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Technical Report

Corrections for Variations in Test Fuel Properties

By

G. D. Thompson

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Sources
Office of Air and Radiation
U. S. Environmental Protection Agency

I. Introduction

General Motors Corporation has recently asserted that the test fuel used at the EPA/MVEL has varied in energy density and carbon content since 1975.[1] General Motors has subsequently requested that a CAFE correction be granted to account for these variations in fuel properties.

GM has submitted data demonstrating that the test fuel used by GM has varied since 1975. Since EPA and GM obtain fuel from the same sources it is probable that the EPA test fuel has also varied in a similar fashion. If so, this is a change which would systematically affect the measured fuel economy of test vehicles and hence corporate average fuel economies (CAFE). This change is similar to previous test procedure changes for which CAFE corrections have been proposed.[2]

The report develops a simple correction based on the energy content per unit carbon of the fuel. The correction proposed by GM is also discussed, as is the problem of limited available data on the test fuels.

II. The Correction for Test Fuel Properties

The EPA exhaust emission and fuel economy measurements determine the quantity of carbon combusted by the vehicle during the test. The carbon balance equation then computes the volume of fuel which must have been burned to yield the measured amount of carbon. The coefficients of the EPA equation are currently fixed numerical values which in effect define a reference test fuel.

If the carbon content of the fuel varies in time, as GM has asserted, then the present carbon balance equation will not give the true volume of the test fuel consumed. It will, however, continue to give the correct quantity of the original reference fuel which would have to be consumed to give the measured carbon. Therefore the carbon balance equation automatically adjusts the fuel economy calculation for whatever fuel is used back to a volume of the reference fuel.

While the carbon balance equation automatically adjusts the fuel economy calculation for the carbon content of the fuel, it does not consider how the engine is affected by the fuel. For long term variations in the fuel properties, such as those which appear to have occurred at the EPA/MVEL, the fuel delivery to the engine will be adjusted to account for the energy content. This will occur automatically with some closed loop fuel control systems and manually through calibration adjustments in other instances. This will be required either to maintain vehicle driveability or to maintain acceptable HC and CO emissions.

Ultimately the energy content is the most important aspect of the fuel to the engine. If the energy content of the fuel decreases the engine must burn more fuel to provide the same amount of work output. Therefore, fuel economy corrections for changes in fuel properties should be formulated in terms of the energy content per unit carbon of the fuel. Since the variations in the fuel properties have been small, it is reasonable to state that the fuel consumption is proportional to the energy content per unit carbon of the fuel. That is:

$$COM_r = COM_t \frac{E_a}{E_r} \qquad (1)$$

Where:

COM_r = the quantity of the reference fuel which would be consumed

COM_t = the measured consumption of test fuel

E_a = the energy content per unit carbon of the actual fuel

E_r = the energy content per unit carbon of the reference fuel

Equation 1 simply states that the quantity of carbon which is burned is proportional to the energy content of the fuel. If the actual fuel has more energy per unit carbon than the reference fuel, say 10 percent more, then 10 percent more carbon of the reference carbon fuel would have to be burned to provide the necessary energy for the fuel economy or emissions test.

Fuel economy is proportional to the inverse of fuel consumption. Therefore equation 1 may alternately be expressed as:

$$MPG_r = MPG_m \frac{E_r}{E_a} \tag{2}$$

Where:

MPG_r = the fuel economy using the reference fuel

MPG_m = the measured carbon balance fuel economy

The energy content per unit carbon of the fuel is not a normally measured parameter but it can be calculated from mass specific heating value of the fuel and the carbon weight fraction. That is:

$$E = L/C \tag{3}$$

Where:

E = the energy content per unit carbon of the fuel

L = the mass specific lower heating value of the fuel

C = the carbon weight fraction of the fuel

Using equation 3 in equation 2:

$$MPG_r = MPG_m \frac{L_r/C_r}{L_a/C_a}$$

$$MPG_r = MPG_m \frac{L_r\ C_a}{L_a\ C_r} \tag{4}$$

The first technical report for fuel economy corrections demonstrated that if each measured fuel economy was corrected by a constant proportion then the corporate average fuel economy (CAFE) would be modified by the same proportion.[1] Therefore:

$$CAFE' = CAFE \ \frac{L_r}{L_a} \frac{C_a}{C_r} \tag{5}$$

Where:

