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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 EPAct/V2/E-89 project results, and the DOE Intermediate Ethanol Blends Catalyst Durability Program. The Immediate Effects Study and EPAct 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 (CO_2), 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.

$$R = \frac{\left(\frac{VOLFEi}{VOLFEr}\right) - 1}{\left(\frac{VOLHVi}{VOLHVr}\right) - 1} \tag{1}$$

VOLFEi is the resultant volumetric fuel economy from a test using a test fuel with a volumetric heating value of VOLHVi. VOLFEr 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].

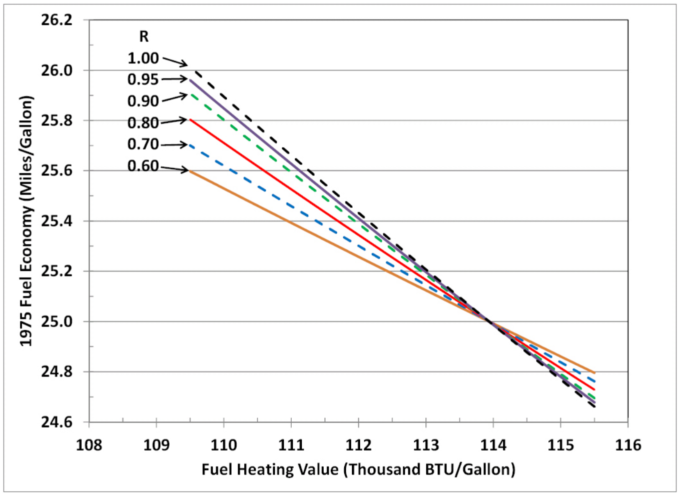

Figure 1. Influence of volumetric heating value and R value on calculated 1975 fuel economy results.

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 value of R. 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.

$$E = V_F * D_F * HV_F * \eta_E * \eta_P \tag{2}$$

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.

$$VOLFE = VOLHV * \eta_E * \eta_P * \frac{Distance}{E} \tag{3}$$

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.

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

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.

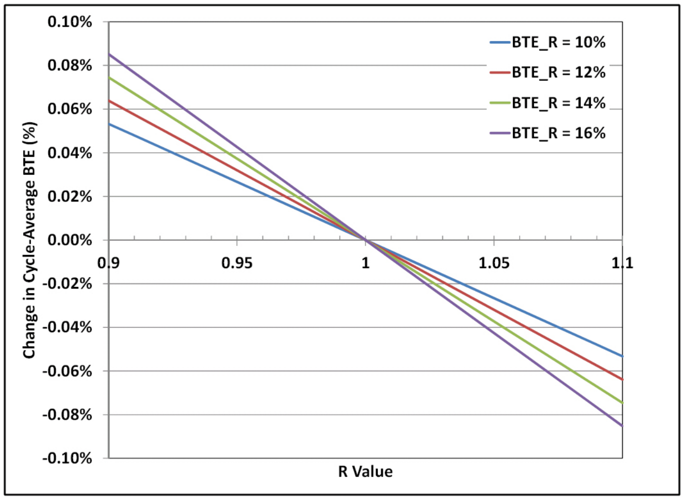

Figure 2. Relationship between R factor and Change in Cycle Average Brake Thermal Efficiency.

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 EPAct/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.

EPAct/V2/E-89 Study

The second study providing data for an R-factor analysis is the EPAct/V2/E-89 fuel effects program (referred to here as “EPAct”), 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 EPAct 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 EPAct 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.

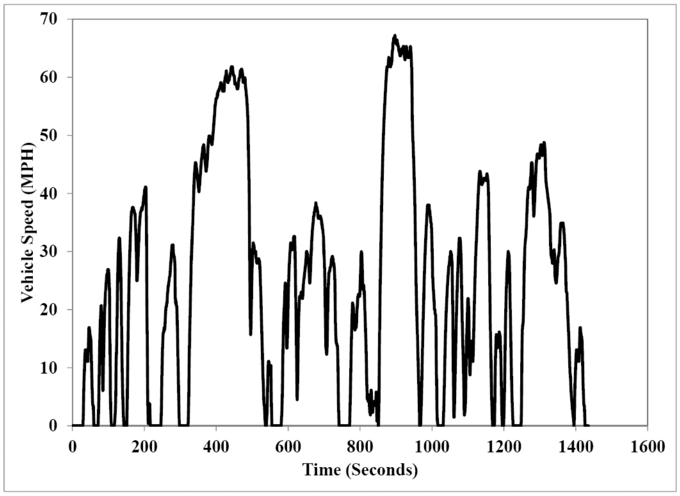

Figure 3. Speed-time profile for the LA92 drive cycle.

Catalyst Durability Study

The final data source for the R factor analyses was the Catalyst Durability Study that was also conducted during the Intermediate Ethanol Blends Program, in which 86 vehicles were studied with extensive aging and emissions tests to examine catalyst durability with ethanol blends [12]. This study utilized the FTP drive cycle, which is shown in Figure 3. Tests were conducted at Southwest Research Institute (SwRI), TRC, and at Environmental Testing Corporation (ETC). Data from tests at SwRI and TRC were included in the R factor analysis. A preliminary analysis was published in 2013 [13].

