

Determination of the R Factor for Fuel Economy Calculations Using Ethanol-Blended Fuels over Two Test Cycles

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ABSTRACT

During the 1980s, the U.S. Environmental Protection Agency (EPA) incorporated the R factor into fuel economy calculations in order to address concerns about the impacts of test fuel property variations on corporate average fuel economy (CAFE) compliance, which is determined using the Federal Test Procedure (FTP) and Highway Fuel Economy Test (HFET) cycles. The R factor is defined as the ratio of the percent change in fuel economy to the percent change in volumetric heating value for tests conducted using two differing fuels. At the time the R-factor was devised, tests using representative vehicles initially indicated that an appropriate value for the R factor was 0.6. Reassessing the R factor has recently come under renewed interest after EPA's March 2013 proposal to adjust the properties of certification gasoline to contain significant amounts of ethanol. This proposed change will likely result in a significant deviation from the CAFE baseline test fuel heating value, and thus increased importance of the R factor. This paper reports on the analysis of fuel economy data from three relatively large vehicle studies recently conducted using ethanol-blended fuels; the analysis determines the value of R for Tier-1 and Tier-2 compliant vehicles. These data sets include the DOE Intermediate Ethanol Blends Immediate Effects Study, the EPA/V2/E-89 project results, and the DOE Intermediate Ethanol Blends Catalyst Durability Program. The Immediate Effects Study and EPA/V2 test program yielded measurements for R of 0.891 ± 0.075 and 0.921 ± 0.010 , respectively for the LA92 drive cycle. Both studies using the LA92 cycle observed a tendency for the R value to rise for E15 and E20 fuels. The results of the DOE Intermediate Ethanol Catalyst Durability Program produced an average R factor of 0.949 ± 0.041 for the FTP cycle. Increasing fuel ethanol content did not have a significant effect on FTP R factor values for the FTP cycle.

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INTRODUCTION

On December 22, 1975, the Energy Policy and Conservation Act (EPCA) was signed into law for the purpose of serving the nation's energy demands and promoting fuel conservation methods. Under EPCA, provisions were put in place requiring that manufacturers' average fuel economies for passenger automobiles meet minimum standards in the 1978 and later model years) also known as the Corporate Average Fuel Economy (CAFE) standards [1]. In addition, it directed the National Highway Traffic and Safety Administration (NHTSA) to establish the vehicle fuel economy standards while the United States Environmental Protection Agency (U.S. EPA or EPA)

was directed to establish vehicle testing and calculation of fuel economy values used by manufacturers for compliance with the CAFE standards.

The Energy Independence and Security Act (EISA) was enacted in the United States in 2007 to decrease petroleum consumption. EISA established a series of biofuel consumption targets, the most well-known being a requirement for the U.S. transportation sector to utilize at least 36 billion gallons (or just over 136 billion liters) per year of biofuels by 2022, at least 21 billion gallons (79.5 billion liters) of which must be derived from non-starch sources [2]. As a result of the EISA mandates, nearly all gasoline in the United States now contains up to 10% ethanol.

EPA has recently proposed a major program, referred to as “Tier 3”, designed to reduce air pollution from passenger cars and trucks starting with model year 2017 [3]. This program considers the vehicle and its fuel as an integrated system, and thus in addition to new vehicle emission standards, also includes updated specifications for federal emissions certification test fuel to better match properties of in-use gasoline including significant ethanol content.

When EPA makes changes to the test procedures used for fuel economy (e.g., Federal Test Procedure (FTP) and Highway Fuel Economy Test (HFET)), they must evaluate the need for an adjustment to the measured fuel economy results to comply with this requirement referred to as a CAFE/fuel economy test procedure adjustments or adjustment factors [1].

As a result of the proposed change in certification fuel under the Tier 3 Program the test fuel will have a significantly lower volumetric heating value. Consequently, EPA must evaluate the need to revise the current fuel economy adjustment factors, with the main focus on the current fuel economy adjustment factor, the “reactivity” or “R” Factor.

R FACTOR

Determination of the fuel economy of a vehicle operated on a chassis dynamometer drive cycle is accomplished by assessing the carbon dioxide (CO₂), carbon monoxide (CO), and unburned hydrocarbon (HC) emissions to compute the total carbon mass emissions of the vehicle on a unit distance travelled basis. Analysis of the test fuel produces a measure of the fuel density and the carbon weight fraction of the fuel. These metrics enable calculation of the carbon mass in a given volume of fuel. Volumetric fuel economy is calculated by dividing the mass of carbon per unit volume of fuel by the carbon emissions on a per unit distance basis to obtain a volumetric fuel economy.

