, which is attached as Appendix A.

II. Discussion

This test program consisted of repeated cold-start FTP and hot-start HFET cycles. Fuel consumption was measured by both methods during each of the cycles.

A. Test Program

A total of 47 paired measurements of fuel consumption were acquired in the course of this test program. The test vehicle was a 1979 Chevrolet Nova with a 250 CID engine. The standard EPA emissions and fuel economy tests were conducted with four different sets of tires mounted on the vehicle, three sets of radials and one of bias-plys. Use of both test cycles resulted in fuel consumption being measured over a range of approximately 90 to 160 cm^3/km.

A more detailed description of the test program is given in the technical report on tire effects on emissions and fuel economy.2/

B. Data Reduction

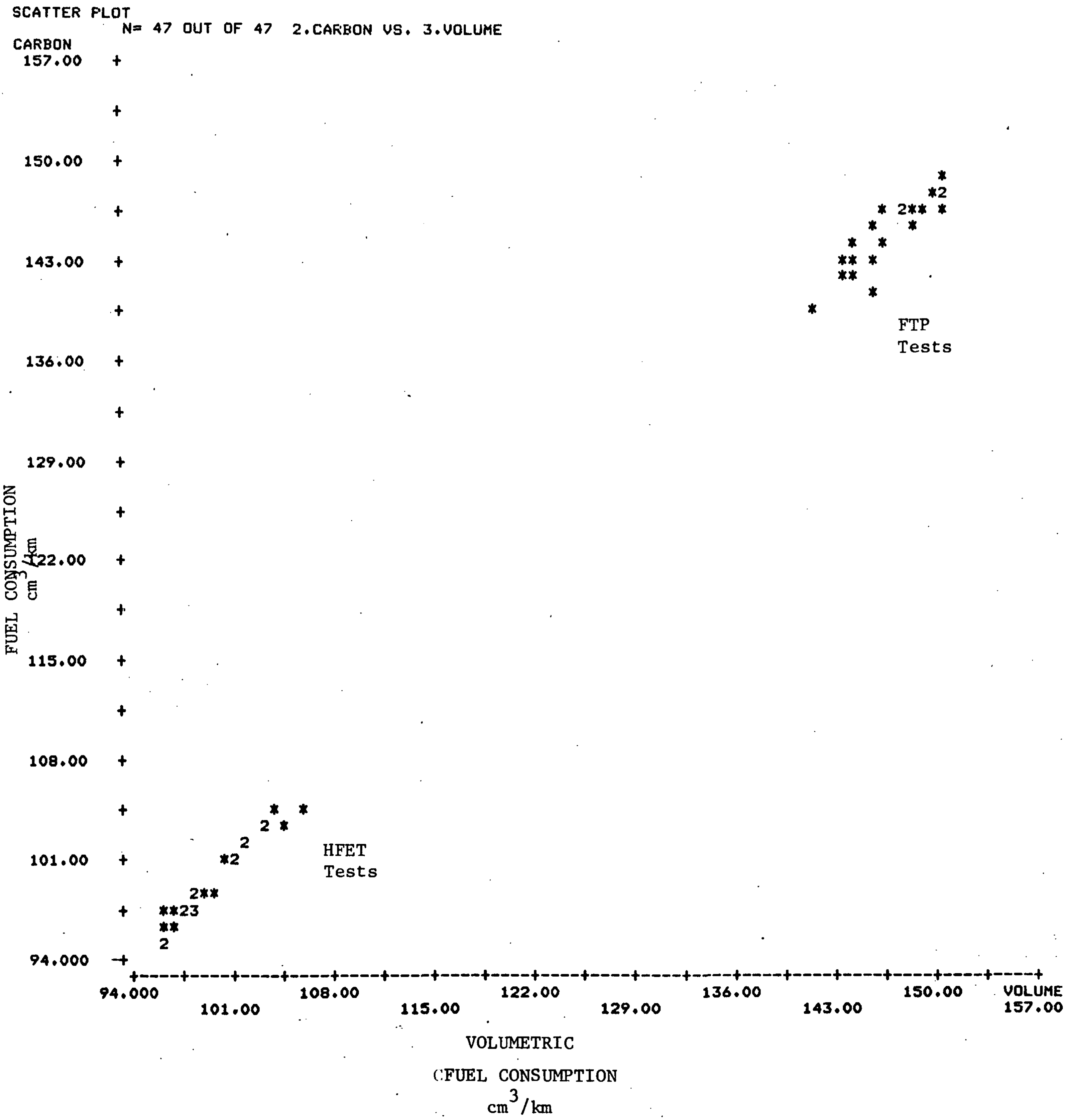
The basic data reduction was use of the standard EPA computer analyses of the FTP and HFET data. This data reduction is the same as that used in the previous investigation, and is discussed in greater detail in the corresponding section of that report, Appendix A.