Table 1. Vehicle models from V1 study included in R factor analysis.

Model Year	Vehicle Model	Engine Family Number	Engine Configuration
2007	Chrysler Town & Country	7CRXT03.8NEO	3.3L V6
2007	Ford F150	7FMXT05.44H7	5.4L V8
2003	Ford F150	3MFXT05.4PFB	5.4L V8
2003	Ford Taurus	3FMXV03.0VF3	3.0L V6
2007	Buick Lucerne	7GMXV03.9146	3.8L V6
2003	Buick LeSabre	3GMXV03.8044	3.8L V6
2007	GM Silverado	7GMXT05.3379	4.8L V8
2007	Honda Accord	7HNXV02.4KKC	2.4L I4
2003	Nissan Altima	3NSXV03.5C7A	3.5L V6
2007	Toyota Camry	7TYXV02.4BEB	2.4L I4
2003	Toyota Camry	3TYXV02.4HHA	2.4L I4
2001	Chrysler PT Cruiser	1CRXV02.4VD0	2.4L I4
1999	Ford Crown Victoria	XFMXV04.6VBE	4.6L V8
1999	Honda Civic	XHNXV01.6TA3	1.6L I4
1999	Toyota Corolla	XTYXV01.8XBA	1.8L I4
2004	VW Golf TDI	4ADXV01.8356	1.8L I4 Turbo

Table 2. Results of fuel analyses in the Immediate Ethanol Effects study.

Test Laboratory	Fuel	D5599 Ethanol (vol%)	D240 LHV (BTU/lbm)	D4052 Specific Gravity	D5291 Carbon (wt%)	D5291 Hydrogen (wt%)	D5599 Oxygen (wt%)
NREL/CDPHE	E0	0.0	18,533	0.746	86.15%	13.05%	0.00%
	E10	9.9	17,873	0.750	81.84%	12.37%	3.65%
	E15	13.9	17,471	0.752	80.72%	12.68%	5.11%
	E20	18.6	17,091	0.754	78.77%	12.92%	6.79%
ORNL	E0	0.0	18,534	0.746	86.83%	12.97%	0.00%
	E10	9.1	17,844	0.750	82.56%	12.62%	3.36%
	E15	14.4	17,485	0.752	80.16%	12.52%	5.27%
	E20	19.8	17,043	0.755	79.66%	12.84%	7.23%
ANL/TRC	E0	0.0	18,542	0.746	86.83%	12.85%	3.62%
	E10	9.9	17,793	0.751	82.29%	12.85%	3.62%
	E15	14.3	17,412	0.752	80.58%	13.41%	5.24%
	E20	19.6	17,044	0.755	78.97%	12.71%	7.17%

Table 3. Vehicle models from EPAct study included in R factor analysis.

Vehicle ID	Model Year	Brand/Model	Engine Family	Engine Size
CCOB	2008	Chevrolet Cobalt	8GMXV02.4025	2.2L I4
CIMP	2008	Chevrolet Impala FFV	8GMXV03.9052	3.5L V6
CSIL	2008	Chevrolet Silverado	8GMXT05.3373	5.3L V8
DCAL	2008	Dodge Caliber	8CRXB02.4MEO	2.4L I4
F150	2008	Ford F150 FFV	8FMXT05.44HF	5.4L V8
FEXP	2008	Ford Explorer	8FMXT04.03DB	4.0L V6
FFOC	2008	Ford Focus	8FMXV02.0VD4	2.0L I4
HCIV	2008	Honda Civic	8HNXV01.8LKR	1.8L I4
HODY	2008	Honda Odyssey	8HNXT03.54KR	3.5L V6
JLIB	2008	Jeep Liberty	8CRXT03.7NE0	3.7L V6
NALT	2008	Nissan Altima	8NSXV02.5G5A	2.5L I4
SOUT	2008	Saturn Outlook	8GMXT03.6151	3.6L V6
TCAM	2008	Toyota Camry	8TYXV02.4BEA	2.4L I4
TCOR	2008	Toyota Corolla	8TYXV01.8BEA	1.8L I4
TSIE	2008	Toyota Sienna	8TYXT03.5BEM	3.5L V6

During the catalyst durability study, matched sets of each vehicle model were studied. Vehicles that were aged using an ethanol-blended fuel (for example E15) were emissions tested using that fuel and E0 at three points during the aging study. These points were referred to as start-of-test (SOT), mid-test (MID), and end-of-test (EOT). E15 and E20 data were available from all vehicle models, and E10 results were available for 5 vehicle models. 18 vehicle models from the catalyst durability study were utilized for the R factor analysis [13]. The 18 vehicles are listed in Table 5. Multiple batches of each fuel were used at each site owing to the much larger size of the program and logistical limitations on fuel storage.

Fuels at SwRI were managed by assigning batches to vehicle models so that each vehicle model used the same fuels throughout the program. Fuel batches at TRC were used chronologically, meaning that several vehicle models used different batches of fuel as the program proceeded.