CAFE' = the CAFE corrected to the 1975 fuel conditions

CAFE = the measured CAFE

Subtracting the measured value from each side of equation 5:

$$CAFE' - CAFE = CAFE \frac{L_r}{L_a} \frac{C_a}{C_r} - CAFE \tag{6}$$

or

$$\Delta CAFE = \left(\frac{L_r}{L_a} \frac{C_a}{C_r} - 1 \right) CAFE$$

Where:

Δ CAFE = the required CAFE correction or CAFE adjustment

The numerical values for the CAFE corrections, or CAFE adjustments, are presented later in Section V.

III. The General Motors Approach

The correction proposed by GM is a more complex two step approach.[2] First, the carbon balance measured fuel economy is corrected to a true volumetric fuel economy based on the carbon content of the test fuel. Then an empirical sensitivity coefficient is used to adjust this volumetric fuel economy to a fuel economy of the 1975 model year fuel.

The correction to the volumetric fuel economy of the test fuel is:

$$MPG_t = MPG_m \frac{CV_a}{CV_{cb}} \tag{7}$$

Where:

MPG_t = the true volumetric fuel economy of the test

MPG_m = the measured carbon balance fuel economy

CV_a = the carbon volume fraction of the test fuel

CV_{cb} = the carbon volume fraction assumed in the carbon balance equation

In order to correct the present volumetric fuel economy to the fuel economy which would have occurred with 1975 fuel the GM approach assumes that the correction is proportional to the change in the volumetric heating values of the fuel. A dimensionless sensitivity coefficient is defined as:

$$R = \frac{MPG_t - MPG_r}{MPG_r} - \frac{LV_t - LV_r}{LV_r} \qquad (8)$$

Where:

R = the sensitivity coefficient

MPG_r = the fuel economy with the 1975 fuel

LV_t = the lower volumetric heating value of the test fuel

LV_r = the lower volumetric heating value of the reference fuel

Solving equation 8 for the reference fuel economy gives:

$$MPG_r = MPG_t \left[\frac{1}{(R \frac{LV_t}{LV_r} - 1) + 1}\right] \qquad (9)$$

Using equation 7 for the test fuel economy gives the total correction as:

$$MPG_r = MPG_m\left[\frac{CV_a}{CV_{cb}} \quad \frac{1}{R(\frac{LV_t}{LV_r} - 1) + 1}\right] \qquad (10)$$

Equation 10 uses the volumetric heating values and the volumetric carbon fraction of the fuel. Both of these parameters are, however, usually measured and reported on a mass specific basis. The conversion from mass specific to volume specific for either of these parameters is, using the carbon fraction as an example:

$$CV = (C)(S)(MH_2O) \qquad (11)$$

Where:

S = the specific gravity of the fuel

MH_2O = the mass of a unit of water

Using equation 11 and the similar equation for the heating value of the fuel in equation 10 gives the final correction equation by the GM method:

$$MPG_r = MPG_m \frac{C_a S_a (mH_2O)}{C_{cb} S_{cb} (mH_2O)} \quad \frac{1}{R[\frac{L_t S_t (mH_2O)}{L_r S_r (mH_2O)} - 1] + 1} \qquad (12)$$

$$= MPG_m \frac{C_a S_a}{C_{cb} S_{cb}} \quad \frac{1}{(R \frac{L_t S_t}{L_r S_r} - 1) + 1}$$

Rearranging terms results in:

$$MPG = MPG_m \frac{C_a S_a}{C_{cb} S_{cb}} \quad \frac{L_r S_r}{R(L_t S_t - L_r S_r) + L_r S_r} \qquad (13)$$

$$= MPG_m \frac{C_a S_a L_r S_r}{C_{cb} S_{cb} L_t S_t} \left[\frac{1}{R(1 - \frac{L_r S_r}{L_t S_t}) + \frac{L_r S_r}{L_t S_t}}\right]$$