C. Data Analysis

A scatter plot of the paired fuel consumption data appears as Figure 1, with carbon balance measurements on the vertical axis and volumetric on the horizontal. The cluster of points at upper right represents the FTP test results, while those at lower left represent the HFET test results.

Figure I

Carbon Balance vs. Volumetric Fuel Consumption



Analysis of the data showed no evidence of nonlinearity in the relation between volumetric and carbon balance measurements; thus only linear regressions of these data were fitted.

Application of the linear model:

$$F_c = a + bF_v \qquad (1)$$

where:

F_c = fuel consumption (carbon balance);
F_v = fuel consumption (volumetric);
a,b = constants,

requires use of the method of least-squares to determine the appropriate values of the constants a and b. The equation that results from using this model to describe the relationship between the two methods of measuring fuel consumption is:

$$F_c = 4.315 + 0.9552\ F_v \qquad (2)$$

The nonzero value of the constant a in the righthand side of equation (2) implies that a positive constant offset exists between these methods. The correlation coefficient r of equation (2), which is a measure of how well the linear model describes the relationship between the fuel consumption measurements, is greater than 0.99, indicating that this equation fits the data very closely.

However, a constant positive offset of 4.32 cm^3 between the results of the two methods is difficult to satisfactorily explain. Evaporative losses from the carburetor of the test vehicle, after the fuel has passed through the flow meter but before it is burned and converted to exhaust gases, would logically lead to a constant offset, but such an offset would be negative, as would any constant offsets due to exhaust system leakage. Also, equation (2) predicts that the carbon balance measurements will be greater than volumetric for fuel consumption rates below approximately 96 cm^3/km, while this relationship would be reversed when fuel consumption exceeded 96 cm^3/km. Very few of the data points obtained in this program were at fuel consumption levels below 97 cm^3/km, thus such a reversal it not evident from these data.

It is interesting to note that in twelve of the 47 paired measurements of fuel consumption taken in this program, the carbon balance measurement of fuel consumption was actually slightly greater than the corresponding volumetric measurement. These cases all occurred in the HFET cycles, at fuel consumption rates between 96 and 105 cm^3/km, and were interspersed among other pairs in which volumetric measurements were greater. Thus, these instances do not provide support for the reversal in the relationship between the results of the two methods predicted by equation (2). The difference between the two consumption rates, when the carbon balance measurement was greater, averaged 0.5 percent, and never exceeded 0.8 percent.

Due to the theoretical problems with the results and interpretation of the linear model regression, a simple proportional model was investigated. The proportional model is a linear model similar to equation (1), except without the constant term a. The closest proportional relation of the results of the two methods of measurement is given by:

$$F_c = (0.9893)\ F_v \qquad (3)$$

Equation (3) states that carbon balance measurements of fuel consumption will be about 1.1 percent higher than will corresponding volumetric measurements. The coefficient of correlation of this equation is very nearly as high as that of equation (2), $r > 0.99$.