Table 4. Fuel properties for the EPAct study fuels.

Fuel ID	D5599 Ethanol (vol %)	D4809 Net Heating Value (Btu/gal)	D4052 Density (g/ml)	D5291 Carbon Mass Frac.
1	10.0	108,412	0.7211	0.8170
2	0.0	113,752	0.7220	0.8512
3	10.4	109,404	0.7350	0.8161
4	9.9	110,450	0.7346	0.8221
5	0.0	116,567	0.7573	0.8658
6	10.6	109,941	0.7342	0.8152
7	0.0	112,975	0.7208	0.8516
8	0.0	113,481	0.7191	0.8512
9	0.0	115,429	0.7454	0.8703
10	9.8	112,887	0.7644	0.8347
11	10.3	112,093	0.7596	0.8368
12	9.8	111,455	0.7517	0.8332
13	0.0	116,653	0.7540	0.8676
14	0.0	112,657	0.7223	0.8528
15	0.0	114,749	0.7428	0.8688
16	10.8	112,231	0.7636	0.8340
20	20.3	106,589	0.7425	0.7806
21	20.1	109,165	0.7754	0.7990
22	20.5	105,747	0.7371	0.7824
23	20.3	106,936	0.7476	0.7834
24	20.5	106,700	0.7422	0.7847
25	20.0	108,938	0.7702	0.8062
26	15.2	109,893	0.7593	0.8148
27	14.9	109,395	0.7434	0.8027
28	15.0	111,429	0.7699	0.8178
30	9.8	111,135	0.7508	0.8317
31	20.1	109,294	0.7742	0.7990

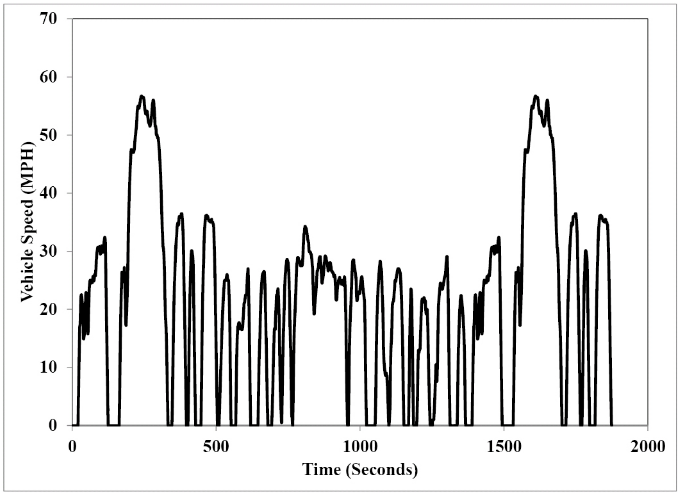

Figure 4. Speed-time profile for the FTP drive cycle.

The carbon, hydrogen, and oxygen fractions did not sum to 100% for some of the SwRI fuels, presumably due to incomplete recovery during the American Society for Testing and Materials (ASTM) D5291 test due to the volatility of the test fuels. In such cases, the carbon and hydrogen weight fractions were adjusted by computing a scaling factor to account for the incomplete recovery. The reported carbon and hydrogen fractions were multiplied by the scaling factor so that the sum of the carbon, hydrogen, and oxygen fractions summed to 100%, and these adjusted fractions were used in calculation of the fuel economy results and the R factor values. The oxygen fractions were accepted as correct and not adjusted, since they were determined through a different test, ASTM D5599.

The heating value results for three fuels used at TRC were found to be suspect. Since all of the ethanol blends at TRC were derived from a single batch of E0, the relationship between fuel oxygen content and heating value would be expected to be linear. Three heating value results were found to deviate considerably from a linear behavior. The remaining fuel analysis results were used to construct a best-fit line and the resulting best-fit relationship was used to calculate the appropriate heating value results for the three suspect fuels based on their measured oxygen content. This relationship is shown in Figure 5. The square data points indicate the suspect values. The hollow circles indicate the heating values that were used in calculations. Additionally, a previously-published correlation based on the carbon, hydrogen, and oxygen weight fractions was used to estimate the suspect heating values for comparison [14]. In all three cases, the estimate based on carbon, hydrogen, and oxygen weight fractions confirmed that the originally reported values of heating value were suspiciously low. The values estimated from the weight fractions were within 100 BTU/lbm of the values estimated using the remaining data from this study. Thus, the values estimated from heating value and oxygen content of fuels in this study were used in R factor calculations, as shown in Figure 5. Carbon fraction, density, and heating value for the SwRI fuels are shown in Table 6. Similar data are shown for the TRC fuels in Table 7. Fuels with adjusted parameters as discussed previously are highlighted with a light-gray background in both tables.