However, the calculation of a fuel economy result from the certification test cycles is more complicated. In 1986, EPA introduced the R factor to address issues associated with test fuel variability and the resulting complexities it introduced into the Corporate Average Fuel Economy (CAFE) calculations [4,5,6]. The R factor, first investigated by J.C. Ingamells of Chevron Research, relates the sensitivity of vehicle fuel economy results to changes in the volumetric net heating value of the fuel [7]. R is defined according to Equation 1.

$$R = \frac{\left(\frac{VOLFE_i}{VOLFE_r}\right) - 1}{\left(\frac{VOLHVi}{VOLHVR}\right) - 1} \quad (1)$$

VOLFE_i is the resultant volumetric fuel economy from a test using a test fuel with a volumetric heating value of VOLHVi. VOLFE_r is the resultant volumetric fuel economy from a test using a reference fuel with volumetric heating value of VOLHVR. EPA uses the R factor to establish a linkage between test

results with modern certification fuels and equivalent test results (on an energy consumed per unit distance basis) conducted with a 1975 certification fuel known as Indolene [4,5,6]. This linkage maintains consistency in terms of CAFE reporting and compliance since the CAFE regulations were originally put in place in 1975 when Indolene was in use as a certification fuel.

The R factor was assigned a value of 0.60 based on limited testing conducted in the 1970s and 80s using carbureted vehicles [4,6]. The references for the 0.6 value do not provide an uncertainty value or a means of estimating it from the underlying data. More comprehensive testing performed in the context of the Auto/Oil study in the early 1990s found an R value of 0.92 ± 0.21 for a test fleet covering model years 1983-1985, and a value of 0.93 ± 0.05 for a test fleet of model year 1989 vehicles with current technology at that time. [6]. However, as of this writing, the R factor used in fuel economy calculations specified in the Code of Federal Regulations remains at 0.6 [5].

Figure 1 shows how much the calculated 1975 fuel economy value depends upon both R and the volumetric heating value of the test fuel, with the value of R determining the slope of the line. This example is for a vehicle with an arbitrary, uncorrected fuel economy of 25 miles per gallon. The volumetric heating value of the reference fuel was taken to be 113,936 BTU/gallon, which is consistent with that of 1975 Indolene [6].

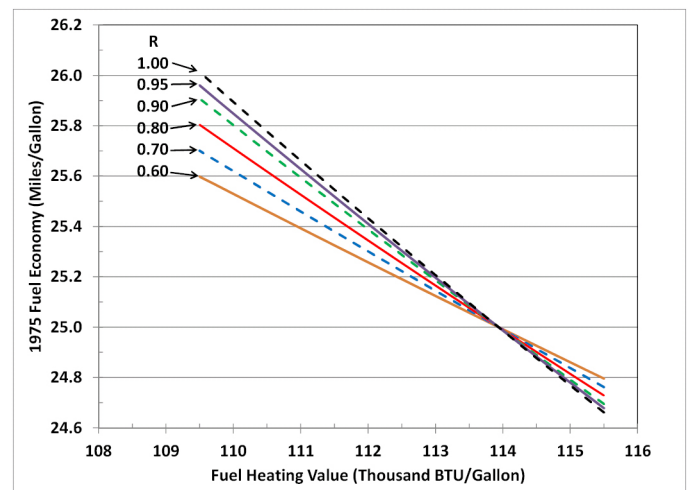


Figure 1. Influence of volumetric heating value and R value on calculated 1975 fuel economy results.

If the test fuel has the same heating value as the reference fuel, the value of R is of no consequence, and the uncorrected value of fuel economy is the same as the 1975 fuel economy result. As the test fuel heating value moves further from that of the reference fuel, the difference in the resulting 1975 fuel economy value resulting from different values of R becomes larger. The inclusion of ethanol in certification gasoline will result in a significant reduction in the volumetric heating value of the test fuel, increasing the importance of the R factor. It is worth noting that if the volumetric heating value of the test fuel

is higher than that of Indolene, as was the case for a number of the E0 fuels reported in this paper, the 1975 fuel economy result is highest for low values of R. For fuels with heating values that are lower than Indolene, such as the ethanol-containing fuels reported in this paper, increasing the value of R also increases the 1975 fuel economy result. If, for example, the fuel economy data in Figure 1 is assessed at a test fuel volumetric heating value of 111,000 BTU/gallon (consistent with an E10 fuel blend), moving from an R value of 0.6 to a value of 1.0 increases the 1975 fuel economy result by about 0.25 miles per gallon. This level of difference is significant in terms of calculation of the corporate average fuel economy for a given vehicle manufacturer, and is the reason for increased interest in the value of R.