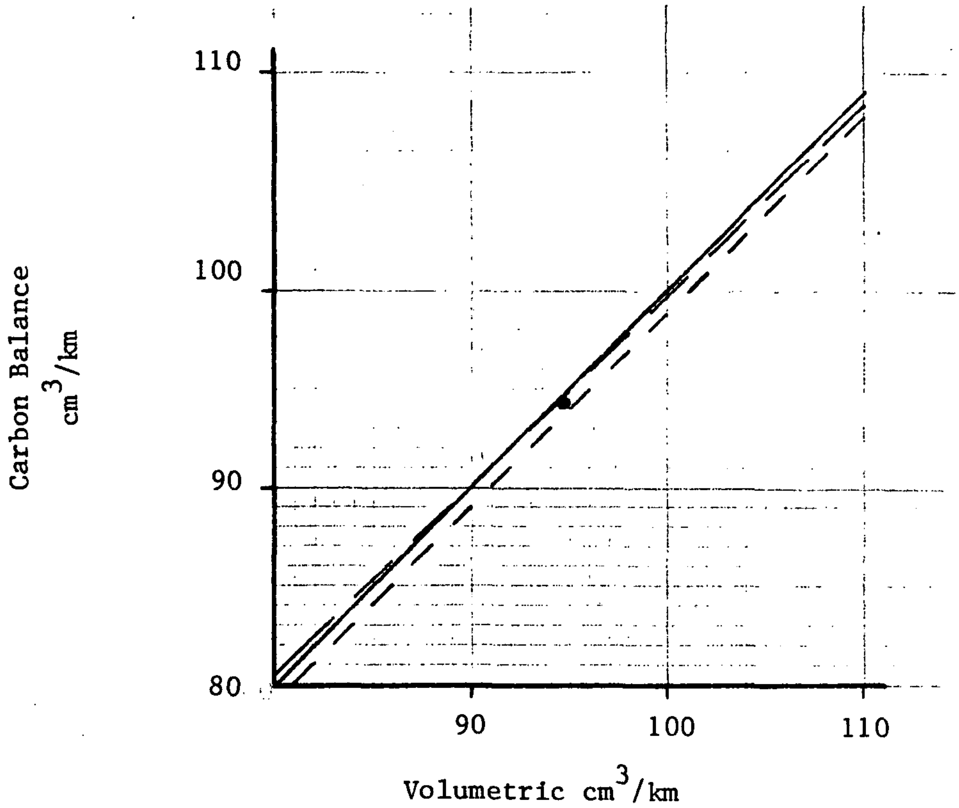
A relative comparison of equations (2) and (3) to each other, and to the line representing equality in the measurement methods, appears as Figure II. The mean of the data points from each of the driving cycles is also shown.

The previous analysis of this question was conducted using fuel consumption measurements taken during steady-state testing. As noted earlier, the data analyzed in this discussion were collected during repeated FTP and HFET driving cycles. The HFET cycle bears more resemblance, in its speed-vs-time characteristics, to steady-state operation than does the FTP cycle. If the observed differences in fuel consumption measurements are in some manner dependent on the type of driving done in the test, then the differences in the HFET paired measurements should correspond to those observed during steady-state testing more closely than would those based on FTP measurements.

In this program, the carbon balance method yielded fuel consumption rates averaging 0.2 percent lower than the volumetric method during HFET cycles. In the FTP cycles, carbon balance averaged 1.6 percent lower than volumetric. The steady-state tests resulted in carbon balance figures averaging 3.1 percent below volumetric figures. The fact that the FTP results from this analysis are closer to the earlier steady-state results than are those from the HFETs suggests that the driving cycle over which fuel consumption is measured is not an important parameter in determining the extent of the difference between the two methods of measurement.

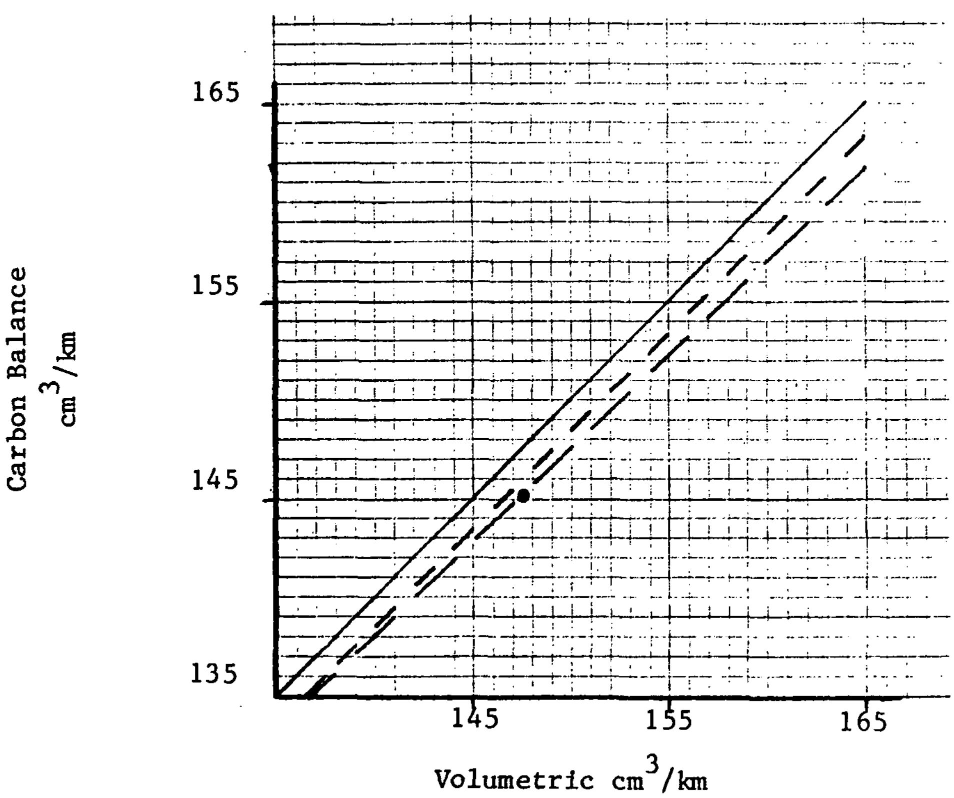
The ranges over which fuel consumption was measured were (approximately) 90-110 cm^3/km for the HFET tests, 100-135 cm^3/km for the earlier steady-state tests, and 140-155 cm^3/km for the FTP tests. Taken together, these points provide additional support for stating that the difference between results obtained by the two methods is proportional. In both analyses, this difference is seen