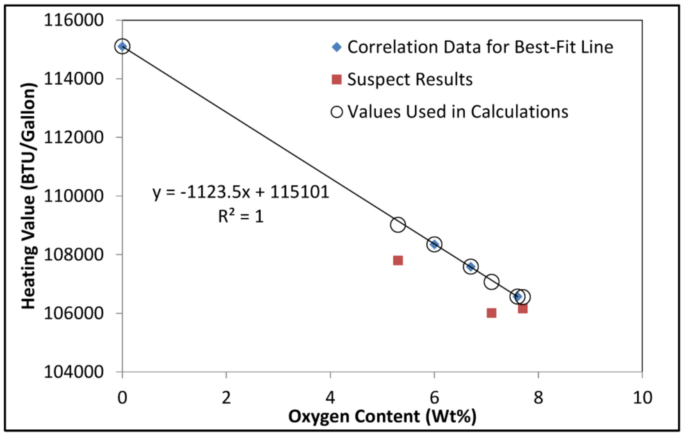

Figure 5. Adjustment of heating values for three TRC fuels.

Table 5. Vehicles from the catalyst durability study included in R factor analysis.

Model year	Vehicle model	Engine family number	Engine Configuration
2007	Honda Accord	7HNXV02.4KKC	2.4L I4
2006	Chevrolet Silverado	6GMXT05.3379	5.3L V8
2008	Nissan Altima	8NSXV02.5G5A	2.5L I4
2008	Ford Taurus	8FMXV03.5VEP	3.5L V6
2007	Dodge Caravan	7CRXT03.8NEO	3.8L V6
2006	Chevrolet Cobalt	6GMXV02.4029	2.4L I4
2007	Dodge Caliber	7CRXB02.4MES	2.4L I4
2002	Nissan Frontier	2NSXT02.4C4B	2.4L I4
2002	Dodge Durango	2CRXT04.75B0	4.7L V8
2009	Jeep Liberty	9CRXT03.74PO	3.7L V6
2009	Ford Explorer	9FMXT04.03DC	4.0L V6
2009	Honda Civic	9HNXV01.8XB9	1.8L I4
2009	Toyota Corolla	9TYXV01.8BEA	1.8L I4
2005	Toyota Tundra	5TYXT04.0NEM	4.0L V6
2006	Chevrolet Impala	6GMXV03.9048	3.9L V6
2005	Ford F150	5FMXT05.4R17	5.4L V8
2003	Toyota Camry	3TYXV02.4HHA	2.4L I4
2003	Ford Taurus	3FMXV03.0VF3	3.0L V6

R FACTOR CALCULATION

The Auto/Oil study published in 1993 focused on a regression technique to calculate values for the R factor [6]. In this approach, each vehicle was individually tested on every fuel included in the study. The average of all vehicle results for each fuel was calculated and these values used in a regression with volumetric heating value. The slope of the best-fit line through these data is related to R in a defined way, allowing R to be calculated from the slope of the line. As discussed previously, the vehicles in the Immediate Effects Study and the EPAct/V2/E-89 study were each tested with all of the ethanol-blended fuels. R-factor results for individual vehicles in the EPAct study were calculated in a similar manner described for the Auto/Oil program. Volumetric fuel economy results across all test fuels were regressed on fuel net heating value (NHV) for each vehicle (approximately 60 observations with replicates) using a least-squares method. Figure 6 shows the weighted composite dataset, with trend lines indicating increasing fuel economy with NHV for each vehicle (weighted composite was calculated using the standard FTP factors of 0.43 times bag 1+2 plus 0.57 times bag 2+3). The resulting slope values were then used with the high and low NHVs to compute R for each vehicle. Uncertainty was computed as 95% confidence intervals derived from the standard error values for each vehicle's slope. Test fleet average R-values for the EPAct study were calculated by fitting a mixed model to the dataset treating vehicle as a random effect. The model-estimated slope and its standard error were used to compute R and its confidence intervals in the same way as for the individual vehicles.

Screening for outliers was done for each vehicle's fuel economy dataset using a test of whether points fell outside a range defined as three times the inter-quartile range above the 75th percentile or below the 25th percentile. No observations were found to be outliers by this method.

The slope method is very useful when each vehicle in the study is tested using a relatively large number of fuels, as was the case for both the Auto/Oil and the EPAct studies. Although the Immediate Effects study did test each car with every fuel, there were only four fuels studied. Thus, individual R values for each fuel and vehicle were calculated, as described below.

Table 6. SwRI test fuel properties.

Vehicle	E0 Fuel			E10 Fuel			E15 Fuel			E20 Fuel		
	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)
2007 Accord	0.869	0.744	115,495	0.831	0.748	111,491	0.815	0.752	109,656	0.792	0.754	106,727
2006 Silverado	0.869	0.743	115,138	0.829	0.751	111,296	0.812	0.751	108,849	0.794	0.752	107,213
2008 Altima												
2008 Taurus	0.878	0.742	116,328	0.832	0.748	111,707	0.817	0.751	109,844	0.795	0.752	107,269
2007 Caravan												
2006 Cobalt	0.866	0.744	114,784	Vehicles not tested on E10			0.813	0.751	109,483	0.793	0.753	107,330
2007 Caliber												
2002 Frontier												
2002 Durango	0.866	0.743	115,083				0.811	0.752	108,782	0.798	0.753	107,549

Table 7. TRC test fuel properties.