But the carbon balance and the reference parameters are the same, that is:

$$C_{cb} = C_r \qquad (14)$$

$$S_{cb} = S_r$$

And the test and actual parameters are the same:

$$S_t = S_a \qquad (15)$$

Therefore:

$$MPG_r = MPG_m \frac{C_a}{C_r} \frac{S_a}{S_r} \frac{L_r}{L_a} \frac{S_r}{S_a} \left[\frac{1}{R - R \frac{L_r S_r}{L_a S_a} R + \frac{L_r S_r}{S_a S_a}}\right]$$

$$= MPG_m \frac{C_a}{C_r} \frac{L_r}{L_a} \left[\frac{1}{R + \frac{L_r S_r}{L_a S_a} (1 - R)}\right] \qquad (16)$$

IV. Discussion

The correction developed in Section II of this report and that developed by GM are quite different in their basic concepts. Mathematically, however, the results are related. The relationship is most easily shown by considering equation

16 in the special case where R = 1. In this case:

$$MPG_r = MPG_m \frac{C_a}{C_r} \frac{L_r}{L_a} \quad (17)$$

Equation 17 is identical to equation 4 of the EPA approach.

The parameter R may be considered as the efficiency with which the vehicle engine adapts to fuel variations. Mathematically the difference between the EPA and GM methods is simply this efficiency value. GM proposes an efficiency value of 0.6 based on tests with multiple fuels in fixed vehicle configurations. However the variations in the EPA fuel properties have occurred slowly while the vehicles were continuously tested and modified. It is unreasonable to expect that a 1985 vehicle carefully calibrated on 1984 test fuel would use the higher energy per gallon of this fuel as inefficiently as would a 1975 vehicle which had been calibrated on 1975 fuel. As long as the variations are gradual it is more logical to assume that the vehicles will adapt to these variations with high efficiency, either automatically through closed loop fuel control systems or through manual calibration changes.

A second area of questionable accuracy with the GM approach occurs when the energy content per unit volume of the fuel decreases. In this case, the efficiency term reduces or discounts the calculated correction. For example, if the energy content per unit volume decreased by 20 percent, the fuel economy correction would only be about 10 percent. It is unlikely that vehicles could tolerate a significant decrease in the energy density of the fuel without experiencing an equivalent decrease in fuel economy.

V. Results

The EPA approach and the GM approach both require data on the lower heating value and the carbon weight fraction of the fuel. Neither of these parameters were routinely measured by EPA in the past. Therefore, these data are not presently available at EPA although efforts are being made to acquire whatever data may be available from fuel suppliers. GM did submit data on the density and other properties of their test fuel. The GM data are given in Table 1. Using the hydrogen/carbon ratios submitted by GM, the carbon weight fraction of the fuel may be calculated by:

$$C = (12.011)/(12.011 + 1.008\ HC) \quad (18)$$

Table 1

Test Fuel Properties*

Calendar Year	Specific Gravity	API Gravity	Aromatics Volume %	Avg. Dist. Temp., °F	Hydrogen/ Carbon Ratio
1979	0.739	59.97	26.5	220	1.85
1980	0.742	59.20	26	222	1.86
1981	0.747	57.92	26.7	219	1.81
1982	0.749	57.42	29.8	220.3	1.80
1983	0.749	57.42	31.8	220	1.79
1984	0.751	56.92	31	221	1.77

* Data Submitted by General Motors, Reference 1.

Where:

HC = the hydrogen/carbon ratio

12.011 = the atomic weight of carbon

1.008 = the atomic weight of hydrogen

The heating values of the fuels may be estimated by empirical equations developed by ASTM or a simplier equation from Marks' Mechanical Engineering Handbook.[3,4] The carbon weight fractions, the specific gravity of the fuel and the estimated heating values are given in Table 2. Both the heating values and the variation in the heating values calculated by the different methods are notably different. The variations computed by the method of Marks' handbook are so small that the effect from the change in heating value is insignificant.