The value of the R factor indicates whether the fuel economy change is smaller, larger, or the same as the change in fuel volumetric heating value between the test fuel and the reference fuel. To examine situations in which the fuel economy change is not the same as the heating value change, it is useful to translate the definition for the R factor to cycle average engine efficiency. Consider a vehicle conducting a driving cycle. The energy delivered to the road during the cycle can be written as in Equation 2.

$$E = V_F * D_F * HV_F * \eta_E * \eta_P \quad (2)$$

In this relationship, E is the energy delivered to the road to move the vehicle. V_F is the volume of fuel consumed, D_F is the density of the fuel, and HV_F is the heating value of the fuel on a mass basis. η_E is the cycle-average engine efficiency, and η_P is the lumped cycle average efficiency of the remainder of the powertrain. Dividing both sides of the equation by the distance traveled during the cycle and gathering terms, the equation can be re-written as Equation 3.

$$VOLFE = VOLHV * \eta_E * \eta_P * \frac{\text{Distance}}{E} \quad (3)$$

When written in this way, the previously introduced terms VOLFE and VOLHV emerge. The equation can be written both for a test fuel (subscript i) and for the reference fuel (subscript r). These expressions can then be substituted into the equation for R (equation 1). Assuming the vehicle powertrain and the drive cycle are constant, the distance, E, and η_P cancel, leaving equation 4 that relates R, VOLHV, and η_E , which is now written with subscripts i and r to reflect the potentially different engine efficiencies when the two different fuels are used.

$$R = \frac{[VOLHV_i * \eta_{Ei} - VOLHV_r * \eta_{Er}]}{[VOLHV_i - VOLHV_r] * \eta_{Er}} \quad (4)$$

At this point, it becomes obvious that R must be equal to unity if the two cycle average engine efficiencies are equal. Thus, R values different from unity are a result of differences in engine efficiency that result from the use of two different test fuels. It is

also noteworthy that the change in engine efficiency for a given value of R is linked to the corresponding change in volumetric heating value of the fuel. Figure 2 shows the relationship between R and the brake thermal efficiency change for a notional change in VOLHV from 115,254 BTU/gallon to 109,247 BTU/gallon. This energy change is typical for a change from an ethanol-free fuel (as the reference fuel) to a splash-blended fuel containing 15% ethanol by volume (as the test fuel).

Readers should note that the brake thermal efficiency values listed in the legend are assumed cycle-average values typical for the FTP, not peak efficiency values for the engine, which would tend to be significantly higher [8]. The change in cycle average brake thermal efficiency (y-axis) for a given value of R increases as the reference value of brake thermal efficiency increases, meaning that the error associated with using an incorrect value for R is more significant with more efficient engines. The value of R is also very sensitive to small changes in cycle average engine brake thermal efficiency, particularly when a relatively large change in the volumetric heating value of the fuel is considered.

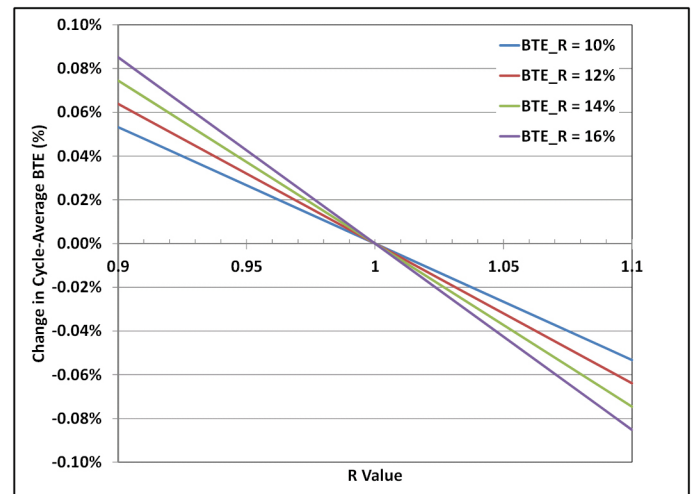


Figure 2. Relationship between R factor and Change in Cycle Average Brake Thermal Efficiency.

R values greater than unity indicate that the percent change in fuel economy is greater than the corresponding percent change in volumetric heating value. For the cases considered in Figure 2, where the volumetric heating value was lower for the test fuel than for the reference fuel, a value of R greater than unity means that the fuel economy declined more than would be expected from the change in volumetric heating value. In such a case, R values greater than unity mean that the cycle average engine efficiency has declined on the test fuel relative to its efficiency on the reference fuel.

R values less than unity indicate that the percent change in fuel economy is smaller than the corresponding percent change in heating value. For the case considered in Figure 2, where the volumetric heating value was lower for the test fuel than for the reference fuel, a value of R less than unity means that the fuel

economy declined less than would be expected from the change in volumetric heating value. Such a value of R indicates that the cycle average engine efficiency has increased for the test fuel compared with the reference fuel.