Start of Test

Vehicle	E0 Fuel			E15 Fuel			E20 Fuel		
	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)
2009 Civic	0.872	0.743	115,205	0.809	0.751	108,441	0.801	0.753	107,680
2009 Explorer									
2009 Corolla									
2009 Liberty									
2005 Tundra							0.792	0.754	106,648
2006 Impala									
2005 F150									
2003 Camry							0.792	0.752	106,659
2003 Taurus									

Midlife Test

Vehicle	E0 Fuel			E15 Fuel			E20 Fuel		
	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)
2009 Civic	0.872	0.743	115,205	0.809	0.751	108,441	0.792	0.754	106,648
2009 Explorer									
2009 Corolla									
2009 Liberty									
2005 Tundra							0.792	0.752	106,659
2006 Impala									
2005 F150									
2003 Camry							0.795	0.752	106,910
2003 Taurus				0.813	0.749	109,111	0.797	0.752	107,161

End of Test

Vehicle	E0 Fuel			E15 Fuel			E20 Fuel		
	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)	Carbon Fraction ASTM D5291	Density (g/cc) ASTM D4052	LHV (BTU/gal)
2009 Civic	0.872	0.743	115,205	0.809	0.751	108,441	0.792	0.752	106,659
2009 Explorer									
2009 Corolla				0.813	0.749	109,111	0.797	0.752	107,161
2009 Liberty									
2005 Tundra									
2006 Impala									
2005 F150									
2003 Camry									
2003 Taurus									

The vehicles in the catalyst durability study were tested such that one vehicle of each model was tested with one ethanol-blended fuel plus E0. Thus, while it is possible to use the regression method to calculate the R factor from the EPACT study data, it is not possible to use this method for the results of the catalyst durability study.

Accordingly, a different method for R factor calculation was adopted for the immediate effects and the catalyst durability studies. The average fuel economy for a given vehicle (not vehicle model) was calculated for each fuel and at each test interval. For example, consider a 2009 Ford Explorer from the catalyst durability study. Two of these vehicles used an ethanol-blended fuel: one used E15 and the other used E20. Both were also tested using E0. These tests occurred three times during the program, at SOT, MID, and EOT. The average fuel economy of the E15 vehicle was computed for tests where it used E0 and again for tests using E15. These average values were used with the appropriate fuel property information to calculate an R value for the E15 vehicle at each test interval, with the E0 results taken as the reference fuel results. Similarly, R values for the E20 vehicle were calculated. This process was repeated for each vehicle included from the catalyst durability study. Similarly, R values were calculated based on the E0 and each ethanol-blended fuel for each vehicle in the Immediate Effects Study.

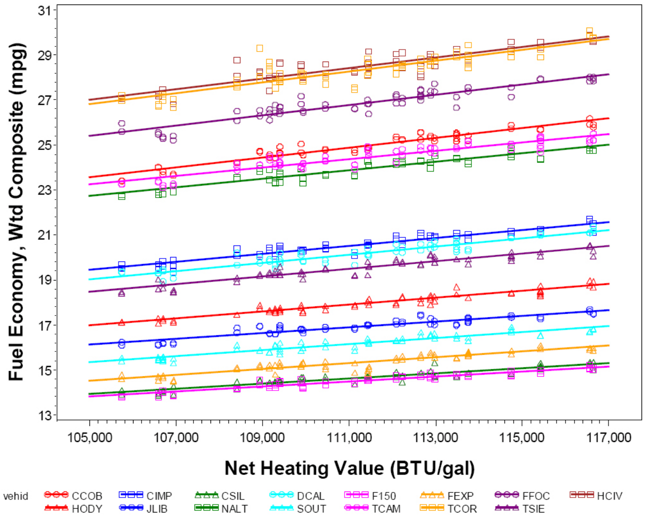

Figure 6. Weighted composite fuel economy dataset from the EPAct study.

The calculated R values for each vehicle were averaged in several characteristic groupings for analysis of the results. In each case, a 95% confidence interval was calculated for the average. The confidence intervals varied considerably in magnitude according to variability and the number of data points used in the average. For example, an average R value was computed for each vehicle model. These results typically have the largest confidence intervals, since only 6 values (for vehicles models tested with E15 and E20) or 9 values (for vehicles tested with E10, E15, and E20) were included in the average.

RESULTS

R factor values calculated from the Immediate Effects Study using the LA92 drive cycle test results are shown in Figure 7. The results show that there is no statistically significant difference between the average values for the Tier 2 and pre-Tier 2 fleets. Average values are less than 0.9 in all cases except for the E20 data. The average R value tends to increase for all fleets with increasing fuel ethanol content, indicating that cycle average engine efficiencies decreased as ethanol content increased. However, an analysis of variance (ANOVA) test was conducted and confirmed that differences in R values between the test fuel groupings were not statistically significant at the 95% confidence level. The total fleet average R factor on all fuels for the LA92 cycle was 0.891±0.075, and for the Tier 2 fleet was 0.858±0.087. A t-test determined that the difference between the Tier-2 fleet and the Pre-Tier-2 fleet averages was not statistically significant. The number of observations available for each individual vehicle was too low to obtain meaningful R values by vehicle.