Figure II



HFET

- ● Mean of HFET pairs
  Vol = 99.6 cm^3/km
  CBal = 99.4 cm^3/km



FTP

- ● Mean of FTP pairs

Vol = 147.5

CBal = 145.2

KEY

______________ (solid line)	$F_c = F_v$	
- - - - - - - - - -	$F_c = (0.9893)\ F_v$	(EQN 3)
— — — — — —	$F_c = 4.315 + (0.9552)\ F_v$	(EQN 2)

to be greater as the rate of fuel consumption increases.

There are reasons to accept the results of volumetric measurements, which are direct measurements of fuel flow rate, as being less susceptible to error than the indirect carbon balance measurements. Flow meters used in this testing, and in the earlier steady-state testing, were calibrated to within their rated accuracy of 0.5 percent. The carbon balance method, which measures fuel consumption indirectly, relies on calibration of the instruments used to measure each of the components of the vehicle exhaust that contain carbon: CO, CO_2, and hydrocarbons. The potential exists for error tolerances to accumulate in the same direction.

The difference in the results of the two methods is small and relatively consistent, and it was less in this program than was observed in the earlier steady-state testing. Measurements taken during both programs were characterized by high degree of precision; and since the difference has changed over time, it appears likely that the cause lies with instrument calibrations. It would appear that slight alterations in the calibration of instruments used in the carbon balance method could eliminate the difference in the results of these methods.

III. Conclusions

1. It is concluded that direct volumetric measurements of fuel consumption show greater rates of consumption than do carbon balance measurements taken in the same tests. As a result, fuel economy estimates are higher when based on carbon balance measurements than they would be if based on volumetric data. In this investigation the observed difference ranged from 0.2 percent at the lower fuel consumption rates, to about 1.6 percent at the higher rates.

2. The difference in the results of these two methods appears to be proportional. Available data show the difference in carbon balance and volumetric measurements increasing with increases in the rate of consumption.

3. The most likely source of the difference between the results of these methods is the laboratory calibration of instrumentation. This is indicated by the proportional nature of the offset, and the fact that different investigations have shown evidence that the proportionality differs over time.

IV. Recommendations

1. In future test programs involving a fairly large number of repeated tests, fuel consumption should be measured by all three available methods: carbon balance, volumetric, and gravimetric. This would provide a basis to determine which measurement method is the more accurate.

2. Fuel consumption data should be collected under conditions of lower fuel flow rates, under 90 cm^3/km. Analysis of paired measurements of fuel consumption at these lower levels should allow a final determination of whether the difference is strictly proportional, or proportional with a small constant offset.

3. If the volumetric method is determined to be more accurate than the carbon balance method, then the effect of lab calibrations of the instruments used should be investigated more thoroughly. It should be possible to bring the carbon balance measurements of fuel consumption into agreement with the volumetric measurements, resulting in more accuracy in the EPA fuel economy estimates.

Reference

1/ Turton, Dale "Fuel Consumption Measurements--Carbon Balance vs Flow Meter," EPA Technical Report, SDSB 79-28, July 1979.

2/ Jones, Randy and Terry Newell, "The Effects of Tire Rolling Resistance on Automotive Emissions and Fuel Economy," EPA Technical Report, SDSB 80, Draft: May 1980.

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