Table 2 demonstrates that a major uncertainty in the computed correction will be the heating values of the present and past fuels. Measured data would be highly desirable since both of the methods of this report have questionable aspects. The ASTM method was developed for aviation fuel, primarily kerosene-like jet fuels and may not be applicable to automotive gasoline. The method published by Marks is a much more general approach for a wide range of petroleum products and its precision in estimating the heating values for different automotive gasolines is also questionable.

The results of Table 2, together with a CAFE value, are sufficient to calculate the correction by either the GM or EPA approach. Most manufacturers have CAFE's near the CAFE standards. Therefore, using the CAFE standards is a reasonable approach to estimate the typical CAFE correction for the fuel change. These corrections, based on the CAFE standards are given in Table 3.

VI. Conclusions

It is appropriate to develop a CAFE correction for changes in test fuel parameters. The following equation is the simplest and most logical correction:

$$\Delta \text{ CAFE} = \left[\frac{L_r C_a}{L_a C_r} - 1\right] \text{CAFE}$$

Table 2

Test Fuel Properties

Calendar Year	Specific Gravity	Carbon Weight Fraction	Lower Heating Values ASTM* (Btu/lb)	Lower Heating Values Marks' ** (Btu/lb)
1979	0.739	.8656	18,517	19,035
1980	0.742	.8650	18,515	19,013
1981	0.747	.8681	18,481	19,013
1982	0.749	.8688	18,434	19,008
1983	0.749	.8694	18,407	19,014
1984	0.751	.8707	18,412	19,014

* Calculated by the method given in Reference 3.
** Calculated by the method of Reference 4.

Table 3

CAFE Correction

Model Year (1)	CAFE Standard (MPG)	CAFE Corrections: GM Method (5) ASTM (2) (MPG)	GM Method (5) Marks (3) (MPG)	EPA Method ASTM (2) (MPG)	EPA Method Marks' (3) (MPG)
1980(4)	20	0	0	0	0
1981	22	0.022	0.036	-0.013	0.010
1982	24	0.201	0.190	0.116	0.097
1983	26	0.307	0.259	0.214	0.133
1984	27	0.362	0.282	0.281	0.148

(1) All vehicles of any model year are assumed to be tested in the previous calendar year.
(2) Lower heating value from ASTM calculation.
(3) Lower heating value from Marks' Handbook calculation.
(4) 1980 model year (i.e., 1979 calendar year taken as the reference).
(5) The CAFE corrections as calculated by GM were based on the GM CAFE's, not the CAFE standards. GM's calculated CAFE corrections were .0208, .1934, .2722 and .3228 mpg for model years 1981 through 1984, respectively.

Where:

L_r = the lower heating value of the reference fuel

L_a = the lower heating value of the actual test fuel

C_a = the carbon weight fraction of the actual test fuel

C_r = the carbon weight fraction of the reference fuel

This correction is based only on the energy content per unit of carbon of the fuel. Other, more complicated correction equations can also be developed.

Relatively little actual fuel data are available. For example, no measurements of the heating value of the 1975 reference fuel are known. The lack of data is a major cause of uncertainty in this correction.

Calculated corrections for model year 1984, the year with the greatest CAFE correction, range from 0.148 mpg to 0.362 mpg depending on the method of the calculation used and estimated heating values of the fuel.

References

1. Letter to R. E. Maxwell, Certification Division, Office of Mobile Sources, U.S. EPA, from W.S. Freas, General Motors Emission and Fuel Economy Operators, August 15, 1984.

2. "CAFE Corrections for Test Procedure Changes," Thompson, Glenn D., U.S. EPA, OAR, OMS, ECTD, SDSB, October 1983.

3. "Standard Methanol for Estimation of Heat of Combustion of Aviation Fuels," ASTM Standard D 3338, 1979.

4. Marks' Standard Handbook for Mechanical Engineers, Baumeister, Avallone, Baumeister, McGraw Hill 8th Edition, 1978.