Since the EPAct study generated a larger number of observations on each vehicle, it was possible to determine R values by vehicle, as shown in Figure 8. The results show that there is significant variation in response among vehicles. The average R value for the EPAct test fleet was 0.921±0.010.

R values can also be calculated for the individual emission bags, as well as subsets of the fuel matrix containing different ethanol levels. Test fleet average values for these results are shown in Figure 9. Differences between bags don't appear to be meaningful, however these results suggest the R value found for E15-E20 test fuels is higher than for E0 or E10 fuels. Note that results shown by ethanol level for the EPAct study describe the effect of a change in heating value at fixed ethanol level, while results for the "All Fuels" group (as well as the other studies in this paper) include the change in ethanol level as part of the change in heating value.

Both studies using the LA92 cycle suggest with varying levels of statistical confidence that R values increase as ethanol content in the fuel increases. This trend indicates that cycle average engine efficiency for the LA92 cycle declines marginally as the fuel ethanol content increases. Referring to Figure 2, this marginal decline is very small, on the order of 0.05-0.085% brake thermal efficiency. It is not possible to determine a precise reason for this decline from the data, and it is likely that differences occur across vehicle models.

Reduction of knock-limited operation resulting from the higher octane ethanol blends would cause engine efficiency to increase. Although this effect may be present, the results suggest it is of smaller impact than other effects that tend to decrease engine efficiency.

One possible effect that could explain the observed decrease in efficiency is that the use of learned fuel trim during open loop conditions results in greater fuel use with the oxygenated fuels than with the non-oxygenated baseline fuel. Such a shift could increase fuel consumption without changing the useful work output of the engine, and thus cause the efficiency to decline slightly. This hypothetical effect, if correct, could explain the results observed from both studies on the LA92 cycle, but may not be the only plausible explanation. Additional studies designed to examine this issue are needed in order to firmly establish the cause of the ethanol effects on the LA92 cycle R values.

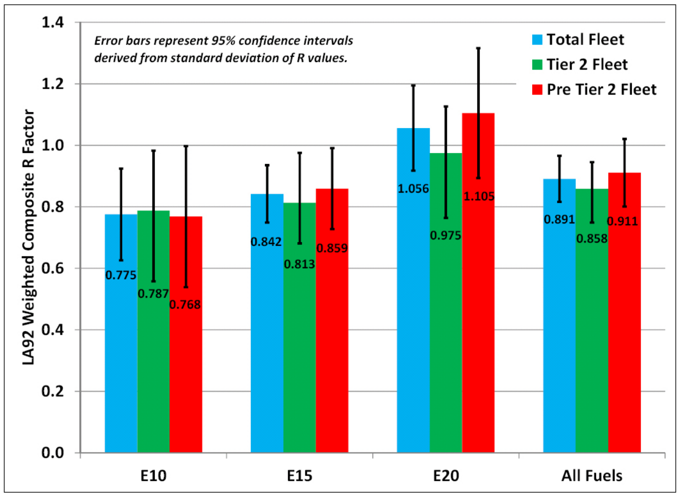

Figure 7. R factor values from the Immediate Effects Study.

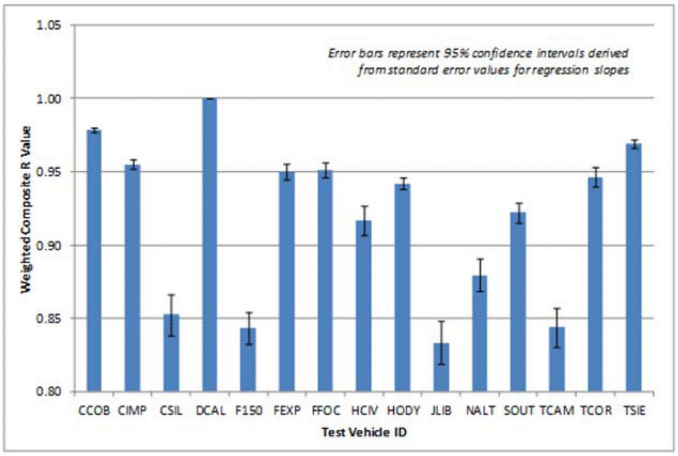

Figure 8. Weighted composite R values from the EPAct study by vehicle using all test fuels.

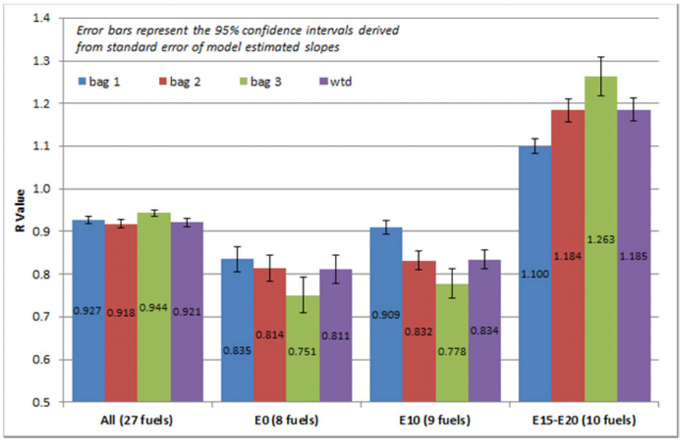

Figure 9. EPAct test fleet average R values by ethanol level and emission bag.