While the R factor was established to account for changes in the volumetric heating value of different fuels, this change is generally accompanied by changes to other fuel properties that may have an impact on fuel economy. For example, blending higher levels of aromatics into gasoline can increase the volumetric heating value while blending ethanol into gasoline lowers the heating value. However, both of these actions increase a fuel's octane rating and heat of vaporization, both of which can improve knock resistance. Stoichiometric air/fuel ratio will also change. Since the R factor is very sensitive to cycle average engine efficiency, marginal changes in efficiency caused by changes in fuel formulation can significantly influence the value of R . Thus, while R is intended to represent the fact that efficiency changes within an engine and vehicle are not directly proportional to the volumetric heating value of the fuel, there can be other impacts on fuel economy that may also be attributed to the R factor in an empirical test program.

This paper reports on analysis of the data from three relatively large emission test programs, though none of them was designed specifically to evaluate fuel effects on R . The analyses examined the relationship between volumetric fuel economy and volumetric heating value when ethanol blends of up to 20% in gasoline were used in both the FTP and the LA92 drive cycle.

EXPERIMENTAL DATA

Three sources of fuel economy and fuel heating value data for modern cars were utilized in the analyses reported in this paper. The first was the Immediate Ethanol Effects Study that was conducted as a part of the DOE Intermediate Ethanol Blends Program [9, 10]. The second study was the EPA/V2/E-89 study conducted by EPA, DOE, and CRC to quantify the impacts of five fuel parameters on exhaust emissions of Tier-2-compliant passenger cars and light trucks [11]. The third study was the Catalyst Durability Study that was conducted as part of the DOE Intermediate Ethanol Blends Program [12]. These studies used vehicles that were representative of the dominant engine technologies at the time. The vehicles all used port fuel injection and none were flex-fuel vehicles, for example. Since direct fuel injection had not achieved significant market penetration at the time, this technology was not represented among the data analyzed to determine the R factor.

Immediate Effects Study

The Immediate Ethanol Effects study focused on the short-term or immediate effect of mid-level ethanol blends on emissions and exhaust temperatures in the legacy fleet [9, 10]. This study

utilized the LA92 drive cycle, and was conducted at three test facilities. The National Renewable Energy Laboratory (NREL) supervised testing at the Colorado Department of Public Health (CDPHE), Argonne National Laboratory (ANL) contracted the Transportation Research Center, Inc. (TRC) to conduct tests, and Oak Ridge National Laboratory (ORNL) conducted tests at its facility. Figure 3 shows the speed-time profile of the LA92 drive cycle.

During this study, 16 vehicle models were studied, using four ethanol blends: 0% (E0), 10%, (E10), 15% (E15), and 20% (E20). Each vehicle was tested using each ethanol fuel blend. Data from all 16 vehicle models as shown in Table 1 were included in the R factor analysis. The fuels at all three test sites were sourced from Gage Products. Fuel analyses were conducted to determine ethanol content, heating value, specific gravity, carbon, hydrogen, and oxygen content. The results of these analyses are shown in Table 2. These results were used in calculations of the volumetric fuel economy results from the program and for the R factor analysis.

EPA/V2/E-89 Study

The second study providing data for an R -factor analysis is the EPA/V2/E-89 fuel effects program (referred to here as "EPA/V2"), conducted by Southwest Research Institute between March 2009 and May 2010. Data collection was sponsored by EPA, DOE/NREL, and CRC to quantify the impacts of five fuel parameters on exhaust emissions of Tier-2-compliant passenger cars and light trucks [11]. The resulting dataset includes 926 fuel economy results collected on a test fleet of 15 high-sales vehicles (described in Table 3) driven over the LA92 test cycle at a nominal temperature of 75°F (REF EPA/V2 testing Report).

A set of 27 test fuels was arranged in a matrix optimized to allow analysis and modeling of the five main property effects plus several interactive effects. The range of test fuel properties was chosen to span the typical range found in U.S. market gasoline except for ethanol, which had levels up to 20% volume. A round robin was conducted to measure all test fuel properties, with three or more laboratories providing results for each parameter. One exception is the heating value for fuel 25 where one measurement fell below the expected range and was removed from the average. The resulting properties as used in the R -factor analysis are given in Table 4.

Other procedures used during the EPA/V2 study to ensure high quality data included measurement of fuel carryover in test vehicle tanks to ensure drain/fill procedures were sufficient, monitoring of fuel trim learning to ensure stable values were reached after changes in fuel ethanol level, and randomization of test fuel order for each vehicle.