The R factor results from the Catalyst Durability Study using the FTP drive cycle are shown in Figure 10. The vehicles were grouped according to whether they were certified to the Tier 2 emissions standard or an emissions standard prior to Tier 2 and as a total fleet. R factors were pooled to analyze each of the fleet groupings for each ethanol level and with all fuels combined. In each case, the bar shows the average value, with the error bars indicating 95% confidence intervals. The number of vehicles tested using E10 was considerably smaller than for E15 and E20, and this smaller pool of data resulted in increased confidence intervals for E10 relative to the other fuels.

The results show that the average R factor is slightly lower than unity, but greater than 0.9 in all cases. The pre-Tier 2 fleet average R factor is consistently lower than the Tier 2 fleet, but a t-test confirmed that the difference was not statistically significant. The FTP average R factor for the total fleet on all fuels was 0.935±0.042. The Tier 2 fleet average R factor on all fuels was 0.939±0.051. Results from the 2007 Honda Accords were found to be inconsistent and questionable. For example, the E10 vehicle returned R values for the SOT, MID, and EOT of 0.761, 0.824, and 0.198. Examination of the test results showed that the variability was a result of variability in the reported fuel economy data. The EOT results for the E10 vehicle tested on E0 appeared inexplicably low compared with other tests. Similarly, the E15 vehicle appeared to have tests using E15 that were not consistent, and the E20 vehicle MID test data with both E0 and E20 was inconsistent. These issues caused the calculated R values to vary widely and to magnitudes that do not appear rational, such as the 0.198 result for the E10 vehicle and values greater than 1.1 for the E20 vehicle. No single cause for the questionable nature of the results could be firmly established, and it is worth noting that the inconsistencies are only on the order of about 0.5 miles per gallon. If the results from this vehicle model are eliminated from the analysis, the total fleet average R value increases slightly to 0.949±0.041, and the Tier 2 fleet average becomes 0.958±0.052.

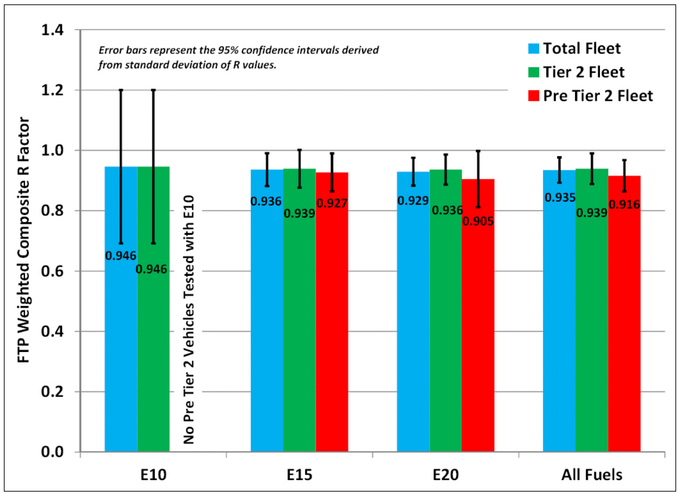

Figure 10. Weighted composite R values from the FTP cycle.

The fleet average R values for most fuels on the LA92 cycle were slightly lower than those observed for the FTP cycle. The E15-E20 fuel average from the EPAct study as well and the E20 fuel average from the Immediate Effects Study was higher than the corresponding fuel average R values on the FTP cycle. As has been previously discussed, differences in drive cycle could give rise to differences in R values depending upon some aspects of engine design and calibration.

The tendency for increasing fuel ethanol content to increase the value of R on the LA92 cycle was not observed on the FTP cycle. The most significant difference between the two cycles is the inclusion of more aggressive acceleration events in bag 2 of the LA92 cycle. It is possible that ethanol specific effects on R, arising from ethanol's higher knock resistance or the application of learned fuel trim during open-loop transients, may arise during these aggressive accelerations. As the trend for downsizing and downspeeding of engines to improve fuel economy progresses, it is conceivable that ethanol effects could become observable on the FTP cycle for future vehicles. These are topics that should be explored in future studies more specifically focused on fuel economy.

Uncertainties in R Factor Determination

An important consideration in conducting experimental analyses for R-factor is the sensitivity of the results to measurement error and variability. Since the differences in fuel economy and fuel heating value being examined are typically small relative to their values, Equation 1 can produce widely varying quotients. This issue is complex because the fuel economy measurements contain test-to-test variability in emission results as well as fuel property measurements that contain some level of uncertainty. The acceptable level of repeatability for the ASTM D240 net heating value test is ±0.40 MJ/kg, or approximately ±172 BTU/gallon [15]. This level of uncertainty in the fuel heating value results in an uncertainty in R of approximately 0.05. Similarly, the uncertainty in R posed by the acceptable repeatability in the ASTM D4052 test for specific gravity is 0.00031, which produces an uncertainty in R of approximately 0.0004 [16]. The acceptable repeatability for determination of the carbon weight fraction by ASTM D5291 is 0.5644% [17]. It is noteworthy, however, that gasoline-range fuels are no longer included in the scope of ASTM D5291 due to their volatility. Nevertheless, variations of this test method are still in wide use for gasoline. The uncertainty in R produced by the level of repeatability stated for D5291 is approximately 0.11. The uncertainties imposed by variability in the ASTM methods have not been included in the R factor confidence intervals reported in this paper.

Additionally, experimental issues beyond test variability can confound determination of the R factor. While it is not practical to calculate the effect that some of these issues could have with a high degree of confidence, it is possible to estimate the direction and magnitude of their impacts. Plotting the fuel economy results versus the heating value for the test fuels (such as in Figure 6) can aid in identifying outliers in the data.

For example, one issue of consequence is that of fuel carryover during test fuel changes. Fuel carryover that results from an incomplete fuel change would have the effect of reducing the difference in volumetric fuel economy measured for the test fuels. Thus, fuel carryover would tend to reduce the value of the numerator in Eq. (1) while the denominator would remain fixed, resulting in a reduction in R regardless of the test order for the fuels. If the fuel carryover level was just 1%, it could result in an error in the actual heating value of the fuel in the tank as high as 81 BTU/gallon, which would cause a reduction in R of roughly 0.025.

Another potential issue is absorption of water from air in the storage tank headspace by ethanol-blended fuel after heating value determination but before vehicle testing. In this case, fuel economy would decline more than expected based on heating value difference and thus would cause the value of R to increase for a change to a fuel with a lower heating value than the reference fuel. If the fuel absorbs water at the rate of 1% of the ethanol volume in the blend, an E20 blend could experience an increase its water content of 0.2%. This change would decrease the actual heating value of the fuel in tank by approximately 200 BTU/gallon and would increase the value of R by about 0.06.

CONCLUSIONS

- The Intermediate Ethanol Blends Immediate Effects Study showed an average R value for the total test fleet and for all fuels of 0.891±0.075 using the LA92 drive cycle.
- The EPAct study showed an average R value for the total test fleet and for all fuels of 0.921±0.010 using the LA92 drive cycle.
- Results for the LA92 drive cycle suggest R factor may be higher for E15 and E20 fuels than for E0 or E10 fuels.
- Fuel economy results from the Intermediate Ethanol Blends Catalyst Durability Study showed an average R value for the total test fleet and for all fuels of 0.935±0.042 using the FTP drive cycle. This value increases to 0.949±0.041 if questionable results from one vehicle model are discarded.
- R values for the FTP cycle were not observed to have a dependence on the fuel ethanol content.
- The R factor calculation is sensitive to experimental variability; hence, large amounts of data are needed to examine R values with reasonable confidence intervals.
- Examination of the results from all three studies shows that R factor values for modern vehicles are closer to unity than the 0.6 value originally established in the 1980s.

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DEFINITIONS/ABBREVIATIONS

ANL - Argonne National Laboratory
ANOVA - Analysis of variance
ASTM - American Society for Testing and Materials
CAFE - Corporate Average Fuel Economy Standards
CDPHE - Colorado Department of Public Health
CO - Carbon Monoxide
CO_2 - Carbon Dioxide
D_F - Fuel density
E - Energy delivered to the road
E0 - Gasoline blend with 0 vol% ethanol
E10 - Gasoline blend with 10 vol% ethanol
E15 - Gasoline blend with 15 vol% ethanol
E20 - Gasoline blend with 20 vol% ethanol
EISA - Energy Independence and Security Act
EOT - End-of-test
EPA - (or U.S. EPA) United States Environmental Protection Agency
EPCA - Energy Policy and Conservation Act
ETC - Environmental Testing Corporation
FTP - Federal Test Procedure
HC - Hydrocarbons
HFET - Highway Fuel Economy Test
HV_F - Mass basis fuel heating value
MID - Mid-test
NHTSA - National Highway Traffic Safety Administration
NHV - Net heating value
NREL - National Renewable Energy Laboratory
ORNL - Oak Ridge National Laboratory
R - R factor
SOT - Start-of-test
SwRI - Southwest Research Institute
TRC - Transportation Research Center, Inc.
V_F - Volume of fuel consumed
VOLFEi - Volumetric fuel economy result for test fuel
VOLFEr - Volumetric fuel economy result for reference fuel
VOLHVi - Volumetric heating value for test fuel
VOLHVr - Volumetric heating value for reference fuel
η_E - Cycle average engine efficiency
η_{Ei} - Cycle average engine efficiency for the test fuel
η_{Er} - Cycle average engine efficiency for the reference fuel
η_P - Cycle average lumped powertrain efficiency